World Renewable Energy Congress – Sweden

8–13 May, 2011
Linköping, Sweden

Editor

Professor Bahram Moshfegh

Linköping Electronic Conference Proceedings, 57
Linköping University Electronic Press
Linköping, Sweden, 2011

http://www.ep.liu.se/ecp_home/index.en.aspx?issue=057
ISBN: 978-91-7393-070-3
ISSN 1650-3740 (online)
ISSN 1650-3686 (print)

Volume 3

Energy End-Use Efficiency Issues

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Review on graphite foam as thermal material for heat exchangers

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Abstract: Due to the increased power consumptions in equipment, the demand of effective cooling methods becomes crucial. Because of the small scale spherical pores, graphite foam has huge specific surface area. Furthermore, the thermal conductivity of graphite foam is four times that of copper. The density of graphite foam is only 20 % of that of aluminum. Thus, the graphite foam is considered as a novel highly - conductive porous material for high power equipment cooling applications. However, in the commercial market, aluminum and copper are still the preferred materials for thermal management nowadays. In order to promote the graphite foam as a thermal material for heat exchangers, an overall understanding of the graphite foam is needed. This paper describes the structure of the graphite foam. Based on the special structure, the thermal properties and the flowing characteristics of graphite foam are outlined and discussed. Furthermore, the application of graphite foam as a thermal material for heat exchangers is highlighted for electronic packages and vehicle cooling systems. The physical problems and other aspects, which might block the development of graphite foam heat exchangers, are pointed out. Finally, several useful conclusions and suggestions are given to promote the development of graphite foam heat exchangers.

Keywords: *Graphite foam, heat exchanger, thermal management*

1. Introduction

Nowadays the power of equipment is increased. For instance, the power of computer chips is increased, and the power of vehicle engines is also increased. This increased power leads to a requirement of an effective cooling method. Currently the thermal management has focused on aluminum and copper heat exchangers, because of high thermal conductivity (180 W/(m.K) for aluminum 6061 and 400 W/(m.K) for copper). However, when the density is considered, the specific thermal conductivity of aluminum or copper (thermal conductivity divided by specific gravity) is only 54 and 45 W/(m.K), respectively. Thus, when the weight is a significant factor, it is necessary to introduce a thermal material with low density, high thermal conductivity and large specific surface area.

An efficient thermal management method is the utilization of microcellular foam materials such as metal or graphite foams, based on the enhancement of heat transfer by huge fluid-solid contact surface area and the fluid mixing. An example of graphite foam application was developed at Oak Ridge National Laboratory (ORNL) in 1997. Klett et al. [1] found that the thermal conductivity of the solid component of graphite was as high as 1700 W/(m.K), which was around four times that of copper. The effective thermal conductivity of graphite foam was more than 150 W/(m.K), which was higher than the value of aluminum foam (2 - 26 W/(m.K)). On the other hand, the density of graphite foam was 0.2 - 0.6 g/cm^3, which was only 1/5 of that of aluminum. The specific surface area was between 5000 and 50000 m^2/m^3.

Because of the high thermal conductivity, low density and large specific surface area, the graphite foam is recognized as an appropriate material for the thermal management. It is primarily focused on the electronic power heat sinks. A large number of studies have been carried out to analyze graphite foam heat exchangers. However, in the commercial market of heat exchangers, aluminum and copper are still the preferred thermal material. Thus, there are several problems blocking the development of graphite foam heat exchangers. Otherwise the graphite foam heat exchangers would be easily found in the market.

In order to promote the development of graphite foam as a thermal material for heat exchangers, this paper will present an overall view or conception about graphite foam heat exchangers. Firstly, the structure of graphite foam is introduced in Section 2. Based on the structure of graphite foam, the thermal properties and flow characteristics of graphite foam are explained in Section 2 as well. After that, the application of graphite foam heat exchangers is outlined in Section 3. In Section 4, potential problems blocking the development of graphite foam heat exchangers are pointed out. Based on the review and analysis, several useful conclusions and suggestions are highlighted in Section 5.

2. Structures and properties of graphite foam

2.1. Structures

Carbon foams were first developed in the late 1960s as reticulated vitreous (glassy) foam [2]. The initial carbon foams were made by pyrolysis of a thermosetting polymer foam to obtain a carbonaceous skeleton or reticulated vitreous carbon (RVC) foam. A blowing technique or pressure release is utilized to produce foam of the pitch precursor. Then the pitch foam is stabilized by heating in air or oxygen for many hours to cross-link the structure, and 'set' the pitch. In this case, the foam does not melt during the further heat treatment. However, stabilization can be a very time consuming and expensive process depending on the pore size. So ORNL [3] developed a new, little time consuming process to fabricate pitch - based graphitic foams without the traditional blowing and stabilization steps. This new foam is believed to be less expensive and easier to fabricate than the traditional foams.

Klett et al. [1] gave an overall view of the structure of the new graphite foam. The average pore diameter is from 275 to 350 μm in the ARA24 - derived foams. The scanning electron micrographs of fracture surfaces, which reveals the pore structure of the ARA24 - derived foams heat - treated at 1000 ℃, are shown in Fig. 1. Inside the foam, there are many spherical pores with small openings. These pores are three - dimensionally interconnected.

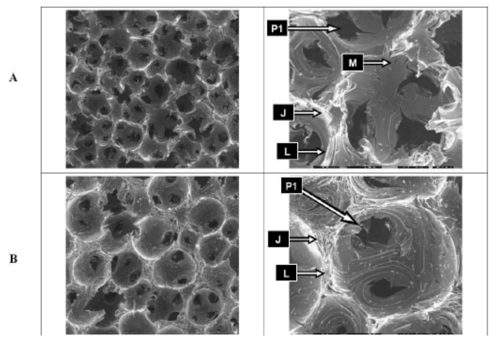

Fig. 1. Photomicrographs of the foams produced from Mitsubishi ARA 24 pitch at different densities A < B (P1: opening pore; M: microcrack; J: junction; L: ligament)[1].

2.2. Thermal properties of graphite foam

Because of the special structure of graphite foam, there are several prominent thermal properties in the graphite foam. The graphite foam made by the ORNL process exhibits high effective thermal conductivity (up to 182 W/(m.K)) and low density (0.2 -0.6 g/cm^3). The data in Table 1 show that the thermal conductivity in the z – plane is much larger than the one in the x – y plane. It implies that the high thermal conductivity of the graphite foam only exists in a certain direction. This is a disadvantage of the graphite foam. Klett et al. [4] found out that the heat inside the graphite lattice was transferred down the graphite lattice fast, because of the very stiff nature of the covalent bonds (as shown in Fig. 2). Moreover, the position and vibration of atoms in the neighboring planes may impede the vibration of atoms in the plane of interest. The crystal perfection controls the thermal performance. In order to achieve high thermal conductivity in the graphite crystal, the structure must be comprised of aligned, straight grapheme planes, and so on.

Table 1. Properties of various graphite foams made by the ORNL method compared to Poco Foam[4].

	Graphitiza-tion rate (℃/min)	Average bulk density (g/cm^3)	z -Plane thermal conductivity k_z (W/(m.K))	x-y Plane thermal conductivity k_{xy} (W/(m.K))
ORNL graphite foam (A)	10	0.45	125	41
ORNL graphite foam (B)	1	0.59	181	60
PocoFoam^{TM}	-	0.61	182	65

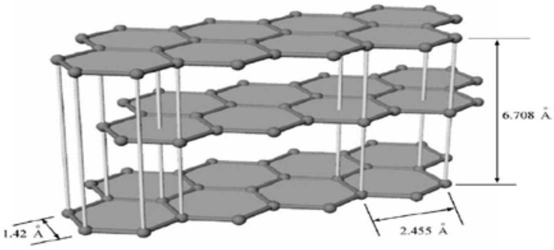

Fig. 2. Planar structure of hexagonal graphite [4].

On the other hand, Yu et al. [5] presented a model which was based on sphere - centered and interconnected unit cubes. The effective thermal conductivity was proved to be a function of the porosity of the graphite foam. Tee et al. [6] used a tapered, anisotropic strut model to predict the overall thermal conductivity of the porous graphite foam. When the size of the foam pores was increased, the convective heat transfer coefficient of the foam was reduced. By using graphite foams as the heat sinks, the enhancement of the convective heat transfer was not only because of its open and inter-connected pores, but also due to its high thermal conductivity and the extremely large surface areas. Furthermore, Straatman et al. [7] validated that the optimal thickness of graphite foam was 3 mm based on the thermal performance. Meanwhile the heat transfer increase was 28 % at low Reynolds numbers (150000). However, at high Reynolds number, the increase of the heat transfer was only 10 %.

2.3. Pressure drop of graphite foam

Graphite foam has a very high thermal conductivity, but it also has very high pressure drop, due to the large hydrodynamic loss associated with the open pores in the graphite foam [8]. Leong et al. [9] investigated pressure drop of four different configurations of graphite foams (as shown in Fig. 3). The pressure drops of these four configurations of graphite heat sinks are shown in Fig. 4. For the same inlet flow velocity, the block and baffle foams present the highest and the lowest pressure drop, respectively. On the other hand, Lin et al. [10] approved that the pressure drop through the corrugated passages could be reduced significantly while maintaining a high heat transfer coefficient. As shown in Fig. 5, for forced convection, the air is forced to go through a thin porous wall of graphite foam. Due to the short flow length inside the graphite foam, the pressure drop could be reduced greatly.

2.4. Advantages and disadvantages

Based on the special microscopic structures in graphite foams, the advantages of these materials can be summarized:

(1) High thermal conductivity (thermal conductivity of solid graphite is 1700 W/(m.K), and the effective thermal conductivity of graphite foam is more than 150 W/(m.K));
(2) Low density (0.2 to 0.6 g/cm^3);
(3) High specific surface area (5000 to 50000 m^2/m^3);

On the other hand, there are some disadvantages for the graphite foam materials:
(1) High thermal conductivity only exists in a certain direction;
(2) Due to the small scale pores and complex structures of the foam, the pressure drop through graphite foam is very high.

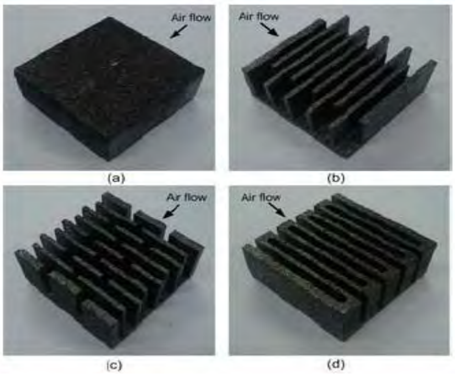

Fig. 3. Tested graphite foam heat sinks of (a) block, (b) staggered, (c) baffle and (d) corrugated configurations [9].

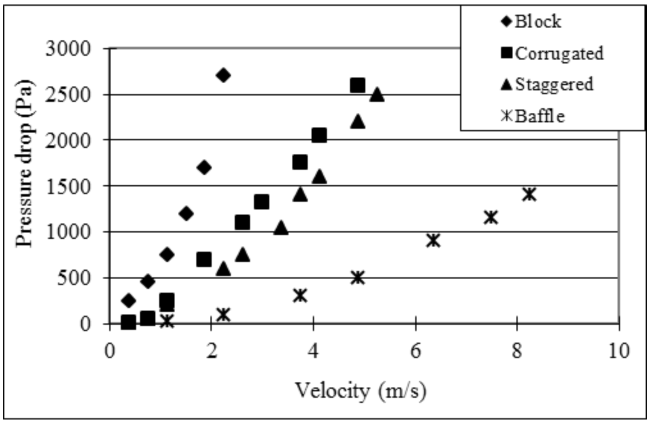

Fig. 4. Pressure drop versus inlet flow velocity of air flow through tested configuration [9].

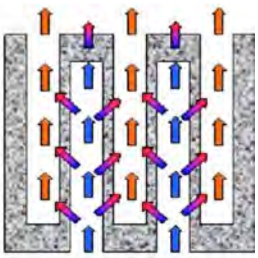

Fig. 5. Flow path inside the corrugated foam [10].

3. Applications of graphite foams

Due to the high thermal conductivity, low density and large specific surface area, the graphite foam is a good thermal material for heat exchangers or heat sinks. The major applications of graphite foam as materials for heat exchangers are: electronic package cooling, vehicle cooling systems, energy storage systems, and others.

3.1. Electronic package cooling

Because of the large internal interfaces and the high thermal conductivity, the usage of graphite foam is considered as an effective cooling method to dissipate the high heat flux in electronic equipment. Furthermore, the coolant of electronic equipment can be air instead of water, due to the high thermal conductivity of graphite foam. The removal of water can avoid shorting the circuitry of electronic equipment by water leakage.

Gallego et al. [11] demonstrated that the foam-based heat sink can be used to reduce the volume of the required cooling fluid or eliminate the water cooling system altogether. In terms of thermal performance, the graphite foam is much better than the aluminum. Meanwhile, the graphite foam heat sinks respond to transient loads faster than the traditional aluminum heat sinks. This response time may be crucial for the power electronics. Williams et al. [12] investigated several different channel - insert configurations as mini - heat exchangers by using both copper fins and graphite foams. The graphite foam was proved to have strong potential as a mini - heat exchanger.

On the other hand, the usage of thermosyphons in the thermal management of electronics is established and the methods for evaporator enhancement are of interest. Gandikota et al. [13] investigated the cooling performance of graphite foams for evaporator enhancement in thermosyphons and in pool boiling with FC-72 as the operating fluid. The exhibited thermal resistance was very low, averaging at about 0.024 K/W at low heat flux. The thermal resistance rose with increasing heat flux, but still remained very low. Lu et al. [14] used the graphite foam as a wick in a vapor chamber. With ethanol as the coolant, the vapor chamber (25 mm x 25 mm x 6 mm) had been demonstrated at a heat flux of 80 W/cm^2. The results showed that the performance of a vapor chamber using graphite foam was about twice that of one using a copper wick structure. Furthermore, Coursey et al. [15] found that 149 W heat load could be dissipated from a 1 cm^2 heated base at the operating temperature of 52 ℃, by usage of a graphite foam thermosyphon evaporator.

3.2. Vehicle cooling systems

Another important utilization of the graphite foam heat exchangers is in vehicle cooling systems. Because of the low density and large specific surface area, it might lead to a light and compact heat exchanger in vehicles. Meanwhile, graphite foam is considered as a potential material to solve critical heat rejection problems that must be solved before fuel cell and advanced power electronics technologies are introduced into automobiles.

The graphite foam could be utilized to produce a light and compact radiator in vehicles. In this case, the radiator might be placed away from the front of vehicles. If the size of the front of vehicles can be reduced, the vehicle does not push so much air in its forward motion. This implies less aerodynamic drag and increase of the fuel efficiency in vehicles. Kett et al. [16] designed a radiator (as shown in Fig. 6) with the carbon foam. Due to the increase of heat transfer coefficients, the number of coolant tubes in the radiator was reduced significantly. A typical automotive radiator with cross section of 48 cm x 69 cm might be reduced to 20 cm x 20 cm at the same heat removal rate. The reduced size will cut down the overall weight, cost, and volume of the cooling system. Thereby the fuel efficiency can be improved. Moreover, Yu et al. [17] compared a carbon foam fin - tube radiator with a conventional aluminum fin - tube radiator. The thermal performance of the carbon foam radiator was increased around 15 % without changing the frontal area or the air flow rate and pressure drop.

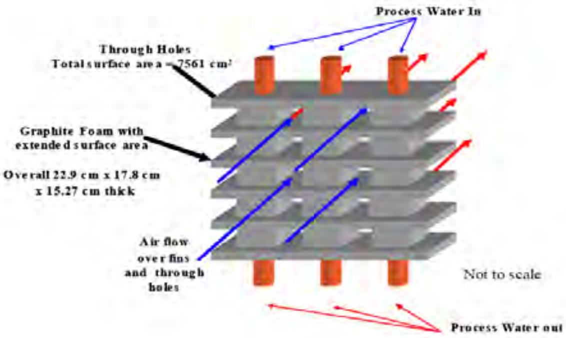

Fig. 6. Configuration of graphite foam radiator [16].

3.3. Energy storage system

Because of the high thermal conductivities in the graphite foam, the time used for heat transfer inside the material will be very short. This is a big advantage for energy storage applications. Lafdi et al. [18] investigated the thermal performance of graphite foams infiltrated with phase change materials for space and terrestrial energy storage systems. Because of the high thermal conductivity of graphite foams, the thermal performance of phase change material and foam system was improved significantly. In the phase change material related energy storage process, the higher thermal conductivity leads to a shorter time to charge or discharge, which implies better system performance.

4. Problems

Even though the graphite foam is an excellent thermal material, it is still very hard to find graphite foam heat exchangers in the commercial market. Thus, there are some problems blocking the development of graphite foam heat exchangers.

The most important problem facing the graphite foam heat exchanger is the high pressure drop. Because of the complex internal structure of the foam, the flow resistance inside the graphite foam is very high. This causes a high pressure drop through the graphite foam. Due to the high flow resistance, it is difficult for the cooling air to reach all the inter - faces and transfer the heat. Thus, the effective area of heat transfer is reduced greatly, which will result in a low thermal performance. Furthermore, the high pressure drop requires large input of pumping power to push the air through the graphite foam heat exchangers, which will cause a low coefficiency of performance (COP, the ratio of the removed heat to the input pumping power). Garrity et al. [19] proved that the graphite foam heat exchanger had lower COP than the aluminum multilouvered fin. In order to reduce the high pressure drop, it is important to adopt an appropriate configuration of the graphite foams, as discussed in [9-10].

The second problem is that the mechanical properties of the graphite foam are not as good as those of the metal foam. The tensile strength of graphite foam with porosity of 75 % is only 0.69 MPa [20]. However, the tensile strength of nickel foam with the same porosity is 18.44 MPa, which is much higher than the one of graphite foam [21]. In order to reinforce the mechanical properties of graphite foam, it might be useful to introduce some other material to the graphite foam. For instance, the compressive strength can increase ten times after the graphite foam has been mixed with epoxy resin. However, by changing the fabrication process to improve the foam's mechanical properties, the high thermal conductivity might sacrifice [22].

The third problem is the dust block. Most research of the graphite foam focus on the electronic equipment heat sinks. Little attention was put to the vehicle radiator applications. The major reason is the dust blocking problem. When the open pores in graphite foams are blocked by dust, the cold air can not reach all inter - faces and bring away the heat. Thus, the effective heat transfer area is reduced greatly and the thermal performance will decrease too. Due to the operating conditions, the dust block problem is more serious in vehicle radiators than in the electronic equipment heat sinks.

Due to these problems, the development of graphite foams is relatively slow and difficult. Much work has to be done before a mature graphite foam heat exchanger appears in the commercial market.

5. Conclusions and suggestions

The graphite foam has very high thermal conductivity, low density and large specific surface area. Because of these properties, the graphite foam is considered as a potential thermal material for heat exchangers. The graphite foam can be used as heat sinks to cool electronic packages. Also the graphite foam can be used as a radiator to cool the vehicle engines. Sometimes, the graphite foam can be used in energy storage applications.

However, due to the complex internal structure of the graphite foam, there is a very high pressure drop when the air flows through the graphite foams. There are also some other problems blocking the development of graphite foam, such as the low tensile strength, and the dust block. In order to promote the development of graphite foams as thermal material for heat exchangers, adopting an appropriate configuration might be useful to reduce the pressure drop through the graphite foam. On the other hand, mixing some other material with graphite foam might be helpful to reinforce the mechanical properties of graphite foam. Thus, much work has to be conducted before the graphite foam is accepted as a thermal material of heat exchangers.

Acknowledgments

The authors acknowledge the financial support from the Swedish Energy Agency and industries.

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The thermal response of heat storage system with paraffin and paraffin/expanded graphite composite for hot water supply

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Abstract: The low thermal conductivity of phase change material (PCM) leads to low heat storage/retrieval rates. The expanded graphite (EG) was used to enhance the thermal conductivity. EG/paraffin composite with the 7% mass fraction of EG was prepared as a good candidate for the latent thermal energy storage (LTES) system. A shell and tube LTES system built for room heating and hot water supply in a family was experimentally investigated. The paraffin and paraffin/EG composite were used as the heat storage material, respectively. The experimental results indicated: The utilization of EG/paraffin composite PCM greatly improved the heat storage/retrieval rates of the LTES system. The LTES system with paraffin/EG composite showed a 44% reduction in heat storage duration and a nearly 69% reduction in the retrieval duration, respectively, compared to those for the system using pure paraffin. The most outstanding advantage, for the LTES system filled with paraffin/EG composite, was that the outlet temperature of water can be maintained at a higher level for a longer term than that with paraffin. However, the LTES system filled with EG/paraffin composite did not show an obvious advantage in the step-by-step heat retrieval mode, compared with paraffin.

Keywords: *Latent thermal energy storage, Paraffin/expanded graphite composite, Heat storage/retrieval rate*

1. Introduction

In a latent thermal energy storage (LTES) system by solid-liquid phase change, energy is stored during melting while it is retrieved during solidification of a phase change material (PCM), thus a LTES system with a good performance requires that the PCM possesses the appropriate phase change temperature, high heat storage density and high thermal conductivity. Besides, a good LTES system also lies on a rational structure design of the system which will decide the filling capacity of PCM and the heat exchange surface.

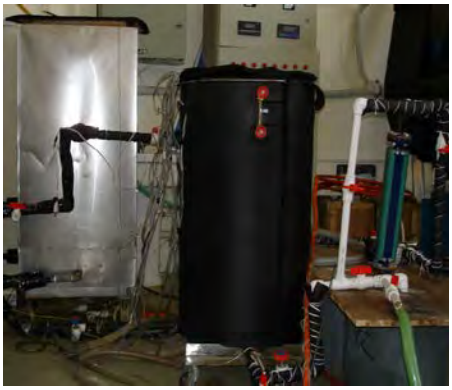
Based on an extensive study by Lane et al. [1] there are about 20,000 substances with the melting point in the range 10-90 oC. Majority of them was abandoned for application due to improper melting point, melting with decomposition or lack of essential reference data [2]. Among these PCMs, normal paraffin of type C_nH_{2n+2} has shown outstanding performance for application in LTES systems for solar heating and cooling [3-4]. This is because of its appropriate melting point, large latent heat, low cost, high stability and compatibility, and a low negative environmental impact. Despite the many desirable properties of paraffin, its low thermal conductivity, generally below 0.4 W/(m·K), is one of the major drawback.

The PCM containers with different geometries have their own advantages and disadvantages. Various LTES techniques have been developed and various encapsulations have been used in LTES systems. Two geometries commonly employed as PCM containers are the rectangular and cylindrical containers [5]. In particular, cylindrical containers accounts for more than 70% in all the used LTES system which commonly involves the three modes. The first is the heat storage unit in which the PCM fills the shell and the heat transfer fluid (HTF) flows through the central tube [6-8]. In the second mode, the PCM fills the tube and the HTF flows parallel to the tube [9]. The third cylinder mode is the shell and tube system [10, 11].

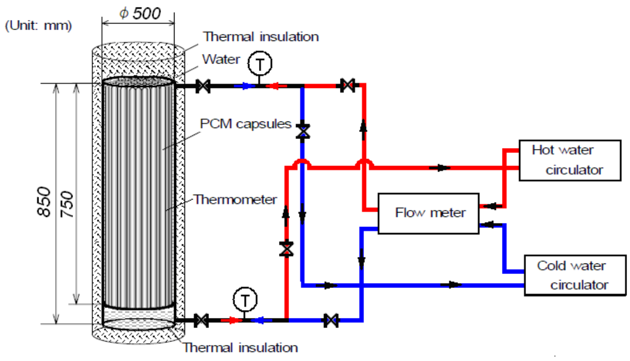
In the present work, expanded graphite (EG), with high thermal conductivity, was added into PCM to form a kind of composite phase change material and to enhance the heat transfer of the inner PCM. EG/paraffin composite PCM with 7% mass fraction of EG was prepared. This ratio was considered as the balance by compromising the heat transfer enhancement and latent heat storage capacity [12]. The EG/paraffin composite PCM was filled in the stainless steel tubes, and then these LTES tubes were compactly arranged in a tank. As a comparison, the paraffin was also used in this system as the heat storage material. The heat storage and retrieval performance of this LTES system, filled with EG/paraffin composite and paraffin, were experimentally tested, respectively. The influence of the HTF flow rate on the performance of the LTES system was also investigated. Moreover, two heat retrieval modes viz.: continuous and step-by-step heat retrieval, which were commonly used in the utilization of LTES system, were executed respectively for testing the heat retrieval performance of the LTES system with two PCMs.

2. Experimental setup and procedure

The PCM used in this study was technical grade paraffin with the purity of 99% and a melting temperature of 62 °C. The EG was prepared by making the raw expandable graphite (mesh 80, type KP80, from Qingdao Tianhe Graphite Co. Ltd, China) subjected to heat treatment in a furnace at 700 °C for a duration of 15 minutes. These paraffin and EG were used to prepare EG/paraffin composite. The paraffin was heated to a temperature of 85 °C, in order to be liquefied, after which the liquid paraffin was impregnated into EG and was stirred using a roll mixer. Then, the EG/paraffin composite with 7% mass fraction of EG was obtained.



(a)



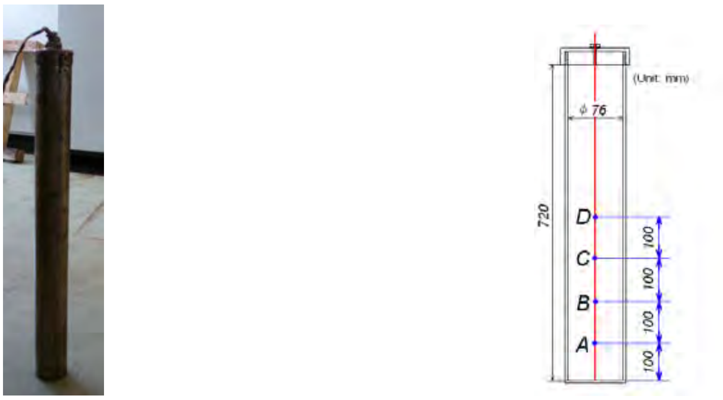
(b)

Fig. 1 Experimental setup (a) Photographic view (b) Schematic of LTES system

The schematic diagram of the experimental apparatus is shown in Fig. 1. The stainless-steel LTES tank, insulated with thermal insulation material of 50 mm in thickness, had a capacity of 166 L (500 mm diameter and 850 mm height), in which 27 heat storage tubes with the 76 mm in inner diameter and 750 mm in height were uniformly packed and supported by a wire mesh. The paraffin and EG/paraffin composite PCM were used as PCMs and water was used as the HTF. A hot water tank was used for heating during the heat storage and cold water from a cold water tank was used for cooling during the heat retrieval. During heat storage, the hot water was supplied from the top of LTES tank and was drained from the bottom, whereas, during heat retrieval, the flowing direct for the cooling water was just reversed. The temperatures of HTF at the inlet and the outlet were measured by two PT1000 platinum resistance temperature sensors.

The schematic of the cylindrical heat storage unit, as shown in Fig. 2, was a vertical tube (stainless steel, outer diameter of 78 mm and wall thickness of 1 mm) in which the PCM was impregnated. Four thermocouples (K-type) were used to measure the temperature of the PCM and were fixed near the centre axis of the tube, as shown in Fig. 2 (b). The heat storage unit which was equipped with thermocouples was set at the center of the LTES tank. The temperature variations of PCM during heat storage and retrieval were monitored and collected using a data logger.

Initially, 80% of the tube volume was filled with the solid PCM at a room temperature of 28 oC. The remaining 20% of the volume was left to accommodate the volume increase of the PCM during melting. Water was used as HTF, whose temperature at the inlet of the heat storage unit was kept at 85 ^{o}C during heat storage and was kept at 28 ^{o}C during heat retrieval. There were three different flow rates of the hot water (100, 150, 200 L/h) during heat storage and three different flow rates of the cooling water (150, 200, 250 L/h) during heat retrieval.



(a) (b)

Fig. 2. LTES unit (a) and locations of the thermocouples (b)

After heat storage of the LTES tank, the heat retrieval experiments were carried out in both continuous and step-by-step heat retrieval modes. In the continuous mode, the cold water of 28 ^{o}C continuously flew through the storage tank until the temperature of the water at the outlet reached 28 ^{o}C; while in the step-by-step heat retrieval mode, the cold water at 28 ^{o}C was impregnated in the LTES tank and had been kept there for one hour. Then, the heated HTF was withdrawn and at the same time the temperature was recorded. The above process was repeated until the temperature of the withdrawn HTF is below 35 ^{o}C. Nearly five batches of hot water could be withdrawn from the LTES tank in the step-by-step heat retrieval mode.

3. Results and discussion

3.1. Heat storage and retrieval performance

In the experiment for investigating the heat storage and retrieval performance of the LTES system, flow rate of the water was kept constantly at 150 L/h and the inlet HTF temperature during the heat storage and retrieval was 85 oC and 28 oC, respectively. The heat retrieval is in the continuous mode.

Figure 3 shows the temperature evolutions at the tested point C (as shown in Fig. 2) of pure paraffin and EG/paraffin composite during heat storage and retrieval circle. It can be found in

Fig. 3 that the tested point in both pure paraffin and EG/paraffin composite experienced three steps during melting, viz.: the sensible heat storage where the temperature rose rapidly, the latent heat storage (phase change) with the isothermal behavior and the following sensible heat storage where the temperature rose rapidly again until it reached the thermal equilibrium. The similar analysis was also effective during freezing. However, a discrepancy between the measured results of pure paraffin and those of the EG/paraffin composite was observed. The heat storage and retrieval durations of the LTES tank with EG/paraffin composite was much shorter than those with pure paraffin, i.e., the addition of EG drastically enhanced the heat transfer of inner PCM.

It took about 8000 s for pure paraffin to finish the heat storage, whereas, it took only 4500 s for EG/paraffin composite to reach the temperature equilibrium with the heating source, showing a 44% time reduction compared with that for pure paraffin. It was obvious that the heat storage rate of the composite PCM was higher than that of pure paraffin. It can also be seen from Fig. 3 that it took about 18000 s for the temperature of pure paraffin to drop from 85 ^oC to 30 ^oC, whereas, it took only 5500 s for EG/paraffin composite to complete the heat retrieval, indicating a 69% reduction in the heat retrieval duration.

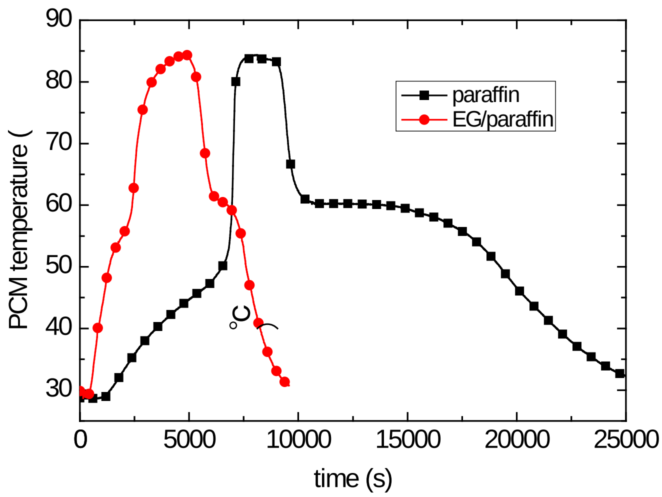
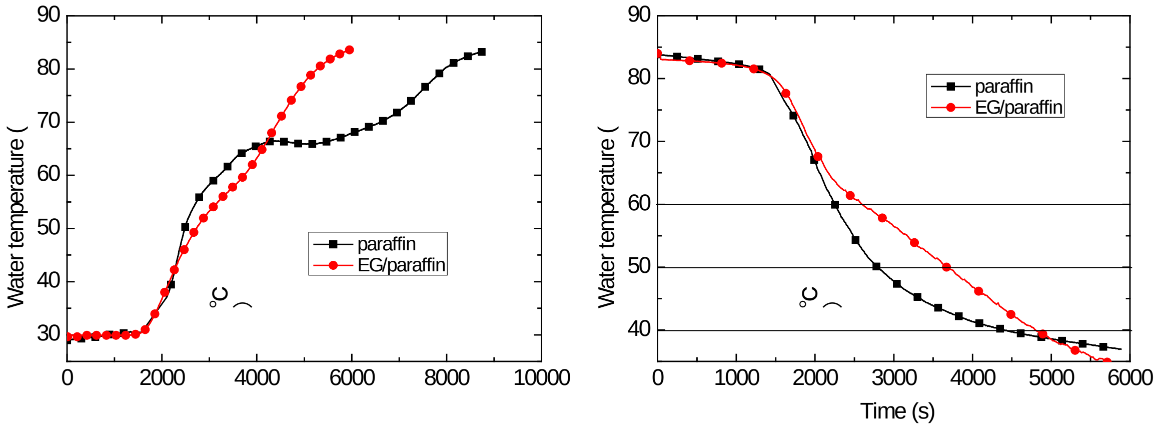


Fig. 3. Temperature evolutions of the LTES unit with pure paraffin and EG/paraffin composite during heat storage and retrieval circle

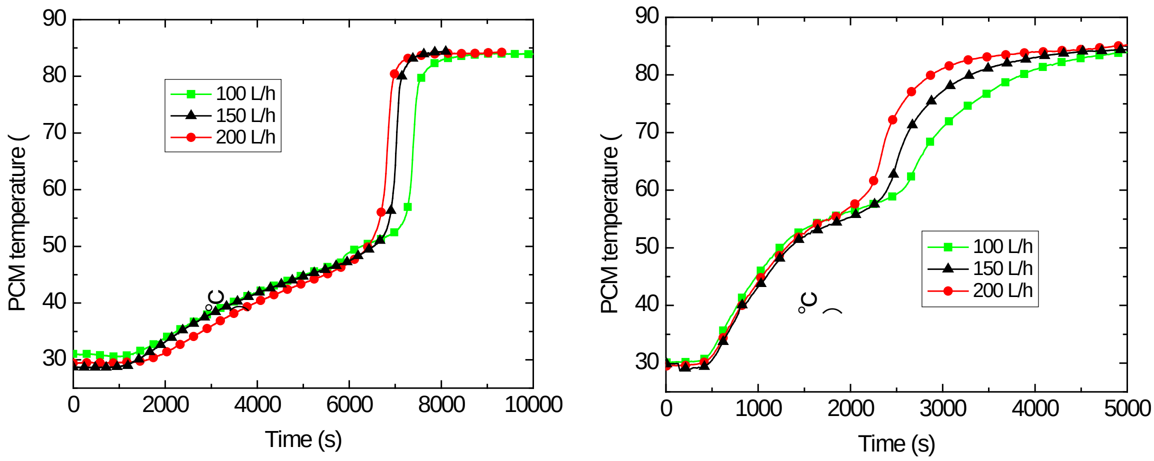
The heat storage and retrieval durations were both considerably reduced for EG/paraffin composite which was attributed to the addition of EG. However, it can also be seen that the effect of EG was more significant in heat retrieval than in heat storage. These phenomena can be attributed to the melting/freezing characteristic of each PCM: the melting of pure paraffin was accelerated during heat storage (melting) because of the intensive natural convection in the melted paraffin, whereas the natural convection did not play significant role in the heat transfer during heat retrieval (freezing); as for EG/paraffin composite, the natural convection could be neglected during both melting and freezing because of the existence of EG.

The outlet temperature evolutions of HTF during heat storage and retrieval are shown in Fig. 4(a) and (b), respectively. During heat storage, the outlet temperature of the HTF in the LTES system filled with EG/paraffin composite was more rapidly raised to the inlet temperature (85 ^oC) than in the system filled with paraffin, as shown in Fig. 4(a),. Moreover, in the earlier stage of the heat storage the outlet temperature of the HTF for the LTES system filled with EG/paraffin composite was higher than that with paraffin. These phenomena both indicated the system filled with EG/paraffin composite had a better heat transfer performance than the system with paraffin.



(a) (b)

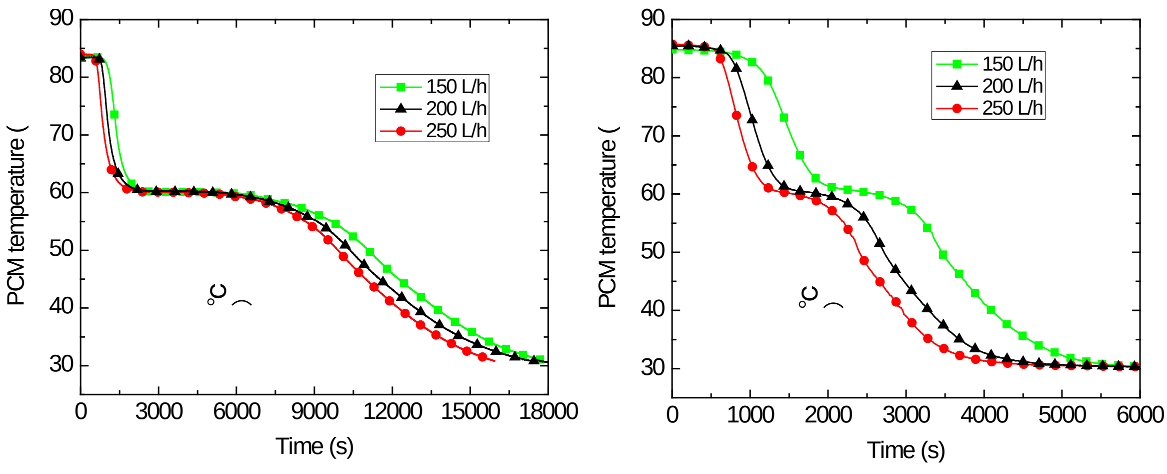
Fig. 4. Outlet temperature evolutions of the HTF during (a) heat storage and (b) heat retrieval



(a) (b)

Fig. 5. Temperature evolutions of the pure paraffin (a) and EG/paraffin composite (b) with the varying flow rate of the HTF during heat storage

As well known, for a LTES system, it is important to have a large heat storage capacity; however, the most important performance is whether it can supply a high heat retrieval power. In an excellent LTES system, the HTF should be heated up rapidly and the temperature of the HTF can be raised to a higher value so as to meet the requirement of the user as the HTF flows through it during heat retrieval. As can be seen from Fig. 4 (b) for the LTES system filled with paraffin/EG composite, the outlet temperature of the HTF could maintain a high level in a longer term than that with paraffin, such as the outlet temperature of HTF of the LTES system filled with paraffin/EG composite could be maintained above 50 °C for another more 1000 s than that with paraffin. Thus, it is indicated the stored thermal energy can be rapidly and intensively released in the system filled with paraffin/EG composite, which was significant for the utilization of the LTES system.



(a) (b)

Fig. 6. Temperature evolutions of the pure paraffin (a) and EG/paraffin composite (b) with the varying flow rate of the HTF during heat retrieval

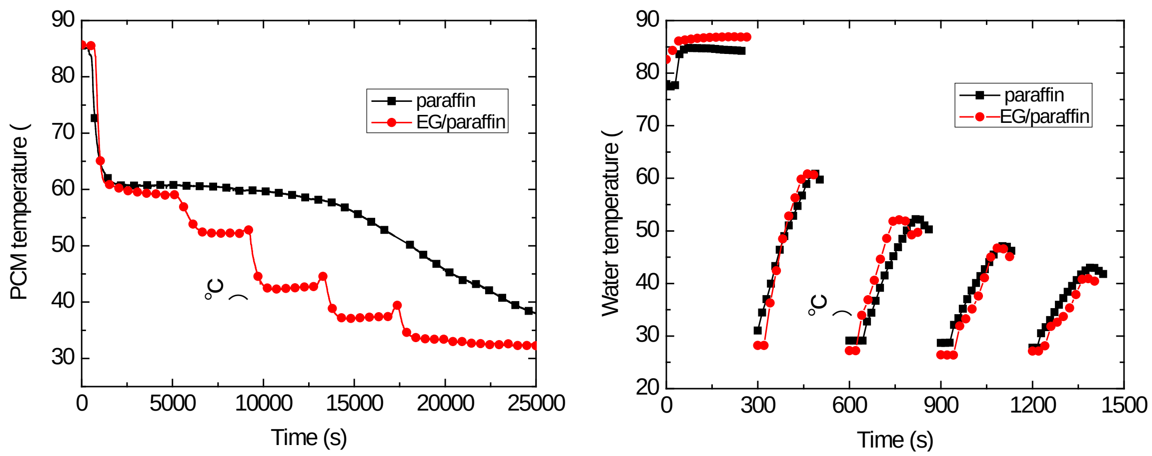
3.2. Influence of the flow rate of the HTF on the heat storage and retrieval performance

Figure 5 shows the temperature evolutions of PCM when varying flow rate of the HTF during heat storage, where Fig. 5(a) is temperature evolutions of the paraffin and Fig. 5(b) is temperature evolutions of the paraffin/EG composite. Figure 6 shows the temperature evolutions of PCM when varying flow rate of the HTF during heat retrieval.

From Fig. 5 and 6, it can be obviously seen that a higher flow rate of the HTF led to a better heat transfer performance and consequently a more rapid heat storage and retrieval. To increase the flow rate is always an effective and positive means during heat storage, whereas higher flow rate of the HTF may cause lower outlet temperature of the HTF during heat retrieval though it can enhance the heat retrieval power.

3.3. Test for the step-by-step heat retrieval mode

For the utilizations of the LTES system, the heat retrieval mode is not only continuous but also discontinuous, for example, the requirement of the hot water is intermittent in the domestic hot water system. Thus, the information about the step-by-step heat retrieval mode of the LTES system was also necessary and the retrieval performance of the LTES system was investigated in such case. Figure 7(a) shows the temperature evolutions of PCM and Fig. 7(b) shows the temperature evolutions of the outlet HTF during step-by-step heat retrieval. In each figure, the performance of the LTES system with paraffin was compared with that with EG/paraffin composite. The experimental result indicated: 1. There is a large difference between the temperature evolutions of the pure paraffin and EG/paraffin composite. This is because the EG/paraffin composite with high thermal conductivity is more sensitive to the varying of the HTF temperature and can quickly response this varying; 2. The temperature evolutions of the outlet HTF in the two LTES systems are almost the same with each other. This is because the waiting duration of one hour in each step is an enough time period to allow new temperature equilibrium is reached and maintained between PCM and HTF for both two LTES systems.



(a) (b)

Fig. 7. Temperature evolutions of PCM (a) and the outlet HTF (b) during step-by-step heat retrieval

4. Conclusions

Paraffin/EG composite PCM with 7% mass fraction of EG was prepared for enhancing the heat transfer of paraffin. The paraffin/EG composite PCM and the paraffin were used in a shell and tube heat storage system and the performance of the LTES system was experimentally investigated. The following conclusions were drawn:

1. The utilization of paraffin/EG composite PCM greatly enhanced the heat storage/retrieval rates of the LTES system. The LTES system with paraffin/EG composite PCM, under the operation condition (flow rates: 150 L/h during both heat storage and heat retrieval; the inlet temperature of HTF: 28 ^{o}C during heat retrieval and 85 ^{o}C during heat storage), showed a 44% reduction in heat storage duration and a nearly 69% reduction in the retrieval duration, respectively, compared to those for pure paraffin.

2. The most outstanding advantage, for the LTES system filled with paraffin/EG composite, was that the outlet temperature of HTF can be maintained at a higher level in a longer term than that with paraffin, which was significant for the utilization of the LTES system.

3. A higher flow rate of the HTF led to a better heat transfer performance and consequently more rapid heat storage and retrieval. It is positive for heat storage, whereas higher flow rate of the HTF may cause lower outlet temperature of the HTF during heat retrieval though it can enhance the heat retrieval power.

4. There was a large difference between the temperature evolutions of the pure paraffin and paraffin/EG composite PCM in the step-by-step heat retrieval mode, whereas the temperature evolutions of the outlet HTF in the two LTES systems were almost the same with each other.

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Effect of different working fluids on shell and tube heat exchanger to recover heat from exhaust of an automotive diesel engine

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Abstract: In this research, experiments were conducted to measure the exhaust waste heat available from a 60 kW automobile engine. The performance of an available shell and tube heat exchanger using water as the working fluid was conducted. With the available data, computer simulation was carried out to improve the design of the heat exchanger. Two heat exchangers were used: one to generate saturated and the other to generate super heated vapours. These two heat exchangers can be arranged in parallel or series. In series arrangement, the exhaust gas was first passed through superheated heat exchanger and then through the saturated heat exchanger. Whereas, in parallel arrangement, the exhaust gas was divided to pass through saturated and superheated heat exchangers. In both cases, working fluid was passed first through saturated heat exchanger and then through superheated heat exchanger. Computer simulation was carried out to investigate the effectiveness of the proposed heat exchanger for different working fluid like water, ammonia, and HFC-134a. It is found that with the exhaust heat available from the diesel engine additional 15%, 13% and 8% power can be achieved by using water, HFC-134a and ammonia as working fluid respectively.

Keywords: *Waste heat recovery, Organic Rankine Cycle, Diesel engine*

1. Introduction

Diesel engines represent a major kind of Internal Combustion Engine (ICE). These diesel engines have a wide field of applications and as energy converters they are characterized by their high efficiency. Trucks and road engines usually use high speed diesel engines with 220 kW output or more. Earth moving machineries use engines with an output of up to 520 kW or even higher up to 740 kW. Diesel engines are also used in small electrical generating units or as standby units for medium capacity power stations. However, Small air-cooled diesel engines of up to 35 kW output are used for irrigational purposes, small agricultural tractors and construction machines whereas large farms employ tractors of up to 150 kW output.

In general, diesel engines have an efficiency of about 35% and thus the rest of the input energy is wasted. Despite recent improvements of diesel engine efficiency, a considerable amount of energy is still expelled to the ambient with the exhaust gas. In a water-cooled engine about 35 and 30-40% [1] of the input energy is wasted in the coolant and exhaust gases respectively. The amount of such loss, recoverable at least partly, greatly depends on the engine load. Johnson [2] found that for a typical 3.0 l engine with a maximum output power of 115 kW, the total waste heat dissipated can vary from 20 kW to as much as 40 kW across the range of usual engine operation. It is suggested that for a typical and representative driving cycle, the average heating power available from waste heat is about 23 kW.

Since the wasted energy represents about two-thirds of the input energy and for the sake of a better fuel economy, exhaust gas from diesel engines can provide an important heat source that may be used in a number of ways to provide additional power and improve overall engine efficiency. These technical possibilities are currently under investigation by research institutes and engine manufacturers. For the heavy duty automotive diesel engines, one of the most promising technical solutions for exhaust gas waste heat utilization appears to be the use of a ‘‘Bottoming Rankine Cycle”. A Rankine cycle using water as working fluid is not enough efficient to recover waste heat below 640 K [3]. The Organic Rankine Cycle (ORC) is a promising process to recover the heat from the exhaust of an engine and generate electricity from it [4, 5]. The ORC works like a simple Rankine steam power cycle but uses an organic working fluid instead of water. A certain challenge is to choose a suitable organic working fluid for the ORC. The working fluid should fulfil safety criteria; it should be environmentally friendly, and inexpensive. Another important aspect for the choice of the working fluid is the temperature of the available heat source. A question, which also has to be considered for using ORC, is whether an organic substance is really better than water as working fluid for a given task.

A systematic approach towards using an installation based on the Rankine Cycle in truck applications dates back to the early 1970s where a research program funded by the US Department of Energy (DOE) was conducted by Mack Trucks and Thermo Electron Corporation [6-8]. Under this program, an ORC system was installed on a Mack Truck diesel engine and the lab test results revealed an improvement of bsfc of 10–12%, which was verified by highway tests. During the following years similar research programs were performed by other research institutes and vehicle manufacturers. Aly [9] was able to produce 16% additional power from the exhaust of a Mercedes-Benz OM422A diesel engine by using R-12 as working fluid for the ORC. ORC systems with capacities from 750 to 1500 kWe were examined by Koebbman [10]. Recently, the solution of Rankine Cycle Systems has increased its potential competitiveness in the market even more [11, 12]. This is a result of technical advancements in a series of critical components for the operation of such an installation (heat exchanger, condenser and expander) but also stems from the highly increased fuel prices. Nowadays, the installation of a Rankine Cycle is not only considered as a feasible solution for efficiency improvement in heavy duty diesel engines for trucks [13, 14] but also for smaller application such as passenger cars [15].

In this project, experiments were conducted to measure the exhaust heat available from a 60 kW automobile engine at different speeds and loads. A shell and tube heat exchanger was purchased and installed into the engine. The performance of the heat exchanger using water as the working fluid was then conducted. With the available data, computer simulation was carried out to improve the design of the heat exchanger. The optimized model of the heat exchanger was then simulated to generate super heated vapour. Ammonia and HFC-134a is used as working fluids. Water is used as reference for comparison. The thermo physical properties of working fluids are compared and presented in Table 1. It is apparent that dry and isentropic organic fluids generally have much lower relative enthalpy drops during expansion than the water-steam mixture. Unlike water, most organic fluids suffer chemical decomposition and deterioration at high temperature and pressure. Therefore, an ORC system must be operated well below the temperature and pressure at which the fluids are chemically unstable. Most organic fluids have relatively low critical pressures and are therefore usually operated under low pressures and with much smaller heat capacities than water-vapour cycles. A suitable organic fluid must have a relatively high boiling point. Based on these features ammonia and HFC-134a are selected for the current study. Finally, power output from the turbine is calculated considering isentropic efficiency of real turbine[16, 17].

Table 1. Thermophysical properties of working fluids.

Parameter	H_2O	NH_3	HFC-134a
Molecular weight	18	17	102
Slope of the saturation vapour line	Negative	Negative	Isentropic
Enthalpy drop across the turbine (kJ/kg)	1570~900	725~70	55~22
Max. Stability Temperature (K)	None	750	450
Critical point (K)	647	405.3	374.15
Boiling point at 1 atm (K)	373	239.7	248
Latent heat at 1 atm (kJ/kg)	2256.6	1347	215.52

2. Experimental setup

The engine used in the current study is a four cylinder Toyota 13B diesel engine which is coupled with a water dynamometer. The specification of the engine is given in the Table 2. The schematic of the experimental setup is shown in Fig. 1. The engine run at different loads with variable speeds and exhaust temperatures were recorded to calculate available heat energy from the exhaust. Then the exhaust of the engine was connected to a shell and tube heat exchanger to study the performance of the heat exchanger and those data were used to improve the design of the heat exchanger by computer simulation.

Table 2. Engine specification.

Engine model	13B
Make	Toyota
Type of engine	4 cylinder charged water cooled diesel engine
Bore	102 mm
Stroke	105 mm
Compression ratio	17.6:1
Torque	217 N.m @ 2200 rpm

3. Heat Exchanger design

The data found from the experiment are used to optimize the design of shell and tube heat exchanger by computer simulation. Effect of important parameter of heat exchanger like radius of the shell, no of tubes, length of the heat exchanger, pressure drop is investigated and final model of the heat exchanger is proposed. The specification of the model of the proposed shell and tube heat exchanger is shown in the Table 3. Two heat exchangers are used: one heat exchanger is used to generate saturated vapor from the liquid working fluid and the second heat exchanger is used to generate super heated vapor from that saturated vapor. These two heat exchangers can be arranged into two configurations, parallel and series as shown in the Fig. 2.

Table 3. Heat exchanger specification.

Heat exchanger type	Shell and tube counter flow, hot fluid in tubes and cold fluid in the shell
Shell inside radius	35.4 mm
No of tube	18
Tube inside diameter	10 mm
Length of the heat exchanger	2 m

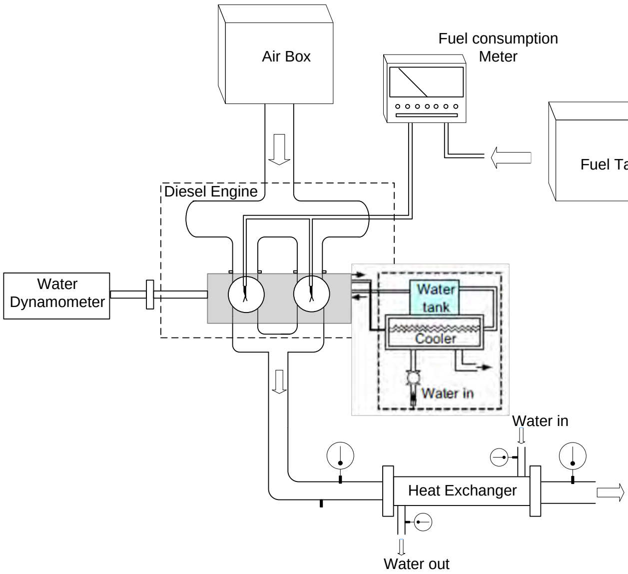

Fig. 1: Schematic diagram of experimental setup.

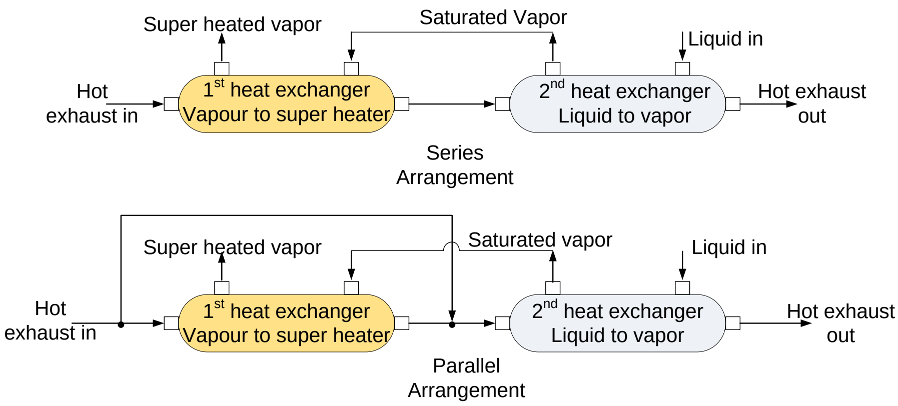

Fig. 2: Heat exchanger arrangement.

4. CFD Model

The optimized design of the shell and tube heat exchanger is modeled for heat transfer between hot and cold fluid in Flow Simulation which is CFD simulation module of Solidworks 2009. The computational mesh used to solve the model heat exchanger contained 109,992 cells. The cold fluid was considered to be liquid phase at 323K with corresponding saturation pressure for the second heat exchanger (Fig. 2) and saturated vapor at working pressure for the first heat exchanger (Fig. 2). The hot fluid considered as air with mass flow rate of 0.10215 kgs^{-1} and temperature of 938 K. The operating pressure of hot fluid is set to101.325 kPa and the cold fluid supply pressure and mass flow rate are varied. Steady and incompressible flow was assumed in all models. The Standard k- ε , a two-equation Reynolds-Averaged Navier-Stokes (RANS) model that is currently the most widely used for calculating flow problems has been used in this model.

5. Results

To design an effective heat exchanger for heat recovery from the exhaust of an engine, it is required to know how much energy is available in the exhaust. So some base line tests are performed. The exhaust gas temperature at various speed and engine power is presented in the Fig. 3. It is found from the figure that engine power and the temperature of the exhaust gases for all three engine speeds show an approximately linear relationship. Exhaust gas temperature increases with increase of power output and speed of the engine. This indicates that heat recovery will be more viable for higher powers.

In the relationship between power and temperature there is a definite relationship between engine power and the amount of recoverable energy present in the exhaust gases. The relationship this time is not linear but there is still a general upward trend, revealing that, as the engine power increases, so does the amount of recoverable energy. This is clearly seen in Fig. 4. This finding is highly significant section in terms of the focus of this research project.

In particular, the potential applications which formed the original thinking behind this project are given credibility, in that the amount of energy which may be tapped is of an order that

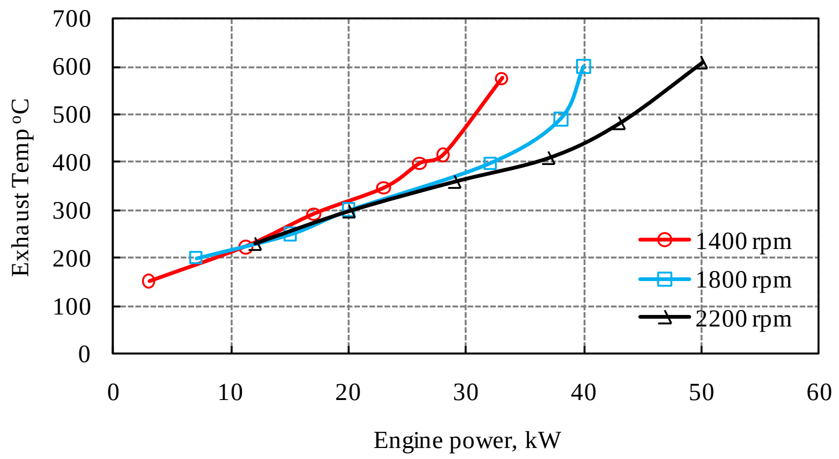

Fig. 3: Exhaust gas temperature variation with engine power from experiment.

justifies the attempt to capture and exploit it. For example, even if the results of just the lowest speed (1400 rpm) are considered, the potential to capture and use what is currently wasted energy, is extremely significant - the maximum recoverable energy for this speed is approximately 17 kW from the exhaust gas with the engine running at 33 kW (which is half the engine's power). Similarly, at 1800 rpm, a maximum value of approximately 21 kW was obtained from the exhaust gases, with the engine running at approximately 39 kW. At 2200 rpm the results show a maximum recoverable potential of approximately 23 kW when running at 45 kW. These results indicate that some 50% of the engine's running load is currently wasted but could be recoverable and converted to a usable form. All the above calculations were based on the abilities of a heat exchanger to be able to reduce the initial exhaust temperature at any particular speed and load to 50°C.

Based on the available data from the experiment, the heat exchanger design was optimized by computer simulation. Fig. 5 shows that the effectiveness of the heat exchanger decreases with the larger shell diameter for all three working fluids. Rubaiyat and Bari [18] found that there is no significant effect of working pressure on heat exchanger effectiveness. They also found that average pressure drop for different parameter of heat exchanger was about 250 Pa[18]. Effectiveness is higher for smaller diameter of the shell because of turbulent flow which facilitates the heat transfer. Heat exchanger effectiveness increases with the length of the heat exchanger as presented in the Fig. 6. It is found from the figure that after 1.6 m length the effectiveness increase is not very significant.

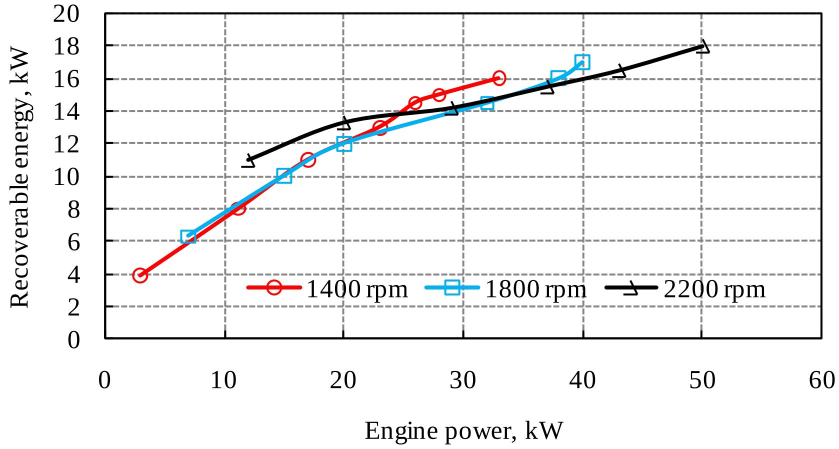

Fig. 4: Recoverable energy variation with engine power from experiment.

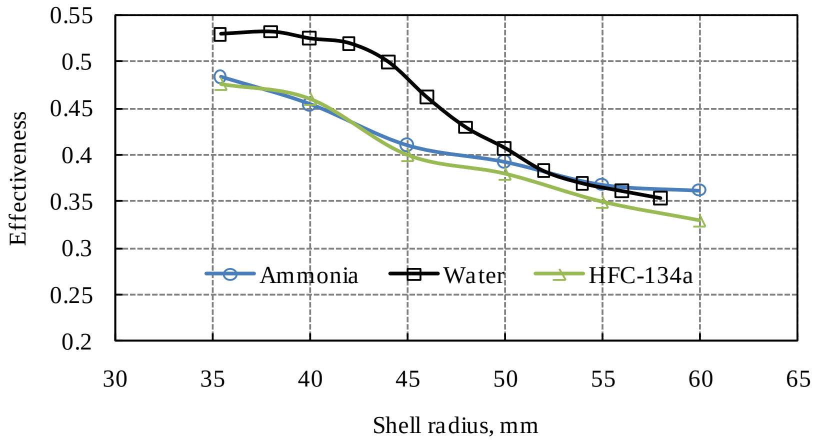

Fig. 5: Heat exchanger effectiveness vs. shell radius from CFD simulation.

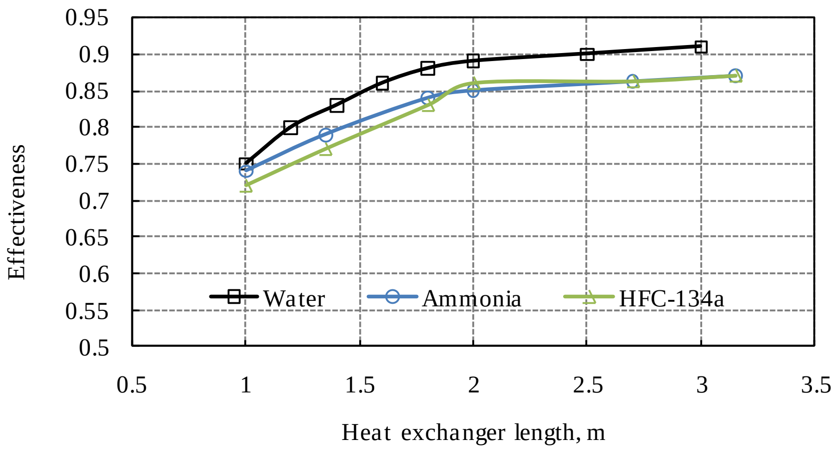

Fig. 6: Heat exchanger effectiveness vs. heat exchanger length from CFD simulation.

Extra power that can be recovered from the exhaust of the diesel engine with the proposed shell and tube heat exchanger model is presented in the Fig. 7. It is found that additional output power increases as the working pressure increases for both the parallel and series

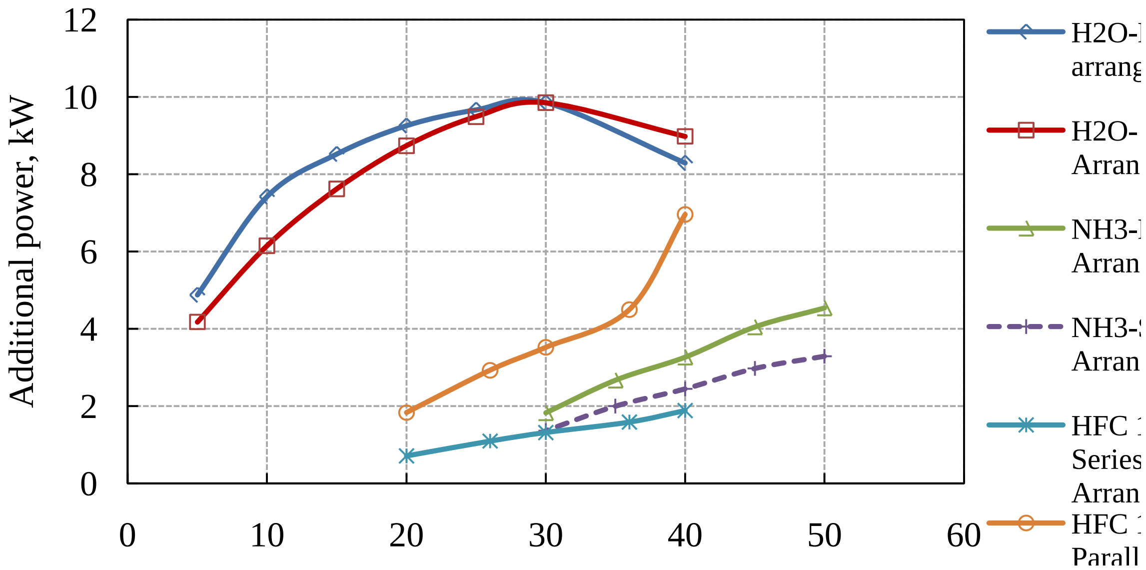

Fig. 7: Additional power output variation for different working fluids with working pressure from CFD simulation.

arrangement (Fig.2) of the heat exchangers for all three working fluids. This is because the condensing pressure was kept constant and as the working pressure increases the enthalpy drop across the turbine also increases. From the figure it is clear that water can recover heat most efficiently from the exhaust of the engine than the other organic fluids. This is because water has very high enthalpy drop across the turbine (Table 1) compared to other two organic fluids. Interestingly, it is found for water that higher power output can be achieved for parallel arrangement below 30 bar working pressure than the series arrangement whereas series arrangement can achieve higher power output above 30 bar working pressure than parallel arrangement. Maximum power output also achieved at the 30 bar working pressure. But other working fluids, ammonia and HFC-134a do not show any trend like that. For both ammonia and HFC-134a working fluid, parallel arrangement of the heat exchangers gives more additional power output. The proposed shell and tube heat exchanger can recover maximum 15%, 13% and 8% additional power from the exhaust of the diesel engine using water, HFC-134a and ammonia as working fluid respectively considering 70% isentropic efficiency of the turbine [16, 17].

6. Conclusion

The experimental and simulation results of the current project proved the concept of heat recovery from waste heat from the exhaust of diesel engines by using different working fluids. This research work shows that ORC can be a good option for waste recovery from diesel engines. This technique can increase the overall efficiency of diesel engine. Hence, this technology will reduce the fuel consumption and thereby will also reduce Green House Gases (GHG) and toxic emissions per kW of power produced. Additional 15%, 13% and 8% more power can be achieved with the proposed shell and tube heat exchanger by using water, HFC-134a and ammonia respectively.

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Working fluid selection for Organic Rankine Cycle applied to heat recovery systems

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Abstract: The selection of suitable organic fluids for use in Organic Rankine Cycle (ORC) for waste energy recovery from many potential sources of low-medium temperature (up to 350 ºC) is a crucial step to achieve high thermal efficiency. In order to identify the most suitable organic fluids, several general criteria have to be taken into consideration, from the thermophysical properties of the fluids leading to the environmental impact and cost related issues. The aim of the study is to elaborate a tool for the comparison of the influence of different working fluids on performance of an ORC heat recovery power plant installation. A database of a number of organic fluids as well as a software (code) which allows the user to select the proper organic fluid for particular application have been developed. Calculations have been conducted for the same heat source and installation component parameters. The elaborated tool should create a support by choosing an optimal working fluid for special applications and become a part of a bigger optimization procedure by different frame conditions.

Keywords: *Organic Rankine Cycle, Database, Heat Recovery*

Nomenclature

$\dot{Q}_{in}$ heat flux input .... kW
$\dot{m}$ mass flow rate .... $kg\cdot s^{-1}$
π pressure ratio
h_i specific enthalpy for process point i... $kJ\cdot kg^{-1}$
T_{high} high system temperature .... °C
T_{low} low system temperature .... °C
p_{high} high system pressure .... MPa
p_{low} low system pressure .... MPa
$\eta_{turbine}$ internal efficiency of the turbine .... %
η_{pump} internal efficiency of the pump .... %
η_{system} system efficiency .... %
P_{pump} power used by the pump .... kW
$P_{turbine}$ output power of the turbine .... kW
$\dot{Q}_{out}$ heat flux output in the condenser .... kW

1. Introduction

Nowadays, with energy demand rising at an ever increasing rate, efficient use of energy has become a major issue. One candidate suitable for improving efficiencies of existing applications and allowing the extraction of energy from previously unsuitable sources is the Organic Rankine Cycle. Applications based on this cycle allow the use of low temperature energy sources such as waste heat from industrial applications, geothermal sources, biomass fired power plants and micro combined heat and power systems.

Waste heat represents the heat produced by machines, electrical equipment and industrial processes which has no practical use. Usually it's generated by fuel combustion or by chemical reaction. The difficulty of capturing, distribution or transformation into other forms of energy comes from the characteristics of the heat source and the high costs connected to the equipment needed to transform the heat into useful energy. Statistical investigations indicate that low-grade waste heat accounts for 50% or more of the total heat generated in industry [1]. There are several types of industrial waste heat sources, some of which are presented in Table 1.

Table 1. Waste heat sources and their quality. [2]

Waste heat source	Quality of waste heat and possible use
Heat in flue gases	The higher the temperature, the greater the potential value for heat recovery
Heat in vapor streams	As for heat in flue gases, but when condensed, latent heat is also recoverable
Convective and radiant heat loss from the exterior of equipment	Low grade – if collected, may be used for space heating or air preheating
Heat losses in cooling water	Low grade – useful gains if heat is exchanged with incoming fresh water
Heat losses in providing chilled water or in the disposal of chilled water	1. High grade if it can be utilized to reduce demand for refrigeration 2. Low grade if refrigeration unit used as a form of heat pump
Heat stored in products leaving the process	Quality depends upon temperature
Heat in gaseous and liquid effluents leaving process	Poor, if heavily contaminated & thus require alloy heat exchanger

Organic Rankine cycle is a Clausius – Rankine cycle which uses an organic fluid instead of water. The replacement of water with organic fluids brings a number of advantages over the classical steam process. Due to their thermophysical characteristics, such as low critical point, low boiling temperature and high molecular mass, the transformation of low temperature heat into useful electrical energy is possible and can be effective (higher efficiency than other possibilities).

Because of the low critical point relative to water and because the temperature level of the heat input is much lower than in the case of steam processes, the working pressures are lower and thus, they lead to a small-scale, low-cost installation which in most cases does not require permanent supervision [6].

Fluid selection for any type of ORC application is a very important step in designing an efficient working system. There are many important aspects that need to be taken into consideration before choosing an organic fluid. In this context a special fluid database with an implemented selection algorithm has been created with the possibility of continuous development.

2. Database

The database has been assembled in MS Excel due to the wide spread of the program and the fact that it facilitates the structuring and organization of data sets in an easy and intuitive way. Another major advantage of MS Excel is the relative ease with which one can import data either from other databases or from experimental data. The characteristics of the fluids have been sorted in two major groups, each containing multiple parameters: thermophysical characteristics and environmental characteristics.

2.1. Themophysical characteristics

One of the thermophysical characteristics of the organic fluids is the slope of the saturation curve in the temperature-entropy diagram. It can be negative, isentropic or positive, as shown in Fig. 1.

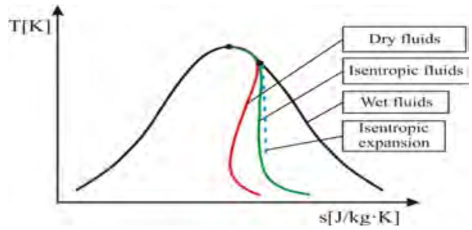

Fig. 1. Typical T-s diagram for dry, isentropic and wet fluids

In the case of dry and isentropic fluids there is no need for overheating. Because of the theoretical isentropic expansion in the turbine, in the case of wet fluids, overheating must be applied in order to avoid the creation of liquid droplets during the expansion in the turbine which would damage the turbine blades. Due to this characteristic the database contains information about the type of saturation curve for each contained fluid.

For practical reasons the low pressure value has been set to just above the atmospheric pressure (0.15 MPa). This limit must be imposed in order to avoid infiltration of air in the installation which would lead to the damaging of components. Also, for the moment, the low temperature value has been set to the value of normal ambient temperature (20 °C). Of course the real frame conditions of a real process, especially the temperature of the cooling medium, determine these values, which can be varied.

Another important characteristic is the boiling temperature at the low pressure value of the fluid. If it's lower than the ambient temperature then the minimal pressure value at which the fluid is in a liquid state at room temperature must be identified and set as the new low pressure value. This has to be done in order to maintain the highest possible value for the pressure ratio π of the expander, as a higher pressure drop yields a higher efficiency and it has been done for each fluid in the database.

There are other thermophysical parameters that must be taken into consideration when choosing a working fluid. Some of these are:
- low freezing point, so that the fluid will not solidify when it's in the low-temperature area of the process;
- the critical pressure and temperature should be above the highest values of these parameters in the process;
- the vaporization heat and the density of the fluid should be high, as a fluid with these characteristics will absorb more energy from the source in the evaporator and thus reduce the required flow rate, the size of the facility, and the pump consumption.

2.2. Environmental characteristics

Although high system efficiency is the main goal when designing heat recovery systems, one has to take into account the environmental characteristics for safety and practical considerations. For example, as the HCFCs still contain chlorine and have an associated Ozone Depletion Potential, they will be phased out in the EU Community from the 1st of January 2010 [3]. So, the availability of HCFCs for equipment servicing following the phase-out may not allow for predictable economical use.

Two main environmental characteristics are the ODP (Ozone Depletion Potential) and the GWP (Global Warming Potential). ODP represents the relative amount of degradation that a fluid can cause to the ozone layer. The standard of reference has been set for trichlorofluoromethane (R11). It has the value of 1 and the maximum potential of ozone depletion among chlorocarbons because of the three chlorine atoms in its composition. [4]

GWP represents a parameter that quantifies the contribution of a given mass of greenhouse gas to global warming. The standard of reference in this case is set for carbon dioxide with a given value of 1. Another important characteristic is the safety classification. After a careful analysis the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) classification has been chosen because of the high number of organic fluids covered and the relative simplicity of the annotations of the safety classes. These are as follows in Table 2:

Table 2. ASHRAE safety classification. [5]

Flammability	Low toxicity	High toxicity
High	A3	B3
Low	A2	B2
Non-flammable	A1	B1

2.2.1. Toxicity classification [5]

Refrigerants are divided into two groups according to toxicity:
• Class A signifies refrigerants for which toxicity has not been identified at concentrations less than or equal to 400 ppm;
• Class B signifies refrigerants for which there is evidence of toxicity at concentrations below 400 ppm.

2.2.2. Flammability classification [5]

Refrigerants are divided into three groups according to flammability:
• Class 1 indicates refrigerants that do not show flame propagation when tested in air at 21°C and 101 kPa;
• Class 2 indicates refrigerants having a lower flammability limit of more than 0.10 kg/m^3 at 21°C and 101 kPa and a heat of combustion of less than 19 kJ/kg;
• Class 3 indicates refrigerants that are highly flammable as defined by a lower flammability limit of less than or equal to 0.10 kg/m^3 at 21°C and 101 kPa or a heat of combustion greater than or equal to 19 kJ/kg.
The database interface allows the user to select the type of installation for which the fluid data will be analyzed. Momentarily the installation layouts that are available are:

- Undercritical single stage;
- Undercritical single stage with recovery;
- Undercritical two-stage;
- Supercritical single stage.

The major fluid parameters are introduced for each existing fluid in the database, with the possibility of adding either other fluids and/or other parameters of interest. The general layout of the existing list with some of the parameters present in the developed program can be seen in Fig. 2:

Working fluid	Boiling point at p=0.1 MPa [°C]	Critical point Temperature [K]	Critical point Pressure [MPa]	Molar mass [g/mol]	Slope	Toxicity group	ODP
R11 (Trichlorofluoromethane)	23,77	471	4,41	137,37	Isentropic	A1	1
R113 (Trichlorotrifluoroethane)	47,6	487,26	3,39	187,37	Positive	A1	0,9
R114 (Dichlorotetrafluoroethane)	3,5	419,1	3,25	170,9	Positive	A1	0,85
R115 (Chloropentafluoroethane)	-39,1	353,1	3,15	154,5	-	A1	0,4
R116 (Chloropentafluoroethane)	-78,2	293,1	3,04	138	-	A1	0
R12 (Dichlorodifluoromethane)	-29,8	385	4,41	120,91	Negative	A1	0,82
R123 (Dichlorotrifluoroethane)	27,6	456,9	3,7	152,93	Positive	B1	0,02
R124 (Chlorotetrafluoroethane)	-11	395,5	3,62	136,5	Isentropic	A1	0,022
R125 (Pentafluoroethane)	-48,5	339,4	3,63	120	Isentropic	A1	0
R13 (Chlorotrifluoromethane)	-81,3	302	3,97	104,5	Negative	A1	1
R13B1 (Bromotrifluoromethane)	-57,75	340,08	3,95	148,91	-	A1	13
R134a (Tetrafluoroethane)	-26,1	374,2	4,06	102	Isentropic	A1	0
R14 (Tetrafluoromethane)	-127,8	227,5	3,75	88	Negative	A1	0
R141b (dichlorofluoroethane)	32,05	477,6	4,25	117	-	-	0,1
R142b (chlorodifluoroethane)	-9,8	410,4	4,12	100,5	-	A2	0,07
R143a (Trifluoroethane)	-47,6	346,1	3,78	84	-	A2	0
R152a (Difluoroethane)	-25	386,5	4,52	66,1	Negative	A2	0
R21 (Dichlorofluoromethane)	8,92	451,7	5,71	102,9	Negative	-	0,04
R218 (Octafluoropropane)	-36,7	345,1	2,68	188	-	A1	0
R22 (Chlorodifluoromethane)	-40,8	363,3	4,99	86,5	Negative	A1	0,05

Fig. 2. Fluid list with selected available fluids and parameters

Each fluid has a series of static parameters, such as ODP, GWP, molar mass, boiling point at atmospheric pressure and others, which are introduced when the fluid is added to the database and which never change. The dynamic parameters such as the cycle efficiency, the mass flow rate and the pressure ratio are calculated and are modified with the alteration of the input parameters which will be described in the following section.

Because the program is developed in MS Excel the interface and the fluid data are stored in the same document on different worksheets. Fig. 3 presents captions from both the interface and the database and the flow of data through them:

Fig. 3. Flow of data through the program

For each fluid from the database there are three worksheets. One contains the liquid and vapor enthalpy and entropy and other parameter values for the fluid along the saturation curve, one contains temperature, enthalpy and entropy values for the different process points and the third worksheet contains the calculation interface for the fluid and all the functions needed to implement the calculation procedure in the program.The user introduces the values for the input parameters, marked by the red rectangles, and the program returns the output parameters, marked with the green rectangles. For example, the program reads the temperature value introduced by the user and, by using the "MATCH" function from Excel, it extracts the values for the enthalpy, entropy and pressure from the first data worksheet (saturation property curve) for each fluid. With these values, the program calculates and extracts values for the parameters for each process point and, finally, it returns the cycle efficiency. This value is introduced in the fluid list and it is updated whenever the input parameters are modified. From here the program returns a list of the fluids which yield the highest efficiencies (the top 4 in example from Fig. 3) for this set of input parameters.

3. Calculation procedure

As mentioned above, beside the general and environmental properties, the program returns the cycle efficiency for each fluid. This is done by employing a set of functions embedded in Excel which interrogate, search, match and return the desired data.

For the moment, the program executes calculations for a standard single stage cycle without recovery. The general layout of the installation, the process points and the T-s diagram (in this case for R114) can be seen in Fig. 4.

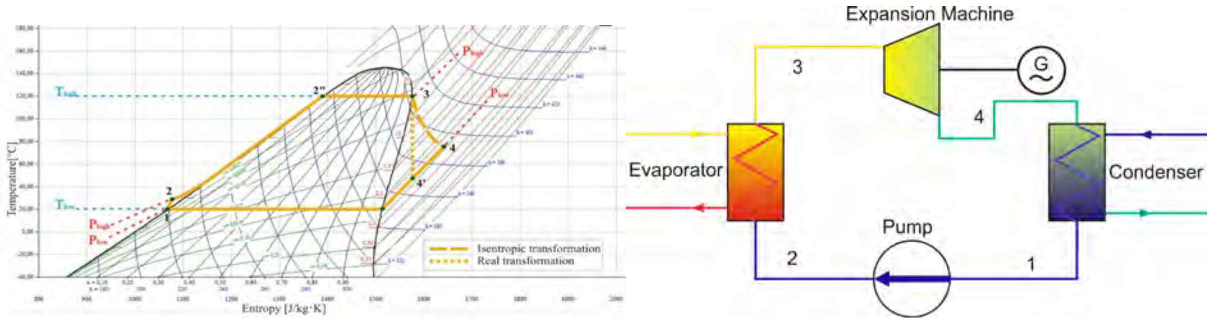

Fig. 4. T-s diagram and installation layout for a simple one-stage process

At the current state, the major input parameters for the program are the heat flux transferred to the system and the temperature at the inlet of the turbine (process point 3 in this case). The program calculates the efficiency of the cycle without overheating. So after introducing the heat flux and the turbine inlet temperature, the program chooses the corresponding pressure from the saturation curve for each fluid. The low pressure value is set to just above the atmospheric pressure (at 0.15 MPa) and the low temperature is set to the standard ambient temperature (20 °C).

With the value of the heat flux, the program calculates the mass flow rate:

$$\dot{m} = \frac{\dot{Q}_{in}}{h_3 - h_2} \tag{1}$$

where h_2 *and* h_3 represent the enthalpy values for process points 2 and 3.
By obtaining the high pressure value from the saturation curve, the program calculates the pressure ratio which is a good indicator for the system efficiency.

$$\pi = \frac{p_{high}}{p_{low}} \tag{2}$$

The internal efficiencies of the turbine and the pump are also input values. They can be selected from a drop-down list within the range of 0% to 100%, leading to a number of four input parameters. The expansion in the turbine is theoretically isentropic. The values for the irreversible process are obtained from the internal efficiency of the turbine.

$$\eta_{turbine} = \frac{h_3 - h_4}{h_3 - h_4'} \tag{3}$$

where the enthalpy values are obtained from the database for each fluid by matching the temperature and entropy values. By obtaining the value for the enthalpy in process point 4 the other parameters are extracted from the database. The power required for the pump is calculated with the following formula:

$$P_{pump} = \frac{v \cdot (p_{high} - p_{low})}{\eta_{pump}} \cdot \dot{m} \tag{4}$$

The output power of the turbine is calculated with the help of the internal efficiency of the turbine and by extracting the enthalpy values for process points 3 and 4 from the database:

$$P_{turbine} = \dot{m} \cdot \eta_{turbine} \cdot (h_3 - h_4) \tag{5}$$

The heat flux extracted in the condenser is calculated with the following formula:

$$\dot{Q}_{out} = \dot{m} \cdot (h_4 - h_1) \qquad (6)$$

After obtaining the values for each of these parameters, the program calculates the system efficiency as follows:

$$\eta_{system} = \frac{P_{turbine} - P_{pump}}{\dot{Q}_{in}} \cdot 100 \ [\%] \qquad (7)$$

The program returns the value for the system efficiency for each fluid in the database. If the input parameters lead to data that is outside the set conditions it will return “N/A” which signifies that the fluid is not suitable for the given input parameters.

In the current version the program returns a list of fluids which allow the highest system efficiencies for the input data set. In the following months more data and calculation procedures will be introduced so the program can calculate efficiencies of other types of installations, as shown in Figures 5, 6 and 7.

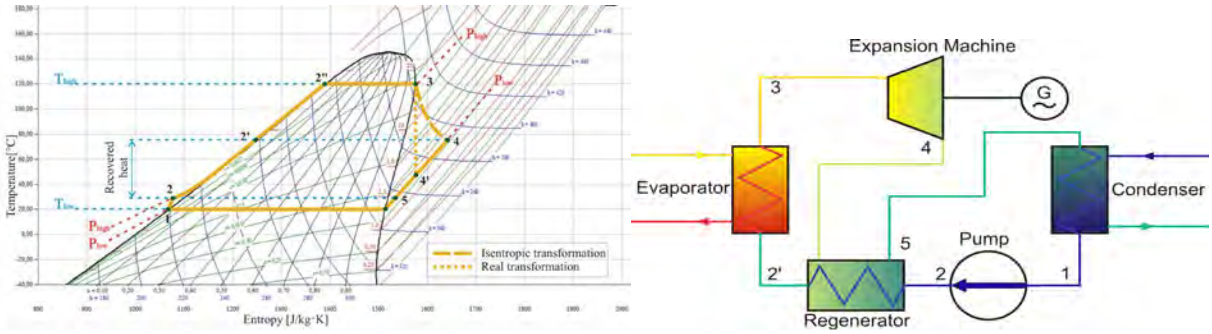

Fig. 5. T-s diagram and installation layout for a one-stage with recovery process

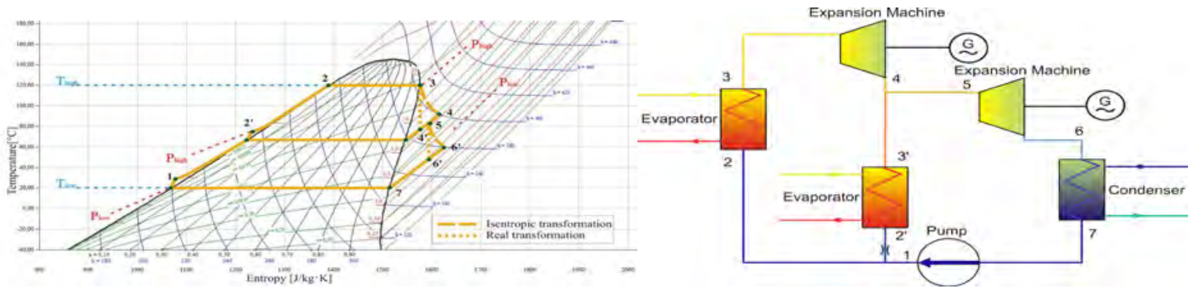

Fig. 6. T-s diagram and installation layout for a two-stage process

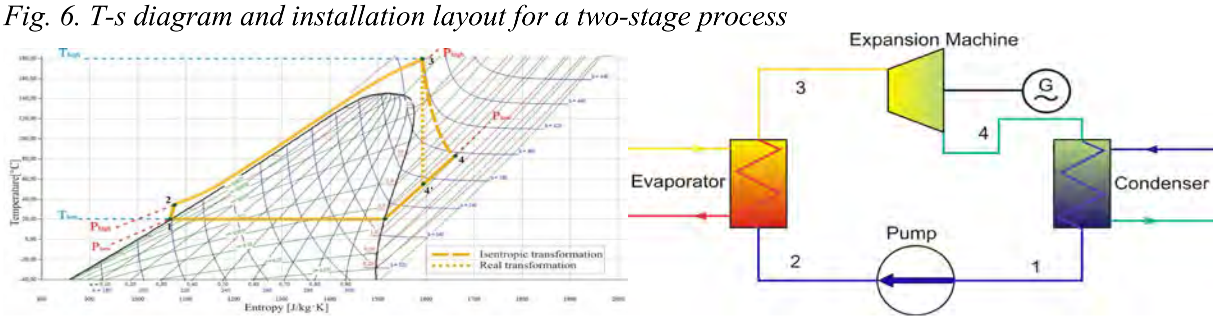

Fig. 7. T-s diagram and installation layout for a supercritical one-stage process

Further steps will consist of introducing the possibility of overheating and thus moving away from the saturation curve, the possibility of modifying the set values for the low pressure and temperature as well as different sorting criteria such as cost, environmental aspects, availability and others.

4. Conclusions

Fluid selection is a major step in designing heat recovery systems based on t he organic Rankine cycle. Although at this moment the sorting criterion for the fluids is the system efficiency, further development of the proposed program will create the possibility for different sorting criteria.

Developing this application has revealed that a program dedicated to fluid selection for heat recovery systems has a high degree of complexity. Although this application can give an idea to the user about the performance of different fluids applied to the same type of installation, one has to remember that the data still has to be compared to experimental data.

While the program is a good indicator for the influence on t he system performance of different organic fluids, returning other fluid parameters in the process, the final decision of selection of an organic fluid for a given set of frame conditions remains to be made by the engineer designing the system. Costs related to fluid purchase, lifetime costs, taxes and availability may lead the designer to choose a lower efficiency yielding fluid.

To increases the level of complexity of the program and to bring the results, from theoretical, closer to real, measurable values, the interface from the heat source and the system will be investigated.

Another task that needs to be considered within the next steps is the investigation of energy and exergy losses in the expansion machine and exergy losses in the heat exchangers.

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Examining the effect of heat storage in a cogeneration system

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Abstract: Small power plants of cogeneration of power, heat and cooling are good solutions of increasing the efficiency of energy consumption for fossil fuels in order to protect natural resources and the environment. However, at moments when heat demand is lower than the heat production of the CHP module, the excess heat has to be rejected to the environment and this fact results in waste of energy. Also, since CHP modules are basically heat driven, when heat demand is lower than a certain value, the module will be switched off just to be switched on later when heat demand increases. This cycle of switching on and off is harmful for the CHP module if it happens repeatedly. A solution is to use heat storage and an alternative control method. In this paper, a CHP system is chosen for an educational building and the design is carried out in two forms, with and without heat storage and the results are compared and judgment is made about the optimal system.

Keywords: *CHP, optimization, environment, heat storage*

1. Introduction

When power is produced traditionally, a large portion of original energy of the fuel is wasted as heat and hardly more than 40 pe rcent of this energy is transformed into electricity. Moreover, usually consumers are located far away from the power plant and this distance causes more waste of energy in distribution of electricity. One way to tackle these problems is using local cogeneration. In this modern method of power generation, power is produced at the location of consumption and the majority of lost heat is recovered to supply heat demands of the user. This results in a considerable improvement in efficiency. Furthermore, since power is generated at the same location where it is consumed, distribution losses will be avoided. The total efficiency of cogeneration power plants amounts up to 90%, while the electrical efficiency of a traditional power plant hardly reaches 40%.

Among different options of power generation in the form of cogeneration, reciprocating engines seem to be the most suitable for buildings which essentially have small demands. They have high power to heat ratios compared to gas turbines and due to advances made in automotive industry, enjoy a higher degree of modernization [9]. Although stationary reciprocating engines have traditionally been diesel engines but some issues like environmental issues and good access, have been promoting the users in recent years to use natural gas as the fuel instead. In Iran, a Persian gulf country with the second largest resource of natural gas in the world, even automobiles are increasingly using gas burning and dual fuel engines.

X Q Kong et al (2004) optimized a trigeneration system (cogeneration of heat, power and cooling) based on gas turbine. In their research a trigeneration system was modeled and then, after specifying constraints and an objective function, the solution was optimized using a linear modeling program [2]. In another work, they examined a co generation system and presented the results as graphs and tables [3]. In 2005 P. Arcuri et al designed optimally a trigeneration system using a mixed integer model. They optimized a trigeneration system for a hospital employing a reciprocal engine as its prime mover [4]. In 2006 E. Cardona and A. Piacentino designed and optimized a trigeneration system for a hospital application from the thermoeconomic point of view [5]. The same researchers carried out another analysis for an apartment building using the thermoeconomic method [6]. In 2008, Behbahani Nia et al. [7]

optimized a cogeneration system based on gas turbine with the aim of minimizing the capital cost in which they considered electricity, heat and cooling demands for each month.

In this paper, a cogeneration system is designed and optimized for the building of mechanical engineering faculty of K.N. Toosi University of technology in Tehran, Iran, using two different strategies, with heat storage and without heat storage. First, energy simulation is carried out using the software Carrier HAP 4.2 resulting in values of electricity and heating demands in all 8760 hours of the year. Later, based on these demands, the main components of the CHP system are designed based on products of the Austrian manufacturer, Jenbacher®. Products of this company are cogeneration modules including the reciprocating engine, heat recovery system and electrical generator all in one, covering a range of capacities from 400kWth to 3MWth.

2. A description of the building

The building of mechanical engineering faculty of K.N. Toosi University of technology is a ten-floor building, including 3 underground floors and covering about 20 thousand square meters of area. The second and third floors contain classes, fourth and fifth floors contain administrative rooms, almost all of which benefit from natural light during daytime. The sixth floor is dedicated to professors' rooms about half of which have access to natural light. The library and some laboratories are placed on the first floor. Ground floor primarily contains public places like the big lobby, the pray place, computer services hall and so forth. The floor -1 contains laboratories, cafeteria, the big restaurant and the amphitheatre. The floors -2 and -3 are for workshops and labs and also sport activity salons. Table 1 shows a list of areas of these floors.

Table 1. Area of each floor of the building

Floor	Area (m^2)	Floor	Area (m^2)
Ground floor	2561.6	Fifth	1005
First	2500	Sixth	1007
Second	1006.9	-1	3100
Third	1005.99	-2	3100
Fourth	1004.36	-3	3100

3. Calculation of loads

Thermal and electrical loads have been calculated using the energy simulation function of the software Carrier HAP 4.2. All parts of the building were modeled and wattages of lights, electrical equipments, geometrical and heat transfer features of rooms were entered in the software. A total of 270 spaces were defined in the process. Another important issue in determining loads is the presence of people in different spaces. Schedules were defined for presence of people in different types of spaces including classes, amphitheatre, computer services salon, corridors, administrative rooms, pray place, restaurant and security compartments, and also for lighting for each of these types of places, based on percentages of full presence or full lighting in different hours of the day and different days of the year. National holidays and weekends were considered based on the year 2009 which covers portions of Persian years 1387 and 1388. The difference of intensity of natural light in summer and winter days and different levels of presence of students and employees in different months of the year and different hours of the day were all considered based on personal observation of the second author who has been a studying in the same building for two years. The monthly distribution of heating and cooling loads resulting from this energy simulation is as shown in figure 1.

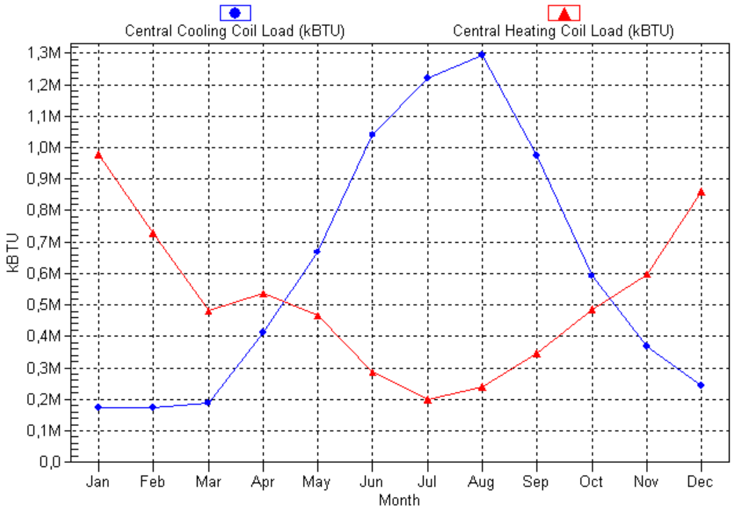

Fig. 1. Heating and cooling loads throughout the year.

The weather conditions were defined based on simulation information of www.Carrier.com of Tehran including hot and cold bulb temperatures and sunlight situation throughout the year.

4. Selection of cogeneration modules

Selection was carried out based on products of Jenbacher, including 13 models of CHP modules. The manufacturer did not reply requests of price quotation and purchase equipment costs and O&M charges were estimated using the information in [9] and by curve fitting. The cost of natural gas and electricity were taken 690 Rials per m3 and 773 Rials per kWh, equal to Iranian unsubsidized rates.

Another issue which was considered in this optimization was the environmental issue. According to [9], emission of pollutants imposes costs which are in fact costs of reduced performance of human beings caused by these pollutants. This fact is considered as costs assigned to pollutants CO, CO2 and NOx. According to catalogs of the manufacturer, using the lean combustion system and SCR catalysts, emissions of CO and NOx caused by their products are limited to 100 mg/Nm3 for Nox and 300 mg/Nm3 for CO. CO2 emission from natural gas combustion is equal to 1.15m3/1m3 Natural Gas according to [11] which by considering the density of carbon dioxide in normal conditions equals to 20420mg/Nm3. Values of emissions of CO and NOx for small boilers are 641mg/Nm3 and 1506 mg/Nm3 respectively, according to [12]. As calculated in [9], the social cost associated with these emissions is 81750 Rials/kg for carbon monoxide, 240 Rials/kg for carbon dioxide and 64240 Rials/kg for Nitrogen oxides. Therefore, the social costs for burning of each cubic meter of natural gas for Jenbacher® reciprocating engines and the boiler are as shown in tables 2 and 3.

Table 2 Emissions and their costs for natural gas-burning boiler

	(mg/m^3)	kg/kWh	Unit cost($/kg)	Unit cost ($/kWh)
NOx	1506	0.014843136	6.424	0.095352306
CO	641	0.006317696	8.175	0.051647165
CO_2	20420	0.20125952	0.024	0.004830228
		Total emission cost($/kWh)		0.151829699

Table 3 Emissions and their costs for natural gas-burning engine

	(mg/m^3)	kg/ kWh	Unit cost($/kg)	Unit cost($/kWh)
Nox	100	0.0009856	6.424	0.006331494
CO	300	0.0029568	8.175	0.02417184
CO_2	20420	0.20125952	0.024	0.004830228
		Total emission cost($/kWh)		0.035333563

5. Choosing capacities of components and optimization

5.1. The case without heat storage

In this section, sizing is carried out in two different strategies, one is the absence of heat storage and the other is its presence. In both strategies, modules of cogeneration and their annual working durations are determined so that the total annual cost is minimized.

For the case where there is no heat storage system, the CHP system is designed based on load-duration curves. These curves are constructed using the hourly load data taken from energy simulation, i.e. first values of heating and electrical loads for all 8760 hours of the year are taken from outputs of Carrier HAP and then, those numbers are put in descending order and plotted against duration, from 1 hour to 8760 hours. According to [13], the largest rectangle which can be circumscribed in that curve represents the optimal choice of the CHP system, in terms of capacity (on the vertical axis) and number of total working hours throughout the year, on the horizontal axis. Here, the basic idea is quiet similar. However, this curve is used here to determine the capacity of the supplementary boiler which is the difference of maximum load with the heat production of the CHP module and its total heat production throughout the year being equal to all heat demand not satisfied by the module.

Electricity is considered as a bi-product of the system that can be used locally or sold to the network. The rates of buying and selling power to the network are very close to each other in Iran [20] and both are assumed to be 773 Rials. If a CHP system is independent from the grid, it can employ batteries to store excess electricity to be used later but when selling power to the grid is possible, using storage of electrical energy is not economical [9].

The control strategy used for the case where there is no heat storage system is as follows: When the number of working hours of the CHP module determined from optimization is plot with load-duration curve, the point where it intersects that curve shows the value of minimum load for operation of the module, i.e. when the thermal load is lower than that value, the module will be switched off and when the load exceeds that value, the module will be switched back on.

In manufacturer's catalogs, two heuristics are suggested:

- The thermal power of the cogeneration power should be between 30 to 50 percent of the peak value of thermal power demand.
- The module of cogeneration should work at least 4000 hours during a year.

Figure 2 shows an example of load-duration curve.

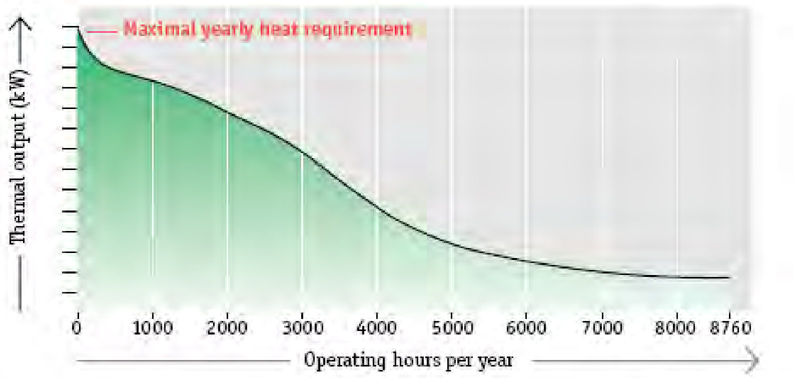

Figure 2. Load duration curve for heating load

Naturally there will be times when the heat demand is higher than the production of modules and at these times this heat shortage is covered by the auxiliary boiler.

Load-duration curves for heating, and electrical loads of our building are shown in figures 3 and 4.

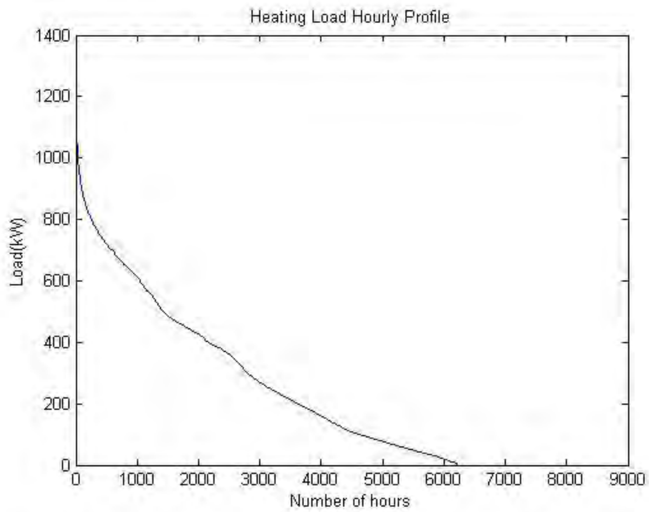

Figure 3. Load-duration curve for heating load

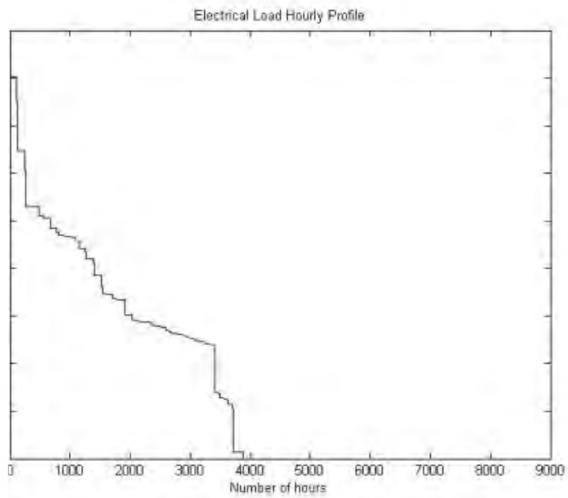

Figure 4. Load-duration curves for electrical load

Now, the objective function for the optimization is defined as the total annual cost of the system. To calculate the total annual cost, first we should annualize capital investments using the capital recovery factor (CRF) .

Where i_r , the interest rate, according to [14] is taken 12 percent, and *n* is the number of years of life time of the system, here taken 20 years. Thus, the objective function is:

$$C_{Ann} = CRF \times (C_{TCM} + C_{TCAB} + C_{TCST}) + C_{O\&M\,Module} + C_{O\&M\,AB} + C_{Emi} - C_{el} \quad (1)$$

Where C_{Ann} is the total annual cost, C_{TCM} is the total capital investment for the CHP module, C_{TCAB} is the total capital cost for the auxiliary boiler, C_{TCST} Is the total capital cost for the storage tank (if included), $C_{O\&M\ Module}$ is yearly O&M plus fuel costs for the cogeneration modules, $C_{O\&MAB}$ is the yearly O&M plus fuel costs for the auxiliary boiler, C_{Emi} is the yearly emission cost and C_{el} is yearly cost of electricity production which is the profit of the system and therefore appears with a negative sign in the total annual cost. The optimization is carried out using the direct search method. For this optimization, decision variables are taken to be capacities of CHP modules and their durations of operation throughout the year. Constraints are defined based on heuristics provided by the manufacturer, namely each module should not operate less than 4000 hours in the year, and the values of capacities of modules and the boiler, naturally may not be negative and the values of working hours of each of modules cannot be more than 8760 hours. Results are as presented in the next section.

5.2. The case with heat storage

If we decide to employ heat storage in our system for more smooth operation and less waste of energy, a different design and operation strategy has to be used. Heat is stored as hot water (90^{o}C) in a well insulated storage tank. Its cost data is taken from [14] and (1) is also used for cost estimation, using two different values of the exponent α (0.3 and 0.65) based on the calculated volume. The cost data is available in terms of volume of the storage tank while in the optimization, the capacity in terms of energy storage is considered. As mentioned in [15], the CHP module receives cooling water at 40^{o}C and sends it out at 90^{o}C. Thus, in order to determine the volume of the storage tank conservatively, we take the unit volume energy of the water stored in this tank as the difference of enthalpy of water in those input and output states.

Thus, by storing each cubic meter of water in the storage tank, we have stored 58.167kWh thermal energy.

After calculating the Purchased Equipment Cost (PEC) in terms of energy storage capacity, we calculate the Total Capital Investment (TCI) based on the Fixed Capital Investment (FCI) and the PEC using the factors listed in table 4. The data in this table are based on results reported in [14]. For costs having upper and lower bounds of the range of value, in absence of other data, the average of the two bounds mentioned in table 4 is used in calculations.

Table 4. Components of total capital investment

I - Fixed Capital Investment (FCI)
A- Direct costs 1- Costs associated with the site
• Purchased Equipment Cost (15-40% FCI) • Installation cost (20-90% PEC) • Piping (10-70% PEC) • Instrumentation and control equipments (6-40% PEC) • Electrical Equipments (10-15% PEC)
2- Off-site costs • Land (0-10% PEC) • Civil, architectural and structural costs (15-90% PEC) • Service facilities (30-100% PEC)
B- Indirect costs
1- Engineering and supervision (25-70% PEC) 2- Construction cost including the profit of the contractor (15% of direct cost) 3- Contingencies (8-25 % the sum of the above costs)
II- Other costs
A- Start up cost (5-12% FCI) B- Working capital (10-20% TCI) C- Research and development (not considered in this paper)

When designing the cogeneration system with heat storage, we need to use load-time curves instead of load-duration curves. These curves show the value of thermal/electrical load at every hour for all 8760 hours of the year. Load-time curves for thermal and electrical loads are shown in figures 5 and 6.

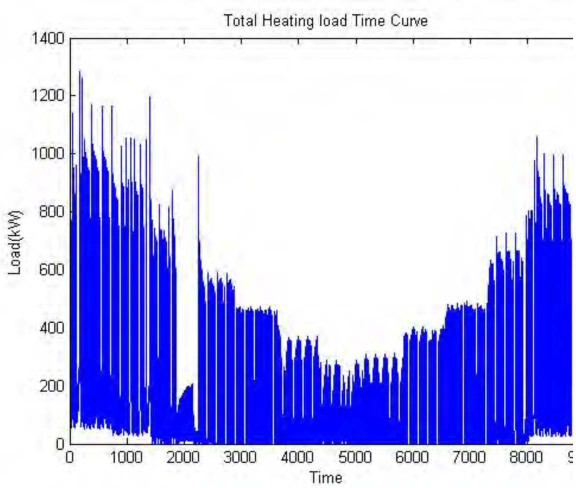

Figure 5. Load-time curve for heating load

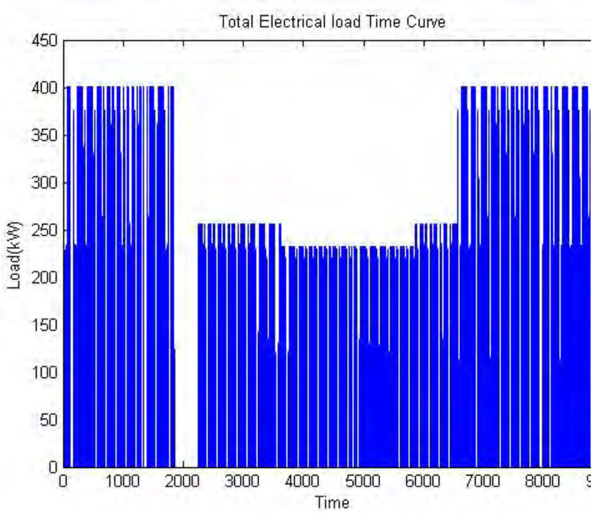

Figure 6. Load-time curve for electrical load

As a r esult of the above mentioned strategy, there will be fewer start-stop cycles and probably, less heat rejection to the surroundings. When optimizing the system in this case, working duration of the module will no longer be a decision variable but instead, the volume of the storage tank will be searched for its optimal value and working duration of the module will be determined from the volume of the storage tank and load-time curve. The other decision variable will be the size of the CHP module, as before. The results of optimization of this case are presented in the following section.

6. Results

Table 5. Optimization results for a CHP module without heat storage

	Capacity	Duration/amount of yearly operation	Capital investment cost (Rials)	O and M +Fuel costs (Rials per year)	Emission cost (Rials per year)
CHP Module	497kWth (J 312L)	4011h	8.63E+09	5.79E+08	1.55E+09
Boiler	786.6kW	439843kWh	3.44E+09	4.25E+07	9.21E+08
Value of yearly electricity production of the CHP module (Rials)				1.35E+09	
Maximum load (kW)				1284	
Total annual cost (Rials)				3.36E+09	
Yearly heat dissipation to surroundings(thermal energy waste)(kWh)				450306	

Table 6. Optimization results for a CHP module with heat storage

	Capacity	Duration/amount of yearly operation	Capital investment cost (Rials)	O and M +Fuel costs (Rials per year)	Emission cost (Rials per year)
CHP Module	497kW(312L)	8550h	8.63E+09	1.24E+09	3.31E+09
Boiler	994.1kW	292966 kWh	3.44E+09	2.83E+07	6.14E+08
Storage Tank	3.474m^3	202.1kWh (Max storage)	3.36E+08	-	-
Value of yearly electricity production of the CHP module (Rials)				2.88E+09	
Maximum load (kW)				1284	
Total annual cost (Rials)				4.06E+09	
Yearly heat dissipation to surroundings(thermal energy waste) (kWh)				1.95E+06	

As it is evident from tables 5 and 6, heat dissipation to surroundings and total annual cost are both higher for the case with heat storage than the simple case. Moreover, as illustrated in results, curves of electrical and thermal loads have more consistency with curves of energy production of the module in the simple case. However, in the case with the possibility of heat storage, more electricity is produced and the module works for a longer total duration, representing a smaller number of switching off and on cycles which is better for durability of the reciprocal engine and the whole module.

7. Conclusion

Heating and electrical loads were calculated for a 10-floor educational building using energy simulation of Carrier HAP®, and based on those loads, cogeneration systems were designed to provide electricity and heating needs of the building. The CHP module was selected among 13 models of a globally renowned manufacturer.

Firstly, a simple CHP system was designed containing a CHP module and an auxiliary boiler. Secondly, the possibility of heat storage was taken into account using a storage tank as heat accumulator. Two different control strategies were considered for these two cases and consequently, design and optimization were also carried out differently.
Comparison of results showed that the simple system excluding heat storage had a lower total annual cost and heat dissipation to surroundings. On the other hand, it had a lower work duration for the CHP module and consequently, a larger number of switching on and off cycles representing its disadvantage to the system with heat storage.

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Low exergy heat recovery for sustainable indoor agriculture

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Abstract: With improved greenhouses, farmers have to ventilate. An air-to-air multi-tube counter flow heat exchanger unit was installed in a greenhouse used for the experimental cultivation of hydroponic tomatoes and cucumbers. This 24m long unit involves a 12" O.D. external shell used to exhaust moist air and five inner tubes to bring fresh air inside. The tests, carried out between March and May in a 576 m^3 enclosure, demonstrated that average efficiencies of η=84% and η=78% were obtainable with air volumetric exchanges rates of 0.5 and 0.9 change per hour, respectively. Latent heat was found to play a major role in the overall heat transfer, contributing about 40% of the total energy exchanged in some situations. The exchanger could be buried underneath the ground or suspended above the crops. The unit made of plastic is durable, rot and rust resistant, affordable, and is ice and frost compliant. A pre commercial implementation with an improved design is now considered in collaboration with Gaz Metro. This paper presents the original prototype that help in reducing the consumption of natural gas, fuel, bunker, or propane.

Keywords: *Heat exchanger, Latent heat recover, Sensible heat recovery, Plastic.*

Nomenclature

A	*Surface area*	m^2
cp	*specific heat*	$J.kg^{-1}$
f	*friction factor*	m^2
D	*diameter of the tubes*	m
h	*heat transfer coefficient*	$W.m^{-2}$
k	*thermal conductivity*	$Wm^{-1}K^{-1}$
L	*contribution of latent heat*	%
l	*length of the tubes*	m
$\dot{m}$	*mass flow rate*	$kg.s^{-1}$
Nu	*Nusselt number, hD/k*	-
Re	*Reynolds number*	-
T	*temperature*	K
i	*specific enthalpy*	$J.kg^{-1}$

1. Introduction

1.1. Context

In recent years, passive infiltration of air into greenhouses has been reduced from three or more air changes per hour to less than one half [1]. The reduction of air infiltration into greenhouses leads to significant reductions in heating costs. However, this may be achieved to the detriment of the crops being grown. Very low air exchange rates can lead to abnormally high levels of humidity both during the daytime and at night.

The characterization of the influences of humidity on plant response has not yet been thoroughly investigated unlike those of light, temperature, and carbon dioxide [2]. This may be, in part, due to the difficulty in measuring and controlling humidity in large enclosures and to relate the humidity measurements to the transpiration rates of the crops [3]. Nevertheless, an afternoon above 95% RH may kill or damage a whole harvest. Furthermore, even when the crops are producing at high levels of humidity without any damage, their production rate is much lower than in a controlled environment.

To avoid excessively high humidity levels, venting and heating often remains the only solution to the farmer and this may annihilate the gains achieved by the reduction of infiltration. Traditional heating and ventilation systems result in an inefficient and expensive use of energy, especially during winter in cold regions of the world. To keep sustainable development strategies, this exchanger should be low cost, user friendly, rot and corrosion resistance, efficient even when ice and frost are present, and, obviously, save energy. The purpose of this study is to design, build, and test such an exchanger to be used in greenhouses located in Northern countries.

1.2. Economics in cold regions

The *Syndicat des Producteurs en Serres du Québec* (SPSQ) [4] lists the problem of humidity control in greenhouses as a top priority for this industry. Table 1 [5] indicates the average annual energy requirement per unit area and its corresponding unit cost of operation, for a greenhouse located in Quebec (Canada), as a function of its dehumidification strategy. The data for unit costs are updated for 2011.

Table 1. Energy requirements and costs as a function of the ventilation strategy in greenhouses.

Dehumidification Strategy	Energy Requirement (MJ/m^2)	Cost* ($\$/m^2$)			Difference with/without ($\$/m^2$)		
		Gas	Oil	Electricity	Gas	Oil	Electricity
None	1672	29,14	44,13	35,76	-	-	-
1 vol/h	1883	32,81	49,70	40,28	3,68	5,57	4,51
Proportional	1980	34,50	52,26	42,35	5,37	8,13	6,59

Cost estimates based on: $37.3MJ/m^3$@$0.48\$/m^3$ and 80% efficiency for natural gas
38.9MJ/L@0.54$/L and 75% efficiency for oil no.2
3.6MJ/kW-h@0.077$/kW-h for electricity

In Table 1, the first row corresponds to unit heating costs when dehumidification is due to exfiltration of moist air only (balanced by infiltration of cold air), while most of the vapour condenses on the roof and the walls of the greenhouse. This situation is mostly found in old installations where passive infiltration is important. The second row shows figures for a situation where a whole change of air is made in the greenhouse in an hour. The last results presented in the third row of Table 1 pertain to the situation where the farmer ventilates to maintain an adequate level of humidity all the time. Table 1 shows that in cold climates: (1) about 13% to 18% of the heating costs of a standard greenhouse are due to humidity management; (2) proportional ventilation is about 5.4 (for natural gas) to 8.1 CDN$/m^2 (for Oil, indeed electricity is cheaper than oil in Québec) per year more expensive than no ventilation. This is twice as much as in the 1990s for which this cost varied from about 2.5 (for natural gas) to 4.7 CDN$/m^2 (for electricity). This represents a minimum extra cost of about 800$/y for a small 144 m^2 unit which results in millions of dollars for the 110 hectares of crops and 134 hectares of ornamental plants being grown in Quebec only. Hence, one of the objectives of the work is to provide an equipment with a low payback period to be used by most farmers. At last, it should be stated that the critical periods for ventilation are fall and spring for which crops are growing and a fast rate and condensation on the walls is not as important as in winter.

2. Methodology

2.1. Description of the prototype

After a feasibility study, it was decided to build a multi-tube counter-flow heat exchanger. In view of the restrictions formulated in the introduction, corrugated and flexible thermoplastic drainage tubing [6] was selected to serve as the core of the multi-tube exchanger, four thermoplastic tubes 76 mm I.D. wrapped around a central 101 mm I.D. tube were used. The external kernel or shell of the exchanger that carries the warm and moist air was a tube 305 mm I.D. with a corrugated outer surface (361 mm O.D.) and a smooth inside surface to permit ease of assembly [7], see Fig. 1.

Due to the unlimited amount of space available within greenhouses and because the major part of the exchanger could be buried or suspended, compactness [8] was not a critical parameter here. As a result the heat transfer area density of the first prototype was about 27 m^2/m^3. The first exchanger prototype was 24.3 m long and involved about 66.9 m^2 of direct exchange area. In the calculation of the exchange area, the effects of the corrugations have been taken into account. This yields about 100% increase over smooth tubes. The surface increase for the 76 mm tube is the same. Fig. 2(a) shows the warm end of the unit: the four gray tubes are carrying the warm moist air which is injected in the external shell. Fig. 2(b) shows the cold end of the prototype.

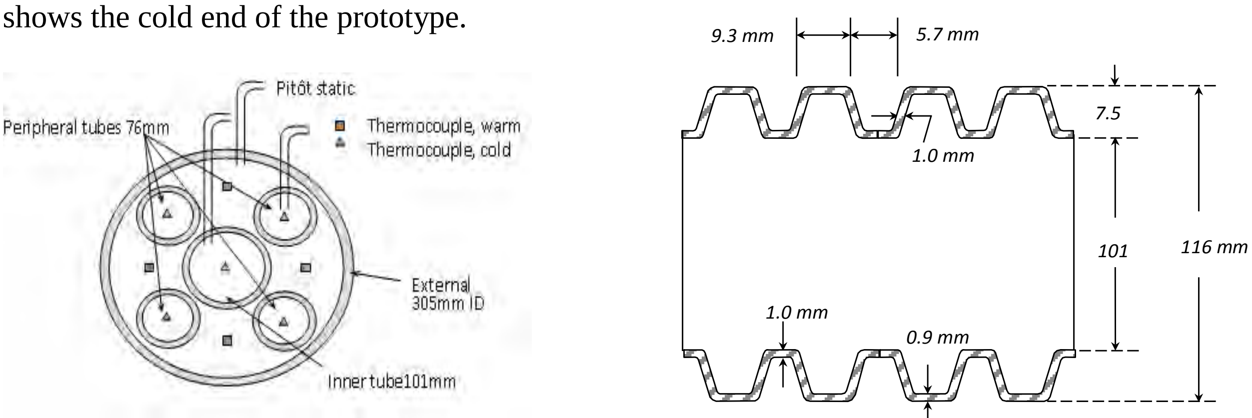

Figure 1: Schematic of the prototype: (left) cross-section; (right) longitudinal cross-section and geometrical details of the 101mm I.D. tube

It can be seen in Fig. 2b that the ventilator is built into the plenum and that the tubes are isolated to prevent condensation in the greenhouse. The overall cost of this prototype, excluding the fans, is much below 2000 CDN$.

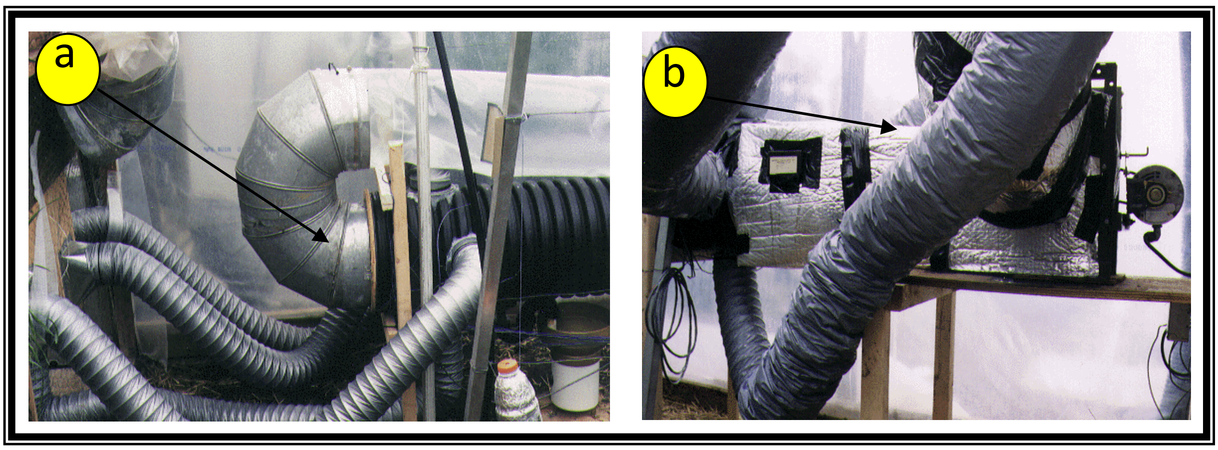

Figure 2: (a) The warm end of the unit; (b) The cold end of the unit

The size of the prototype is justified by the requirement to operate at subzero temperatures for which accumulation of ice should not significantly increase the pressure drop and decrease the overall efficiency. In addition to having a low area density, the original unit has been designed to permit a maximum volumetric exchange rate of one volume per hour in a 576 m^3 greenhouse located at the *Institut des Technologies Agro-alimentaires de St-Hyacinthe*, Québec. The greenhouse is part of a larger complex involving several units. It is entirely covered by polyethylene films on the top and on its sides.

2.2. Numerical design tool

Brundrett et al. [1] proposed a simple model to design heat exchangers to be used as dehumidifiers in greenhouses. In [1], the authors proposed to carry out energy balances along the axis of the exchanger from one volume to the next. In dry and wet zones, the overall heat transfer coefficient is calculated differently while the external kernel is assumed to be adiabatic. These researchers validated their model with respect to results obtained from two prototypes. The prototypes involved two air streams separated by a polyethylene film on which condensation occurred as the warm and moist stream reached its dew point. In [1], the comparison between experimental and predicted performance is reported to be excellent. In that study [1], the discrepancies are believed to be due to heat transfer to the outer shell of the exchanger which is neglected in the model. Nevertheless, based on the model of Brundrett *et al*. [1], a one-dimensional basic numerical design tool was developed and implemented to allow for the design of the above-described prototype. The correlation that was used for the internal and external surfaces of the five tubes that constitute the core of the unit is the acknowledged relation proposed by Gnielinski [9,10] with the entrance correction factor derived by Hausen [11,12]. For the internal Nusselt number this yields:

$$Nu_i = \frac{(f/8)\left(\mathrm{Re}_{D_i} - 1000\right)\mathrm{Pr}}{1 + 12.7\sqrt{f/8}\left(\mathrm{Pr}^{2/3} - 1\right)}\left[1 + \left(\frac{D_i}{l}\right)^{2/3}\right] \tag{1}$$

where Re_{Di} is the Reynolds number, based upon the tube diameter D_i, Pr is the Prandtl number, and f is the friction factor [8]. For corrugated drainage tubes, there are no data available to quantify the relative roughness, ε/D. Hence, after a series of pressure drop measurements, ε was approximated to an average of 0.001m.

The outer shell was assumed to be adiabatic. The predictions then have to include the specifications of the psychometric properties of the hot air, with wet and dry bulb air temperatures and absolute pressure being required. The prediction model thus determines where the warm fluid will experience condensation of moisture by dropping below its dew point temperature. The calculation of the overall exchanger is then divided into two sections: the first where heat transfer occurs exclusively by sensible transfer and the second where heat transfer involves latent as well as sensible heat. The overall heat transfer between the hot and cold fluids is given by:

$$q = \dot{m}_o\left(i_{o,inlet} - i_{o,outlet}\right) = \dot{m}_i\left(i_{i,outlet} - i_{i,inlet}\right) \tag{2}$$

An iterative procedure is employed in the two sections until a balance is obtained in the calculation of the heat transfer with Eq.(2) and that with UA LMTD [8]. The contribution of latent heat to the total heat transfer was estimated with:

$$L = \left[1 - \frac{c_p\,(T_{o,inlet} - T_{o,outlet})}{i_{o,inlet} - i_{i,inlet}}\right] * 100 \tag{3}$$

where subscript *i* refers to the stream inside the tubes and subscript *o* refers to that outside the tubes or into the kernel. The efficiency is defined as:

$$\eta = \frac{T_{o,inlet} - T_{i,inlet}}{T_{i,outlet} - T_{i,inlet}}$$

3. Results

3.1. Global results

In this section overall results are provided for the period extending from March 21st to May 21st. Spring is selected as it corresponds to a critical period as the plants are active and condensation rates on the walls very low due to higher temperatures than those found in the winter. At a rate of $\dot{Q}$=0.5 air change per hour, the average efficiency based on temperature for the whole period of investigation was about : η=84% with a 5% standard deviation. For the results obtained with $\dot{Q}$=0.9 air change per hour, the average efficiency decreased to η=78% with a 3.5% standard deviation.

The experimental results carried out over the two months period indicate that for $T_{i,inlet}$ varying between 1 and 3°C with RH varying between 63% and 70%, the contribution of the latent heat to the overall heat transfer fell within a 39 to 43% range. To obtain such results, the amount of condensation recovered is measured (to estimate latent heat recovery) as well as the overall temperature differences.

The amount of water that condenses on the walls is calculated based on the variation of the absolute water content of the warm moist fluid along the exchanger. A typical rate of condensation is about 1680 mL/h. The maximum condensation rate was found to reach 3200 mL/h when the external temperature was –10^{o}C and the internal temperature 20^{o}C with 85% RH. The maximum power used by the Delhi fans was 637 W, and the rate of heat gained by the cold fluid varied from 874 W at $T_{i,inlet}$ = 14°C to 3 089 W at $T_{i,inlet}$ = -10°C. This indicates a variation in the COP such that: 1.4 < COP < 4.8.

The first day was March 26th, when the volumetric flow rate of warm fluid, $\dot{V}_h$, was 0.099 m3/s and that of the cold fluid, $\dot{V}_c$, was 0.079 m3/s. The profile presented in Fig. 3 (a) is typical of what was observed when the prototype operated at 0.5 air change per hour.

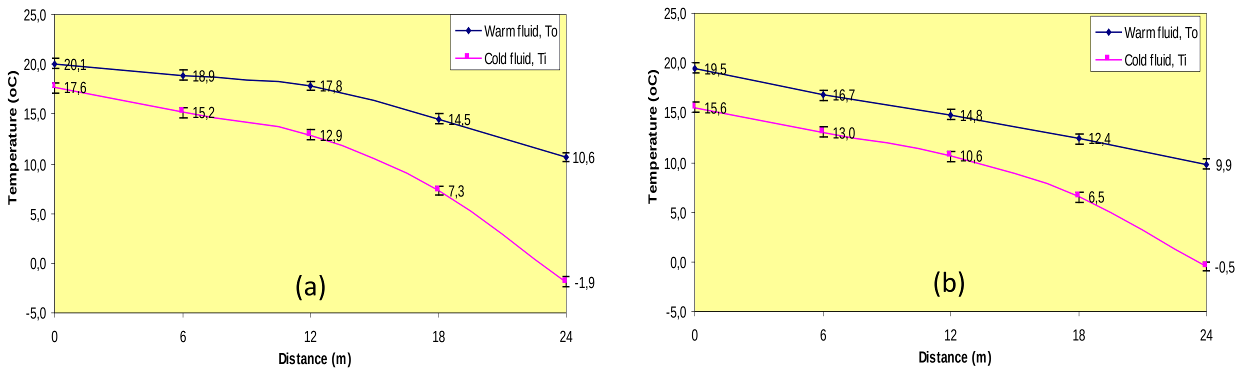

Fig. 3: Temperature distribution. (a) March 26th: 8h10, 0.5 air chg / h; (b) April 5th: 4h50, 0.9 air chg / h

For this case, the relative humidity at the warm exit of the cold stream was 15.7% while it was almost completely saturated at 93.5% at the cold exit of the warm stream. The efficiency was 89%. The heat recovery was excellent: 1948W. And at that time of the day, provided that the fans needed 355W, the COP was 5.51.

Fig. 3(b) shows results for April 5th, when $\dot{v}_h$ was 0.148 m^3/s and $\dot{v}_c$ was 0.141 m^3/s. Similar trends can be observed. For this second case, the relative humidity at the warm exit of the cold stream was 18.9% and the efficiency was 81%. 2856W were recovered while 637W were used: the COP was 4.48.

3.2. Psychometrics results

The relative humidity was also monitored to assess the ability of the unit to fulfil the needs of the plants. It is worth noting that 0.9 air chg/h is not enough to maintain an adequate level of humidity in the complex all year long: it should be adequate about 80% of the time. But for this design, only general characteristics were to be obtained. The test was carried out in the critical period of growth for a greenhouse in Québec. As a result, it was expected that the humidity level would be very high in this period even under operation: traditional ventilation had to be used as a complement. Fig. 4 shows the relative humidity distribution for March 26th.

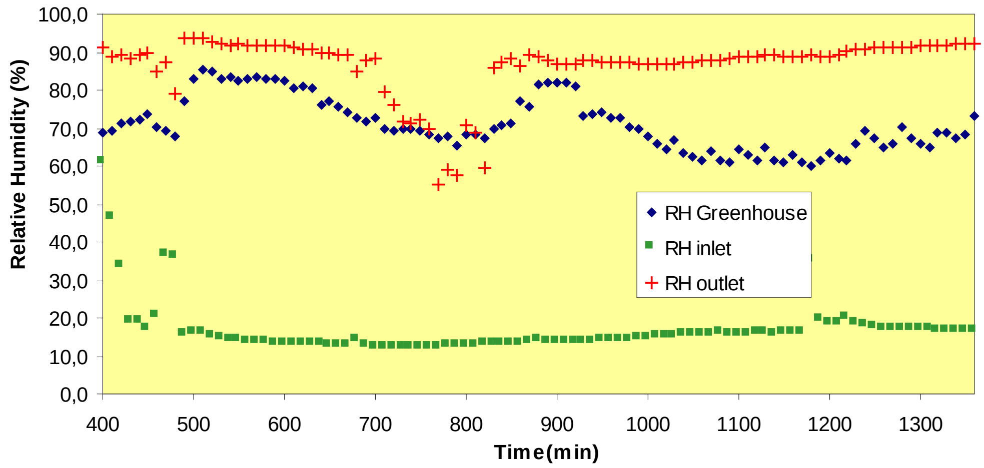

Fig. 4: Relative humidity distribution in the greenhouse on March 26th

The results for the humidity in the greenhouse (diamonds) show a first peak early in the morning: March 26th was sunny and the plants were active early. The humidity had to be lowered with standard ventilation as the unit was not able to deliver a sufficient flow rate to evacuate a sufficient amount of moisture. A second peak appears at about t = 900 min, that is when the sun sets. At that time, the greenhouse had to be closed as the external temperature became too low to maintain an adequate temperature level inside. The interesting part of the curve is that the unit was able to lower the humidity level rapidly after sunset. In brief, a bigger unit would have been needed only in the morning for that day. The inlet stream humidity results (squares) show the period in the day when it stopped: the unit operated almost continuously. The last results (crosses) show that air was saturated in the warm stream except when additional ventilation was used. In these conditions, the humidity level in the greenhouse was below 75%.

Fig. 5 presents typical results obtained for a period ranging from April 5th to April 9th. This sequence demonstrates the performance of the prototype as a dehumidifier over an extended period. At that time, about 300 mature plants of tomato and cucumber were growing. During this period, the exchanger was operated continuously with a RH threshold of 75%. The transpiration cycle of the plants can be interpreted as follows. The photosynthesis activities diminish after sunset. As shown in the figure, the relative humidity then reaches peak lows of about 79 to 82%. The high peaks occur at about noon with maximum relative humidity of about 90 to 91%. On an average, the relative humidity was about 85% in the greenhouse.

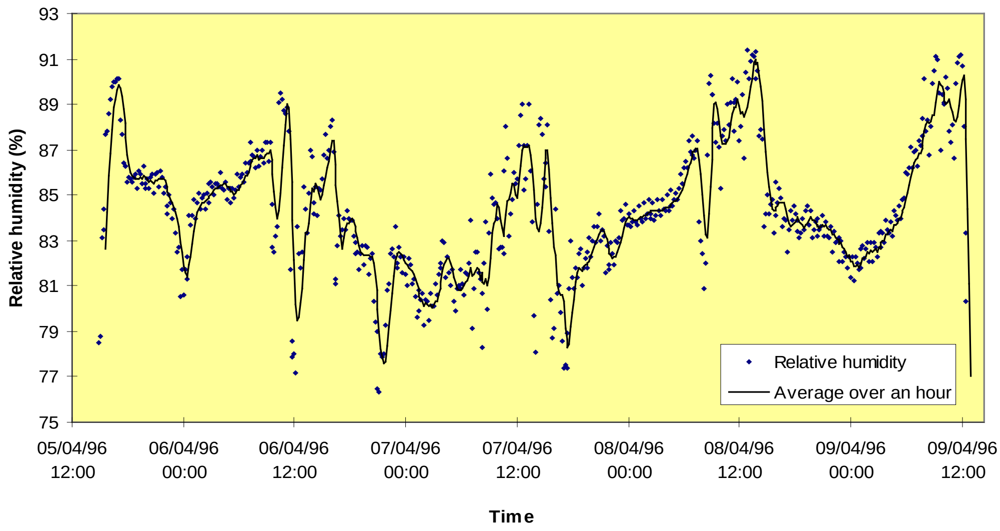

Figure 5: Relative humidity distribution in the greenhouse between April 5th and 9th

Again, it is shown in Fig.5 that the prototype is too small to permit a total compensation for the needs of the plants: the threshold of 75%RH is never reached. This was predicted as the capacity of the exchanger is about 5 times lower than the maximum greenhouse requirement. However, these results are interesting as they permit one to compare the humidity management using the undersized unit with traditional ventilation techniques. Here, the cycles never reach 100% relative humidity which would sometimes be nearly the case with manual ventilation. This indicates that although two to five air changes/h may be needed in critical periods, the smaller unit of about one air change/h can nevertheless permit preventing relative humidity to shoot above 91%. Results from Fig.4 and 5 were used in the design of a second generation of pre-commercial units that are now undergoing a more thorough experimental testing procedure. Knowing both incoming and outgoing volumetric flow rates in conjunction with their relative humidities and temperatures, a mass balance can be performed for water vapor in the greenhouse.

3.3. Payback period

Here the payback period is estimated with no account for the improvement of the crops growth with adequate level of humidity: the "real" performance of the exchanger should be better. The integrated heat recovery is used to estimate the payback with no account of the fan power as if they were used anyway to extract the moisture from the greenhouse. It has been found that the units were able to recover 9840 kW-h over the whole year which corresponds to a cost of 617$ for gas heating and 935$ for oil heating. As the experimental unit costs 1140$ (calculations carried out for a production and installation of 100 per year), the simple payback period is about 1,5 year (from 1,2 to 1,9 years, without subsidy).

4. Conclusion

A prototype air-air counter-flow multi-tube heat exchanger has been designed and built to meet the specific greenhouse requirements of operating in a cold climate. The uncompact design involving plastic components was retained so as to meet the following requirements: (1) low cost, CDN$ < 2000 (1,5 year pay-back period); (2) ease of assembly, maintenance, repair, and operation; (3) corrosion and rottenness resistance; (4) satisfactory operating efficiency when frost present.

The prototype was designed using a basic numerical tool. Drainages tubing were retained as they readily permitted one to meet the design requirements. One of the goals was to convince producers that such a simple design could spare them a substantial part of their yearly heating costs. The unit was assembled and calibrated in a greenhouse used for the experimental cultivation of hydroponic tomatoes and cucumbers during winter. The first series of tests, carried out between March to May, demonstrated that average efficiencies of η=84% and η=78% were obtainable with air volumetric exchanges rates of 0.5 and 0.9 change per hour, respectively, in a 576m^3 greenhouse. Latent heat was found to play a major role in the overall heat transfer, contributing about 40% of the total energy exchanged in some situations.

In conclusion, with sufficient exchange area, simple heat exchangers can be economically used as dehumidifiers in several applications. The encouraging results presented and mentioned here demonstrate that yet other applications could be found for heat exchangers in sustainable development strategies.

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Environmental analysis of various systems for the cogeneration of biogas produced by an urban wastewater treatment plant (UWTP). (III).

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Abstract: To complete the study on harnessing the biogas produced by a UWTP as an energy source, using cogeneration with motor-generators and phosphoric acid fuel cells, in this paper we present the results of the environmental study. This completes the study made of both systems, enabling us to conclude which of the two methods is best in terms of obtaining the largest amount of energy, at the lowest cost, and with minimum impact on the environment.

For the environmental analysis we compared, amongst other parameters, the contaminating gas emissions produced by each cogeneration device, and assessed the financial cost of the environmental damage caused by these emissions. We also bore in mind the emission levels created by the emissions from each system, both immediately around the plant and in the surrounding areas affected by prevailing wind directions. Finally, we compared the noise levels of the two devices and determined the financial cost of applying corrective acoustic insulation where necessary.

The overall study of both systems has made it clear that to evaluate them correctly, it is necessary to internalize all the costs that are currently externalized. This is the only way to find the true cost of each system.

Keywords: *Cogeneration, UWTP, Motor-generators, Phosphoric acid fuel cell, Environmental analysis, Emissions.*

1. Introduction

In the first part of this study [1], it was found that both systems showed substantial differences in terms of their energetic, exergetic and thermo-economic performance. The irreversible factors of both systems are shared out among their components in different ways but, overall, there are fewer of these factors in the phosphoric acid fuel cell system. However, if we take the energy analysis alone into account, the total year-on-year costs are lower for the motor-generation system, and this is the option that would normally be chosen.

In this second part of the study it becomes apparent that if we add up the costs of both thermo-economic analysis and environmental analysis, i.e.: by internalizing all the costs of both systems, cogeneration with phosphoric acid fuel cells is an investment that can be eventually be recovered. However, this is not the case with cogeneration using motor-generators.

2. Methodology

The environmental analysis compares the two cogeneration systems on the basis of the following features:

Emission levels of atmospheric pollutants and greenhouse gases, along with their financial cost.
Emission levels in surrounding and sensitive areas, and their environmental impact.
Noise levels and their financial cost.
Once the environmental impacts have been assessed, they must be assigned a financial cost and this must be internalized with the rest of the system's costs. The cost of externalities has

been evaluated by various international organizations. Two studies are fundamental if we wish to make an assessment of the costs of the externalities of the systems studied in this paper: one is European [2], and was subsequently developed in [4, 5], and the other is American [3]. The American model basically uses resolution algorithms, which are in turn based on the same concept: the cost of environmental damage attributable to each unit of mass or volume of pollutant.

However, we decided to use the European model [2, 4, 5], because its conclusions are better suited to the environment in which this study took place, but mainly because it is a more conservative model insofar as the numeric values that are obtained are always higher than the real ones. This provides us with a safety margin that is always appreciated by technicians.

In order to assign costs to the externalities, it is first necessary to decide which of these should be taken into account. In this study, we considered those that are due to the emission and noise levels produced by the systems.

We also calculated the levels of emission of chemical pollutants (gaseous compounds and particles), depending on the location's various climatic conditions, so as to compare the final environmental impact of the emissions from each system. No cost was assigned to them, however, because taking into account the costs of the irreversible energy factors and the emissions alone was sufficient proof of the financial difference between the two systems.

From the results obtained in the studies mentioned [2, 4, 5], the emission costs for various scenarios can be inferred, as shown in Table 1. These differ depending on the financial valuation of the emissions.

Table 1. Costs of the emissions of pollutants in various scenarios (euros/ton)

ATMOSPHERIC POLLUTANT	LOW LEVEL (€/t)	MEDIUM LEVEL (€/t)	HIGH LEVEL (€/t)
CO_2	9.90	26.40	41.60
CO	506.23	1,055.87	2,494.26
SO_2	1,635.98	1,869.77	4,933.99
NO_X	1,049.27	7,919.03	10,030.77
PM	3,128.55	4,839.41	13,616.33
VOC	1,113.06	5,265.79	6,489.20

In this study, we have chosen the medium-level costs of emissions shown in Table 1, as we consider them to be the most representative. The nomenclature used for the financial costs that have been developed and used in this study (set-up and operation, energy inefficiency, emissons) is as follows:

C_1 (€/year): Set-up and operating costs during the first year. In subsequent years only operating costs will be taken into account.
C_2 (€/year): Costs of energy inefficiency derived from the thermo-economic analysis.
C_3 (€/year): Costs of noise emissions and atmospheric pollutants.

3. Results

The results of the emission and noise levels for each of the two cogeneration systems studied are shown below.

3.1. Level of emissions from the cogeneration system using motor-generators

The combustion reactions of the motor-generators were modelled on the basis of the excess of air n = 1.5 that was considered. Using the formula created with the EES programme [10], we obtained the motor-generator emission results shown in Table 2, and these were compared with those of the phosphoric acid fuel cells.

Table 2. Comparison of gases emitted by biogas cogeneration by motor-generators and in fuel cells, in grams per second.

NOx EMISSIONS(g/s)		SO_2 EMISSIONS (g/s)		CO_2 EMISSIONS(g/s)		CO EMISSIONS(g/s)	
Motor-generator	PAFC	Motor-generator	PAFC	Motor-generator	PAFC	Motor-generator	PAFC
4.51364	0.00214	0.03482	0	731.13516	244.66268	24.48778	0.00497

3.2. Level of emissions from the cogeneration system using phosphoric acid fuel cells.

Using the available data [7, 8], the emissions from fuel cells were modelled on the basis of the level of working power. With the formula created by the EES programme [6], we obtained the emission results that are also shown in Table 2, above.

The SO_2 emissions for fuel cells are negligeable and have not been taken into account. To make a financial assessment of the emissions, we used the average value of emission costs shown in Table 1. Using these values as a reference, we were able to determine the emission costs of all the compounds mentioned in the study.

Table 3 shows the costs resulting from the emissions from each cogeneration system and compound, whereas Table 4 shows the sum of all the costs for each case.

Table 3. Financial comparison of emission costs for NOx, SO2, CO2 and CO emissions, from both cogeneration systems (€/year).

COST OF NOx EMISSIONS (€/year)		COST OF SO_2 EMISSIONS (€/year)		COST OF CO_2 EMISSIONS (€/year)		COST OF CO EMISSIONS (€/year)	
Motor-generator	PAFC	Motor-generator	PAFC	Motor-generator	PAFC	Motor-generator	PAFC
539,285.94	256.02	981.63	0.00	291,219.64	97,452.22	390,071.85	79.25

Table 4. Financial comparison of total costs (C_3) from emissions of NO_x, SO_2, CO_2 and CO, from both cogeneration systems (€/year).

TOTAL COST OF C_3 EMISSIONS (€/year)	
Motor-generator	PAFC
1,221,559.06	97,787.49

As can be seen from Table 4, the total costs of atmospheric emissions from the motor-generators are 5.64 times higher than those of fuel cells.

As shown by the figures in Table 1, the financial cost of emissions is considered to be included in the cost of emissions shown in the previous section. However, in this study, we took into account the dispersion of pollutants according to the atmospheric conditions of the location, and emission maps were subsequently made. This was because the way in which emissions are financially assessed - which currently includes the effects of immissions - needs to be improved. It should be requisite for a device's emission levels to be used simultaneously with emission maps calculated for the device's various weather scenarios. This study will make it possible to achieve a more accurate financial assessment of the environmental impact.

Level of emissions from the cogeneration system using motor-generators.

We show below a summary of the results of the emission level calculations for each pollutant and each cogeneration system. We used the DISPER 3.0 programme [9] and an Excel spreadsheet [10], introducing the emission data calculated in Table 2 into the programme's user interface (except for the CO_2 figures). By also introducing the weather and other relevant location data, we obtained the CO results shown below, in Figure 1, as well as each kind of atmospheric stability for the profile on the XZ plane of the central line of the plume (X axis).

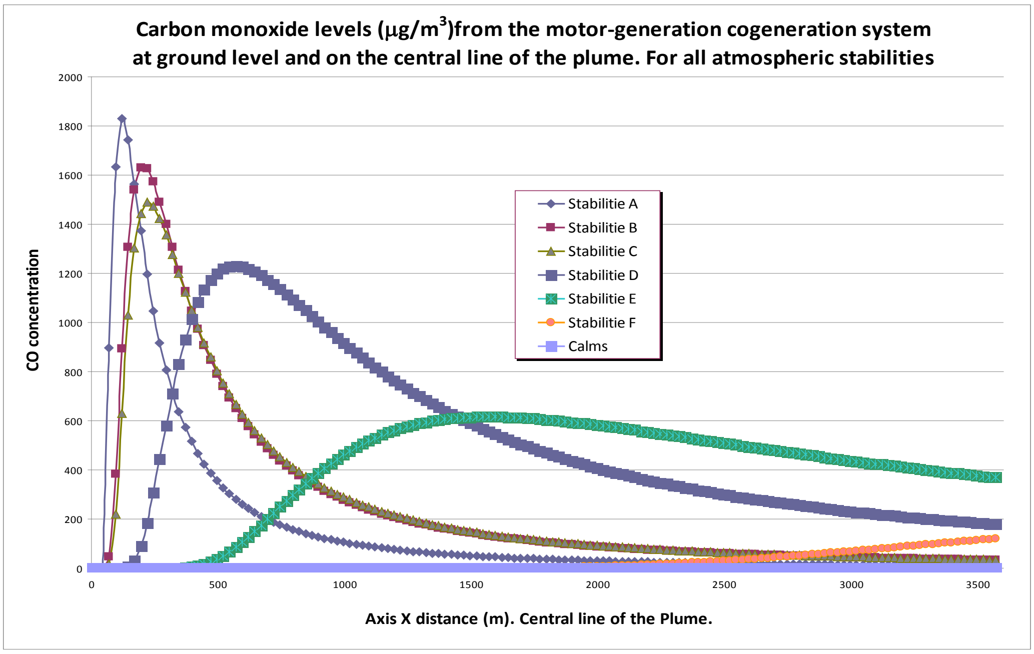

Figure 1. Carbon monoxide levels from the motor-generation cogeneration system at ground level and on the central line of the plume. For all atmospheric stabilities.

As can be seen in Figure 1, the maximum concentration of carbon monoxide immission for the most unfavourable atmospheric stability is:

1800 µg/m^3 = 1,8 mg/m^3 < 6 mg/m^3 (legal limit).

This in no case exceeds the legal limits in force since January 1, 2005 [11].

Level of emissions from the cogeneration system using phosphoric acid fuel cells.

Carbon monoxide is mainly produced in the fuel cell during the process of reforming the biogas vapour to obtain hydrogen. This carbon monoxide has to be removed from the fuel flow into the cell to avoid poisoning the catalyst.

This CO has to be removed from the reformed gas flowing into the fuel cell, because carbon monoxide concentrations as low as 1% in the input flow of these cells can poison the platinum catalyst. Although the operating temperature of the cells is between 150-200ºC, the effects of catalyst poisoning can be detected at concentrations of 10,000ppm of CO in the input flow. The main effect of such poisoning is either an increase in the input flow required to produce the same power, or a drop in the power output [12].

The results of the levels of carbon monoxide emission calculated in this case provide a maximum concentration figure for the most unfavourable atmospheric stability of:

2.5 µg/m^3 = 0.0025 mg/m^3 <<< 6 mg/m^3 (legal limit)

If the above figure is compared to the concentration level of CO emissions from motor-generator emissions for the least favourable atmospheric stability, it can be seen that emissions from the motor-generators are around 720 times higher than those of the set of fuel cells.

Similar results were obtained for the rest of the polluting gases considered in this paper. As for emission and emission levels, the motor-generator cogeneration system is at a clear disadvantage when compared to the phosphoric acid fuel cell system.

The noise level of the motor-generator cogeneration system.

For the calculations in this section, we used the data provided by the manufacturers – which, in both cases, dealt with emissions into the indoor (rather than outdoor) atmosphere of 95 dBA for motor-generators, and 60 dBA for fuel cells [13, 14], as well as current regulations.

To check that the noise level limits set by the current legislation were not exceeded, we used the CUSTIC 1.0 application, by Canarina Software Ambiental [15], to calculate the noise emission levels. These were viewed on isophonic layout maps, for both the installation using motor-generators and the one using phosphoric acid fuel cells.

In the case of the motor-generators, the noise levels calculated in the simulation would exceed the 60dBA day-time limit, beyond the walls of the motor-generation building, unless appropriate corrective measures were put in place. In order to comply with the law, it would be necessary to take corrective measures amounting to 43,500 Euros. With fuel cells, no corrective measures are required

4. Conclusions

By considering environmental effects in our analysis of the two cogeneration systems, we were able to reach the following conclusions.

The most important aspect of this second part of the study is that the environmental cost of the phosphoric acid fuel cell cogeneration system has been valued at 97,787.487 €/year, whereas that of the motor-generator cogeneration system was 1,221,559.061 €/year. As you can see, the latter is far higher than the phosphoric acid fuel cell system.

Furthermore, in the case of motor-generators, acoustic insulation would need to be provided for the building in which they are installed, so as to comply with current legislation on noise emission levels. In the case of the fuel cell cogeneration system, however, no corrective measures are needed to comply with these regulations.

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Research on energy-saving and exhaust gas emissions compared between catalytic combustion and gas-phase combustion of natural gas

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Abstract: In this paper, exhaust gas emissions were compared between conventional gas-phase combustion in both forced exhaust gas concentration of hot-water burner & premixed natural gas/air burner with heater and the catalytic combustion in catalytic honeycomb monolith burner. Test proved that the pollutant emissions of gas-phase combustion **were** higher than that of catalytic combustion. It is shown that the conversion of conventional gas-phase combustion **was** lower than that of catalytic combustion by measured experimental data. It indicated the advantages of energy-saving and environmental protection for the catalytic combustion.

Keywords: *catalytic combustion, exhaust gas analysis, near zero pollutant emissions, energy-saving*

1. Introduction

Catalytic combustion of natural gas has received considerable attention in the last decades due to its practical applications in both power generation and pollutant abatement[1-4]. This reaction has been shown to be effective in producing energy in gas turbine combustors. Compared to the conventional thermal combustion process, using a heterogeneous catalyst can remarkably decrease the reaction temperature, thereby reducing the noxious emissions of nitrogen oxides[5-6]. By enabling the combustion of extraordinarily lean fuel/air mixtures, the catalytic combustion of natural gas provides a low-emission alternative to gas-phase flames[7-9].

In this paper, exhaust gas emissions were compared between conventional gas-phase combustion and the catalytic combustion in catalytic honeycomb monolith burner VI. In order to study the exhaust gas of both forced exhaust gas concentration of hot-water burner & premixed natural gas/air burner with heater and catalytic combustion burner VI, their composition and content were measured, respectively. Meanwhile their combustion efficiency were calculated.

2. Experimental set-up and steps

Figure 1 illustrates the exhaust gas analysis system of catalytic combustion burner VI, The square honeycomb monoliths were 150mm in side of the square and 20mm long, with square-shaped cells which sectional area was 1mm×1mm. The support for all the monoliths tested here was cordierite. The four square catalytic honeycomb monoliths were installed in the burner VI each time. The lengths of catalytic honeycomb monoliths were 20mm for the catalytic combustion burner. In order to decrease the temperature of mixtures in chamber connected with the monolith’s entrance, the 20mm long blank monoliths were inserted between the chamber and the Pd based catalytic monolith’s entrance as assembly of monolith. In the experiment, the reactant gas feeds of natural gas and air were regulated via GMS0050BSRN200000 natural gas meter and CMG400A080100000 air meter with 0~50 L/min and 0~80m3/h of full-scale range , respectively. The two meters were provided electric current through manostat.

In the process of ignition, we need to swept the inside of burner VI by air for five minutes to ensure that there was no residual natural gas. In order to warm the honeycomb monoliths, the burner VI must be ignited by gas phase combustion with the excessive air coefficient at 1.3. When the catalytic surface came to be red, the excessive air coefficient should be adjusted to 2.0. Until it came into the steady state of catalytic combustion, the exhaust gas could be measured by the analyser. At the same time we observed and recorded the data.

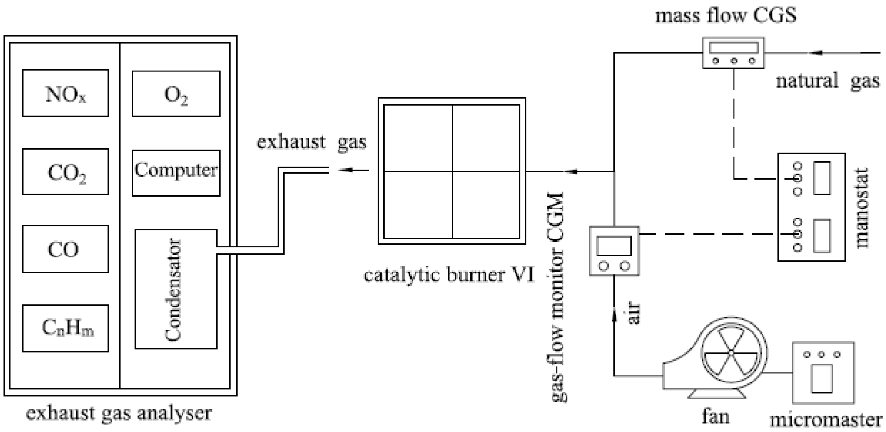

Fig. 1. Exhaust gas analysis system of catalytic combustion burner VI.

Figure 2(a) illustrates the exhaust gas analysis system of premixed natural gas/air burner with heater. This burner was ignited by gas phase combustion with the excessive air coefficient at 1.1 and 1.3. When the water heater came into the steady state of gas phase combustion, we observed and recorded the experiment data from its chimney. Also the Figure 2(b) illustrates forced exhaust gas concentration of hot-water burner with the excessive air coefficient at 1.3. and the exhaust gas concentrations were measured above the burner.

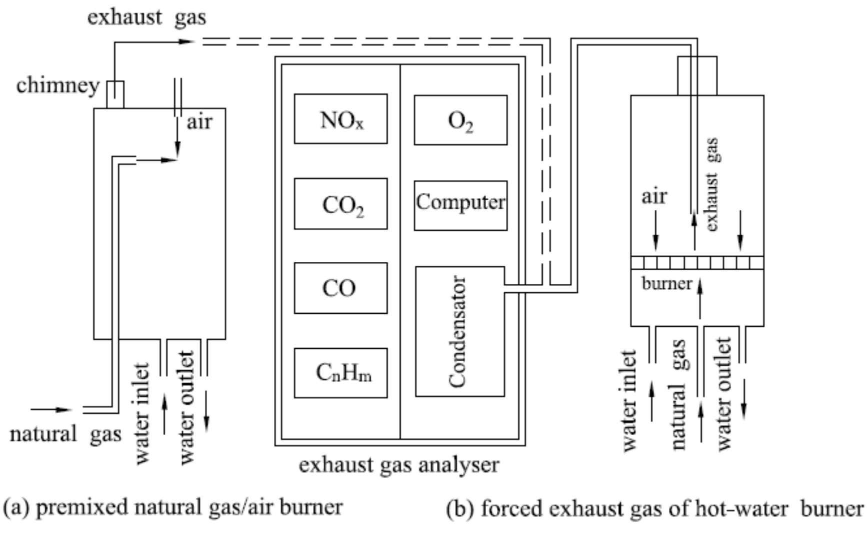

Fig. 2. Exhaust gas analysis system of premixed natural gas/air burner with heater and forced exhaust gas concentration of hot-water burner .

3. Results and Discussion

3.1. Emission characteristics of catalytic combustion and conventional gas-phase combustion

Form figure 3(a) plots the content of NOx was very low , because the temperature(T around 1000℃) of catalytic combustion and gas-phase combustion did not reach the degree which could generate a large number of heat-type NOx. But the emission of NOx in gas-phase combustion ascended gradually with the increase of natural gas flow rate.

The content of CO in catalytic combustion was very small **(closed to 0)**. From the data of CO **[figure 3(b)]** we got that the combustion efficiency of catalytic combustion burner VI is very high and its heat had been released fully. However, the content of CO of gas-phase combustion was higher than that of catalytic combustion. The maximum of CO emission reached about 150 ppm. It was shown that natural gas of gas-phase combustion did not oxidized completely.

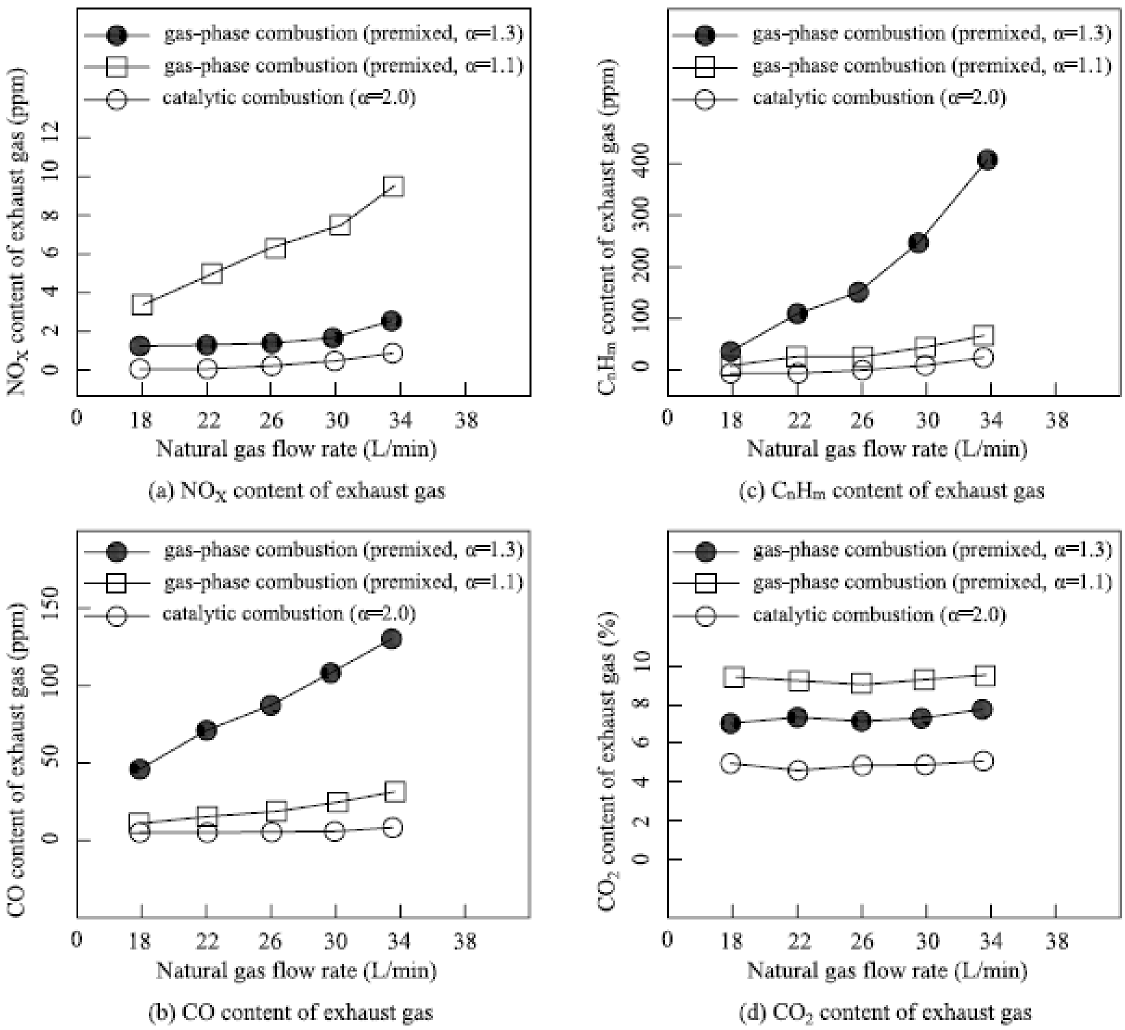

Fig. 3. The exhaust gas content of catalytic combustion and conventional gas-phase combustion（premixed, α=1.3 and 1.1） under the condition of different natural gas flow rate (α is the excessive air coefficient).

The figure 3(c) also shows that there was no C_nH_m from the exhaust gas of catalytic combustion. It was evidenced that the catalytic combustion efficiency was almost closed to 100%. It was seen that the content of C_nH_m in gas-phase combustion was 39.3 ppm～428 ppm. At the same time, C_nH_m was increased quickly with the increasing natural gas flow rate. It proved that the conversion of gas-phase combustion was lower than that of catalytic combustion.

When the excessive air coefficient decreased from 1.3 to 1.1 in premixed natural gas/air burner with heater the conversion of gas-phase combustion increased dramatically, saturating at near 100%, the CO decreased with very lower value (about 8 ppm) in the cases of the high temperature chamber of furnace under certain conditions. But the exhaust gas temperature and heat loss increased from its chimney **with the same water flow rate.** The emission of NOx was increased quickly with the increase of natural gas flow rate. Simultaneously, the nosie happened during the combustion of premixed natural gas/air burner and the blue flame changed gradually into dark red **one.**

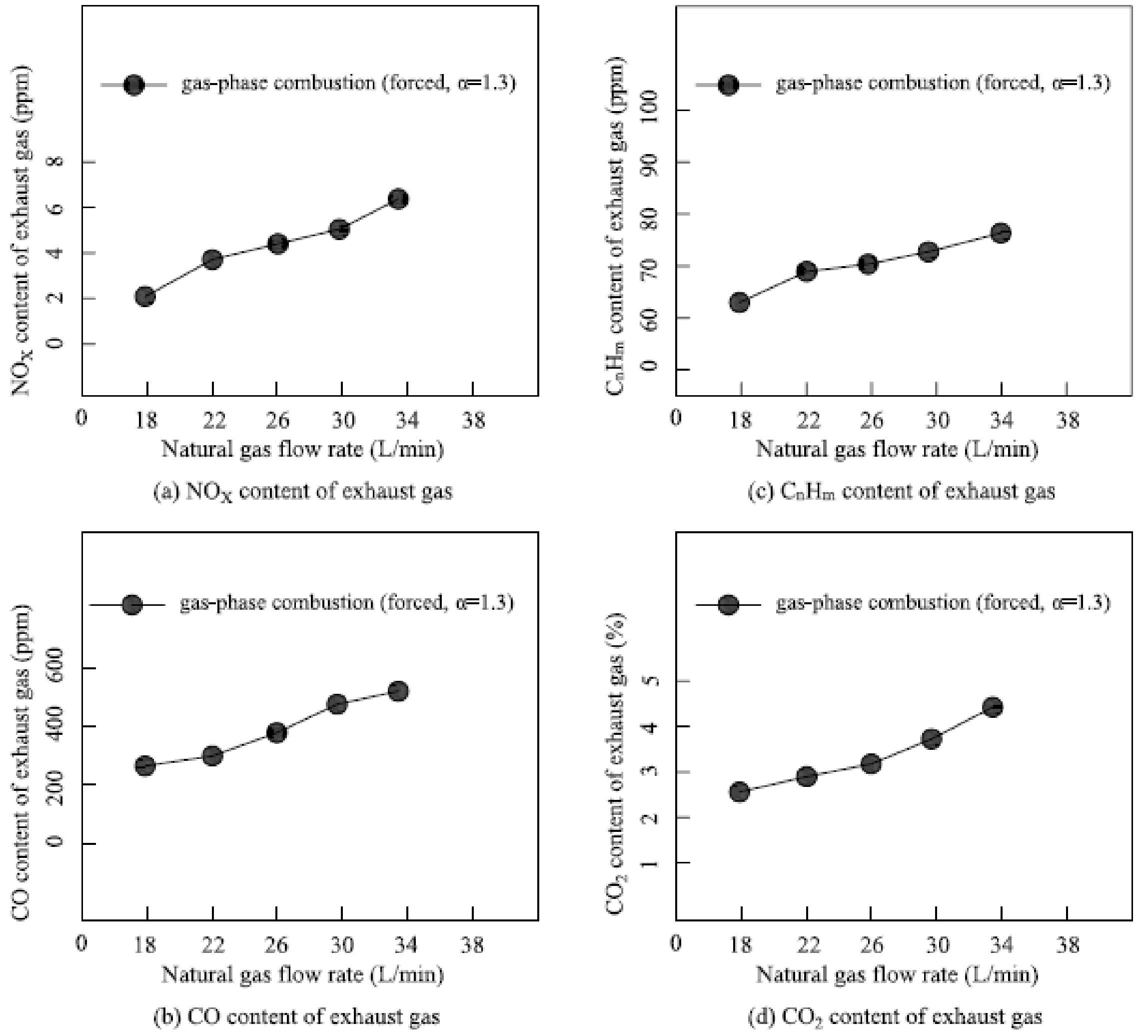

Fig. 4. The exhaust gas content of conventional gas-phase combustion（forced, a=1.3）under the condition of different natural gas flow rate.

The NOx、CO and un-burnt CH_4 concentrations in forced exhaust gas concentration of hot-water burner existed more with the excessive air coefficient 1.3. Its exhaust gas concentrations have been significantly diluted in large space by measured CO_2 data as shown in figure 4. Otherwise, the percentage of CO_2 should remain about 7-8% without vapor by CO_2 analyser.

For all tested of the catalytic combustion, only extremely small amount of CO, unburned fuel and NOx were detected inside the monolith channels and over the open

end of the burner VI. A catalytic combustion process can achieve 'near-zero' pollutant emissions.

3.2. Calculation of combustion efficiency in gas-phase combustion

It was evidenced that the catalytic combustion efficiency was almost closed to 100%. But there were a lot of C_nH_m and CO from the exhaust gas in gas-phase combustion. It proved that gas-phase combustion had not oxidized completely and its combustion efficiency should be calculated. As the main composition of natural gas was methane, so the chemical reaction equation is (1) in the following:

$$CH_4 + 2O_2 = CO_2 + 2H_2O \qquad (1)$$

CO was a kind of intermediate which was generated during combustion of hydrocarbons. The number of C atom remained unchanged in the reaction process. The total volume of CO and CO_2 were the same as that of CH_4 via the reaction equations (1) ($V_{CO} + V_{CO_2} = V_{CH_4}$). Given the volume of methane was 1 Nm^3 (V_{CH4}=1). According to equations (2), the volume of CO was calculated as:

$$\begin{cases} V_{CO} + V_{CO_2} = 1Nm^3 \\ \dfrac{V_{CO}}{V_f^d} = \gamma_{CO} \\ \dfrac{V_{CO_2}}{V_f^d} = \gamma_{CO_2} \\ \dfrac{V_{CH_4}^1}{V_f^d} = \gamma_{CH_4}^1 \end{cases} \qquad (2)$$

Where V_{CO} and V_{CO_2} are the volume of CO and CO_2 in exhaust gas(m^3), respectively. V_f^d is the total volume of exhaust gas. γ_{CO} and γ_{CO2} are ratio of CO volume and CO_2 volume to that of exhaust gas, respectively. $V_{CH_4}^1$ is the volume of unburnt CH_4 in exhaust gas(m^3). $\gamma_{CH_4}^1$ is ratio of CH_4 volume to that of exhaust gas. $\gamma_{CO}, \gamma_{CO2}, \gamma_{CH_4}^1$ are measured by the analyser.

According to equation (3): For 1m^3 CO oxidized completely to CO_2 could generate 12644 kJ heat (H_2=12644 kJ). It proved that the content of CO had an important influence for utilization of thermal energy of the fuel.

$$CO + 0.5O_2 = CO_2 + \Delta T \qquad (3)$$

So, the heat released of unburnt CH_4 and CO were calculated as:

$$Q_{CH_4} = V_{CH_4}^1 \times H_1 \qquad (4)$$

$$Q_{CO} = V_{CO} \times H_2 \qquad (5)$$

Where H_1 is net calorific value of methane under standard conditions which is 33.70MJ/Nm^3. H_2 is calorific value of CO which is 12644kJ/m^3.

The following equations(6) for heat released percent of unburnt CH_4 and CO to reactant (natural gas) was derived:

$$K = \frac{Q_{CH_4} + Q_{CO}}{V_{CH_4} \times H_1} \qquad (6)$$

The combustion efficiency of gas-phase was calculated by equation (7):

$$\eta = 1 - \frac{V^1_{CH_4} + V^2_{CH_4}}{V_{CH_4}} \qquad (7)$$

Where $V^2_{CH_4}$ is the volume of CH_4 which has been used in generating CO, which was $V^2_{CH_4} = \mathrm{V}_{\mathrm{CO}}$.

According to above equations and experimental data, table 1 shows ratio of heat released of unburnt CH_4 and CO and combustion efficiency under the condition of different natural gas flow rate. It was seen that part of the energy were wasted in gas combustion which did not oxidized completely.

Table 1. Ratio of heat released of unburnt CH_4 and CO and combustion efficiency

Natural gas flow rate		L/min	18	22	26	30	34
forced, a=1.3	k_1	%	0.58	0.63	0.65	0.66	0.67
	η_1	%	98.82	98.7	98.63	98.55	98.51
premixed, a=1.3	k_2	%	0.078	0.17	0.27	0.41	0.62
	η_2	%	99.88	99.76	99.66	99.49	99.27
premixed, a=1.1	k_3	10^{-2} %	0.94	1.00	1.05	1.10	1.20
	η_3	%	99.987	99.986	99.984	99.983	99.981

4. Conclusions

Exhaust gas emissions were compared between gas-phase combustion and catalytic combustion in catalytic honeycomb monolith burner VI. It proved that the concentration of pollutant emissions of gas-phase combustion were morehigher than that of catalytic combustion. It was shown that the conversion of gas-phase combustion was lower than that of catalytic combustion by calculated data. It can be concluded that catalytic combustion was completed oxidation combustion of the heterogeneous reaction. The emissions of NOx, unburnt C_nH_m, CO was very small, so the catalytic combustion would not cause serious environmental pollution. Therefore, High combustion efficiency and near zero pollution emissions of catalytic honeycomb monolith burner VI were its advantages which should be applied for industry.

Acknowledgments

The project sponsored by the Beijing Municipality Key Lab of Heating, Gas Supply, Ventilating and Air Conditioning Engineering (KF201002)and Funding Project for Academic

Human Resources Development in Institutions of Higher Learning of Beijing Municipality in 2010（PHR201007127）.

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Experimental and theoretical evaluation of the performance of a Whispergen Mk Vb micro CHP unit in typical UK house conditions

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Abstract: A Whispergen Mk Vb 1KW$_e$ Stirling Engine mCHP unit was integrated into a test rig simulating a typical UK domestic hydronic heating system and tested implementing derived heat demand profiles in the house over the yearly period. The obtained experimental performance was used as input data for static simulations in CANMET Energy RETScreen software to calculate economical and environmental benefits from deployment of the mCHP instead of a condensing boiler. Simulation results show that a 16% annual monetary savings can be achieved due to the introduction of new UK feed–in tariffs. The payback period when using the mCHP system instead of a condensing boiler is about 8 years. These results can be used for determination of strategy for further improvement of the performance of the unit.

Keywords: *Domestic mCHP, Fuel combustion, Energy conversion efficiency*

1. Introduction

mCHP is a promising on-site generation technology which, under particular conditions, can provide energy, carbon and cost savings. The installation of large scale CHP systems (hospitals, airports etc.) has been already proven beneficial due to the high combined efficiency. Those have made the installation of CHP for much smaller applications (domestic) an attractive option and have led to the development of a number of mCHP systems with some being already commercially available.

For small scale domestic applications the Stirling Engine based mCHP systems are considered more suitable due to their quiet operation and high heat/power ratio. The aforementioned, combined with the newly introduced UK feed-in tariff, can have a significant impact on domestic sector carbon emissions and energy consumption.

The scope of this research is to obtain a thorough understanding of the parameters that affect the performance of domestic Stirling Engine mCHP systems and engineer solutions for their feasible deployment. The evaluated deployment scenarios differ mainly in the house size, age and occupancy pattern. These are very important factors which affect the magnitude of the energy demand [1].

2. Methodology

2.1. *Experimental Apparatus*

All experiments were carried out with a 1 kW$_e$ Whispergen Mk Vb Stirling Engine gas fired unit integrated with a test rig which simulates a conventional hydronic space heating system with four panel radiators. The mCHP unit is equipped with two gas burners; the main burner has a heat generation capacity of 6 kW$_{th}$ with no part load operation capability and provides the heat to run the Stirling engine. The auxiliary burner generates an additional 5 kW$_{th}$ and its operation is controlled by the system's electronics. A 150 l tank has been retrofitted to the test rig to allow simulation of Domestic Hot Water (DHW) heating-up and consumption. A three-way valve has been installed to split the water circulation to the two water circuits. The auxiliary burner is controlled by a Honeywell Outside Temperature Compensator (OTC) sensor. A number of meters are used for data acquisition. These include a gas meter, two ultrasonic heat meters and a data logging system for obtaining the mCHP operating parameters during experimentation via a computer interface. The operation of the mCHP unit is controlled by a programmable thermostat-controller device. Unlike pre-commercial prototype Whispergen Mk III system Mark Vb mCHP system does not have a modulation capability, e.g. it can operate only at a full load or is switched off when the heat demand is satisfied.

2.2. *Experimental Procedure*

The procedure followed for the performance evaluation of the Whispergen Mk Vb mCHP includes dynamic and steady state performance analysis and efficiency calculations and carbon emissions analysis, similar to [2, 3]. Heat demand is modeled by determining an occupancy pattern and programming the thermostat-controller to signal it. For the analysis, data is logged every minute [4]. The most important information is provided by the flow and return temperatures, the power generated and the exhaust temperature. The heat meters installed on the water pipes provide information about the water flow rate and the heat generated by the unit. This is sufficient for steady state efficiency calculations. However, since their output cannot be logged to the computer, the temperatures are taken from the engine log for transient state calculations. Then, the generated thermal energy (in $kWh_{thermal}$) is calculated as

$$Q_{gen} = \frac{\sum_{i=0}^{n} Cp_{water}(T_{flow} - T_{return})(\dot{m}_{CH} + \dot{m}_{DHW})}{60} \quad (1.1)$$

where n is the cycle duration in minutes, T_{flow} and T_{return} are the cooling water outlet and inlet temperatures respectively and $\dot{m}_{CH}$ and $\dot{m}_{DHW}$ are the mass flow rates of the heating and the hot water circuits, respectively.

The heat input to the engine is calculated by recording the fuel consumption and using its Low Heating Value. Then efficiencies are calculated as

$$n_{thermal} = \frac{Q_{gen}}{Q_{fuel}} \quad (1.2)$$

and

$$n_{electrical} = \frac{E_{gen}}{Q_{fuel}} \quad (1.3)$$

where Q_{gen} is the heat generated from the mCHP, E_{gen} is the electricity generation and Q_{fuel} is the energy content of the fuel.

The total fuel utilization efficiency is the sum of the thermal and electrical efficiencies.

Another area of interest is the engine’s time response to heat demand signals. Therefore, once heat and power generation values have been obtained, they are plotted against time.

2.3. *Domestic Operation Modeling*

For modeling procedures CANMET RETScreen [5] and EnergyPlus [6] software packages are used in this work. These packages use algorithms based on application of energy balance equations. For example, EnergyPlus uses energy balance equations for a number of zones in the simulated dwelling. Software contains library with a set of material properties used in the structure of the building, data on the climatic conditions and experimental and theoretical correlations to calculate heat losses and the temperature rise inside the house.

Data collected from experiments are used as input to CANMET RETScreen software. This software is a useful tool for comparing a proposed energy plant (mCHP) to a conventional one (grid electricity and gas fired condensing boiler). The user can provide parameters such as the house size and location, the fuel and electricity prices and the operating characteristics of the systems such as their efficiency. Software estimates the annual energy demand and performance of the systems in terms of carbon emissions and economics. There are, however, indications that this software cannot take into account the transient character of the energy demand and of plant operation. Such coarse temporal analyses are likely to lead in over-prediction of the systems' performance [7, 8]. Therefore, the results from RETScreen are used for initial estimations. Then, more detailed models are built in EnergyPlus, which is capable of modeling energy performance on a more detailed basis by considering the transient operational states of the systems under investigation. The results from EnergyPlus are validated by comparing theoretical data obtained with information derived from gas and electricity bills for real houses. The modeled houses are of the semi-detached or detached type which represent a large farction of the UK housing stock [9]. The chosen location was London, UK. Electricity demand data and appliance wattage ratings are found in [10]. Finally, the mCHP unit is programmed to run to meet the demand profile generated by the domestic energy modeling process. For example, *table 1 presents* a mCHP running schedule for a design day during a winter. The operation strategy was based on heat-led mode and focused on minimizing heat generation surplus.

Table 1. mCHP running operation schedule for a typical winter day.

Type of Day	Weekday	Weekend
Morning	2–hours run	6-hours run
Evening	6-hours run	6-hours run

3. Results and Discussion

The performance of the conventional heating system throughout the year was modeled in EnergyPlus software. The results for a design day during the cold season are presented in *Fig. 1*.

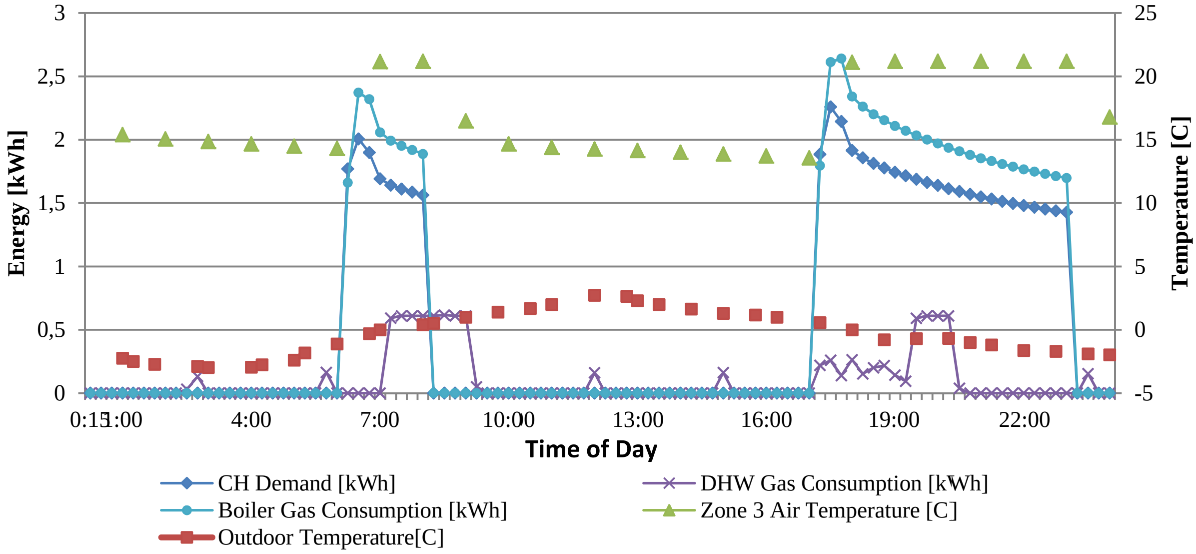

Fig. 1. Demand and temperature profiles on a design day during heating season

It can be seen from *fig. 1* that the gas consumption of the heating system decreases as the ambient temperature raises towards midday. The inner temperature increases once the heating system is fired.

The calculated monthly energy demand profiles are presented in *fig. 2.*

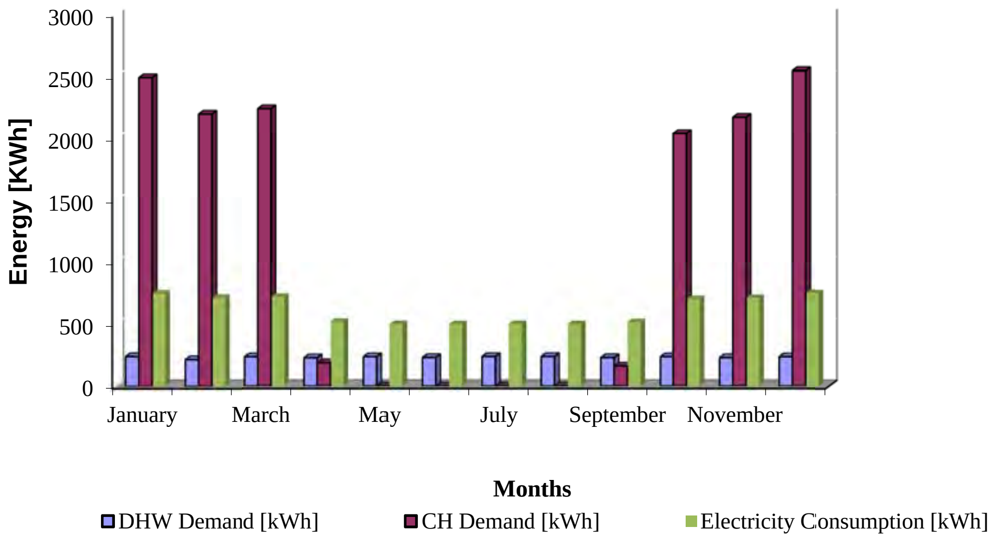

Fig. 2. Calculated monthly energy demand profiles

It can be seen from *fig. 2*, that simulations reflect that the heating and electricity demands are higher during the heating season. The electricity consumption of the heating system has been included in the monthly electricity demand.

The steady state and cycle electrical and thermal efficiencies of the Whispergen mCHP system have been calculated and are presented in *fig. 3*.

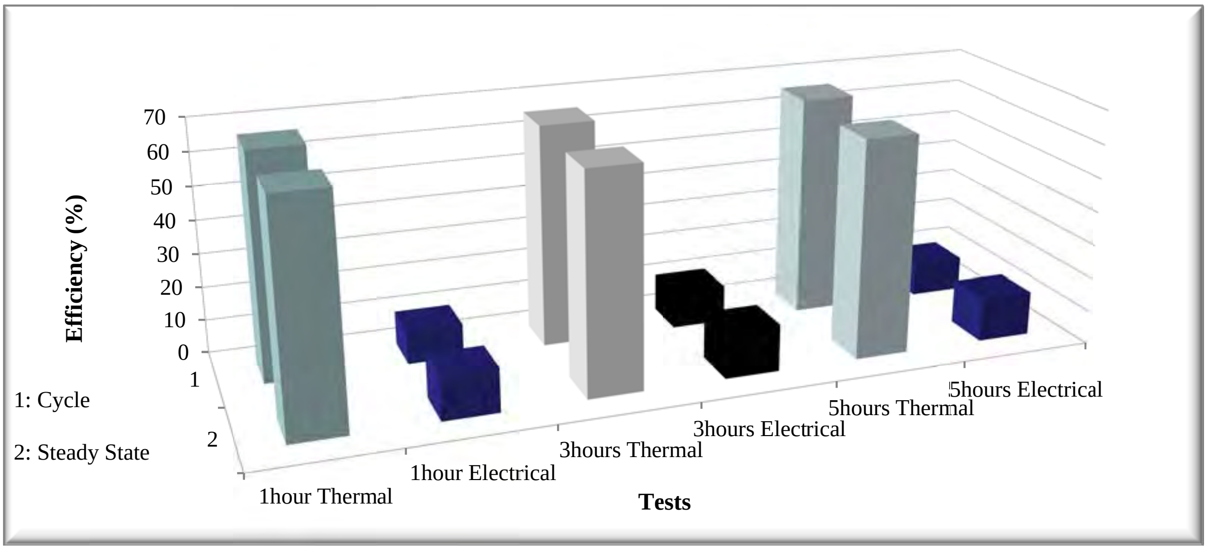

Fig. 3. Steady state and cycle efficiency measurements for different test durations.

It can be observed in *fig. 3* that the thermal efficiency is about 66% for all tests during the steady state operation and for the whole cycle monitoring. The electrical efficiency was found to be about 10% for the whole cycle measurements and 12% for the steady state measurements. These values were consistent for all tests. The thermal efficiency of the mCHP has been found to be considerably lower than that of a condensing boiler. This finding is consistent with [11]. In cycle and steady state measurements, the thermal efficiency remained at approximately the same level. This is due to the water circulator pumping water throughout the system after the combustion process has ended to allow more effective cooling of the engine (*fig. 5*). The cycle electrical efficiency is affected by the dynamic performance during start-up (*fig. 4*) and is lower than the steady state efficiency. It is believed that this low performance is caused by the lower gas pressure of the working gas inside the Stirling engine. This was a design trade-off to avoid wear of moving parts.

The start-up and rundown characteristics of the Whispergen Mk Vb mCHP are presented in *fig. 4* and *5*, respectively.

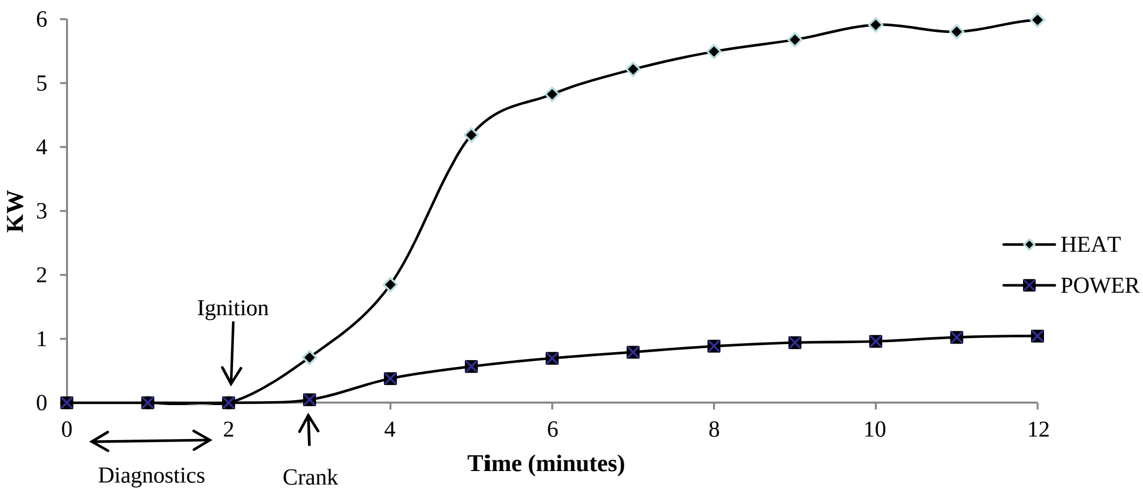

Fig.4. Breakdown of Whispergen Mk Vb start-up characteristic.

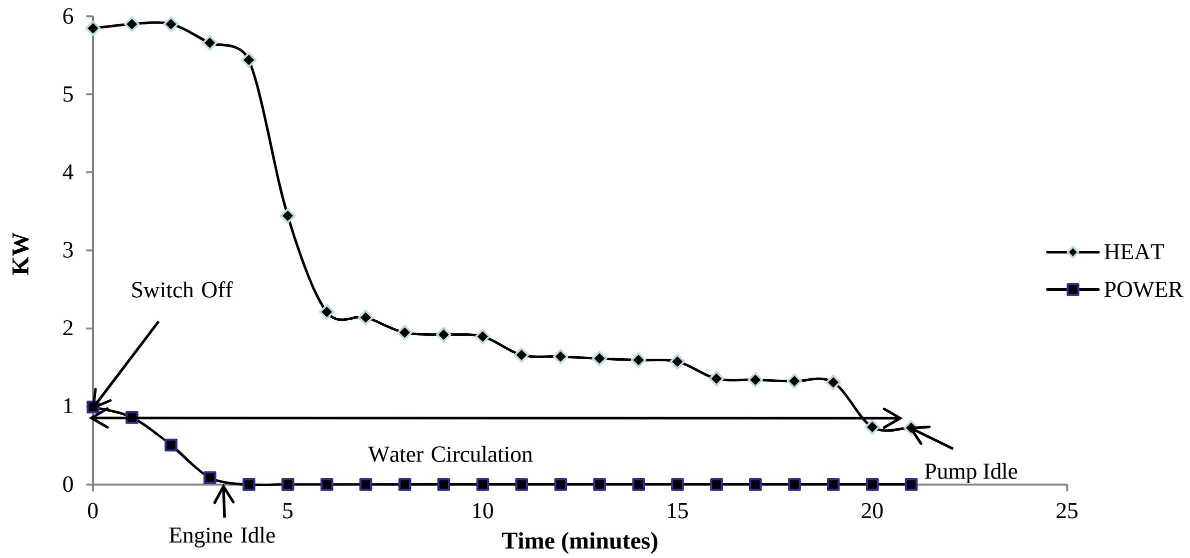

Fig. 5 Breakdown of Whispergen Mk Vb run-down characteristic.

The results presented above were used as input data for RETScreen software and a comparison between the mCHP system and a conventional energy scenario including a condensing boiler and grid electricity was carried out. The results are presented in *table 2* for two houses with different heat demands.

Table 2. Annual performance of mCHP compared to a conventional system for 2 houses.

House Type	5 kWth semi -detached	9.5 kWth detached
Annual Benefits	£-54	£87
Annual carbon savings	-500 Kg	300 Kg

Results obtained using RETScreen indicated that the particular mCHP system would be unfeasible for a relatively new semi-detached house with a low heat demand. The feasibility of the system was considerably improved for a larger house with a higher heat demand. Similar results can be found in literature [12]; however, different methods and models were used. It is believed that the particular software neglects the transient performance of both the mCHP unit and the heating boiler, as well as the dynamics of domestic energy demand and energy pricing. Furthermore, the estimated electricity demand does not include the electricity consumption of the heating boiler which may add up to the electrical about 10% of the boiler rated output [11]. Additionally, the software sizes the conventional heating boiler based on solely heat demand (5 kW_{th}). In reality, this demand would be met by a 15 kW_{th} boiler. This over sizing limits the efficiency of the boiler. The software prediction is more encouraging for the detached type house as the mCHP displaces more grid electricity by operating for longer periods to meet the higher heat demand. The economic savings are attributed to the recently introduced feed-in tariff (10 pence per every kWh of electricity) [13] and the carbon savings are associated to the carbon intensity of the displaced grid electricity.

The mCHP was tested using the programmer controller to set conditions for typical days during the annual period. The transient characteristics of its performance including the hot water consumption and reheating were included in all calculations and the yearly performance was modeled. The heat generated from the mCHP is plotted in *fig. 6*. The temperature line illustrates the increase of the heat load when the hot water consumption occurs. This additional heat load is met by the auxiliary burner. It can be seen from *fig. 6* that the total heat generation for approximately two hour period is equal to 11.5 kW_{th}.

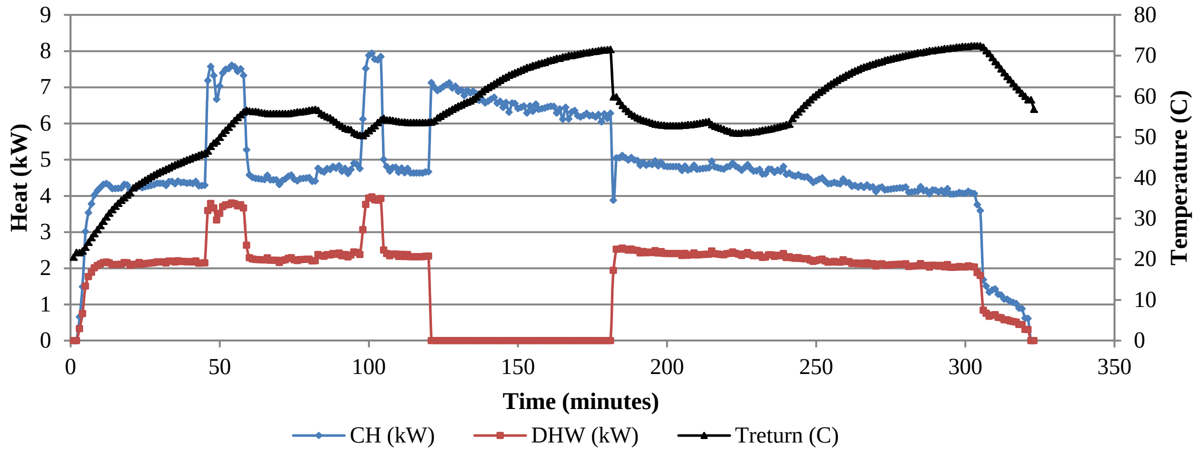

Fig. 6. Heat generation during the evening of a winter weekday

The annual performance of the mCHP compared to the dynamic simulation results of the conventional heating system is presented in *table 3*. The price of the mCHP unit and condensing boiler installed is about £3500 and £750, respectively. The simple payback period is calculated taking into account the difference in the capital cost, fuel consumption and the feed-in tariff.

Table 3. Annual performance of MCHP compared to a dynamically modeled conventional system.

Heating Plant	mCHP
Annual monetary savings	16%
Annual carbon savings	0.17%
Simple Payback Period	8 years

4. Conclusions

The feasibility study demonstrates that the mCHP compared to a condensing boiler in conventional domestic energy scenario can provide annual monetary benefits of up to 16% (taking into account new feed-in tariff, difference in the fuel consumption and assuming the same level of maintenance costs).

The performance of the mCHP is enhanced by a hot water consumption. This additional heat load caused the cooling water temperature to drop at around 50 ^{o}C where condensation is believed to take effect. This improved the mCHP thermal efficiency from 66% to 73%. This improvement however was associated with marginal carbon savings (0.17%) compared to a conventional energy scenario. This is believed to be caused by the low electrical and thermal efficiencies of the particular unit along with the electricity generated during the pre-heating period which is not consumed and therefore does not displace any grid electricity. To support this conclusion, research on the previous Whispergen Mk III mCHP unit [9] with 10% higher overall efficiency indicated higher carbon saving potential. The difference between the current results and those obtained by RETScreen is believed to be due the the deficiencies in electricity demand modeling, energy pricing variations and the thermal efficiency of the mCHP varying with the heat demand.

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Performance analysis of integrated wind, photovoltaic and biomass energy systems

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Abstract: In this paper performances of different combinations of integrated RE systems are analyzed and compared for various suitable locations in India for a load demand of 1.5 MW. These combinations of integration of REs are wind energy system (WES) and photovoltaic (PV) system; PV system and biomass energy system (BES); and BES and WES. Maximum annual electricity generated by integrated PV system and BES 8,672 MWh while maximum annual income from electricity export is $ 561,078 from integrated BES and WES system. Reduction in net annual greenhouse gas (GHG) emission is found highest of 8,850 tonnes of CO_2 in the case of integrated BES and WES with income from the GHG reduction of $ 177,013 and total annual saving/income of $ 738,091. Equity payback period of integrated BES and WES is estimated as minimum of 2.7 years when cash flow becomes positive.

Performance analyses and cash flows of the integrated RE systems are carried out using RETScreen software tool. It is concluded from the results that integration of BES with another RE is more feasible than without BES in terms of electricity generation, electricity export income, GHG emission reduction, income from carbon trading and equity payback period.

Keywords: *Emission, Renewable Energy Integration, World Renewable Energy Congress 2011*

1. Introduction

Integration, which is also referred as hybridization, of renewable energy (RE) sources involves combining two or more systems of energy resource that naturally over a period of time. This time scale is derived directly from sun (such as for thermal, photochemical, and photoelectric), indirectly from the sun (such as for wind, hydropower, photosynthesis, energy stored in biomass), from other natural movements and mechanisms of the environment (such as for geothermal and tidal energy). The depletion of fossil fuels reserves, the increasing demand for electricity and the harmful effect of CO_2 output on the climate force nations - especially developed countries and their governments - to find new ways of generating the sufficient amount of energy in demand. The integration of alternative energies to reduce emissions and to conserve available fossil sources is a well known fact.

Like other developing countries, India faces a formidable challenge in meeting its energy needs and providing adequate and affordable energy to all sections of society in a sustainable manner. The country today faces an energy demand-supply gap of 8% with peak shortages to an order of 11%-12%. The hospitality industry is one of the major energy and water intensive sectors and to deal with the situation, the utilization of RE sources has to maximize for meeting energy demands [1].

An evaluation of integrated system of PV and wind energy sources of those systems has been done to study reliability of the systems [2]. The supply pattern of different RE sources can be intermittent with different patterns of intermittency. It is often possible to achieve a better overall supply pattern by integrating two or more sources, sometimes also including a form of energy storage system. In this way the energy supply can effectively be made more secure, less intermittent, or more firm. [3]. A comparative study has been made for energy security of the two locations for the same load demand by simulating hybrid renewable energy systems (HRESs) [4].

Some of the reasons of using integrated/HRES are outlined as under:

- Reduction of greenhouse gas (GHG) emissions through increased use of RE and other clean distributed generation
- Increase in use of integrated distributed systems and customer loads to reduce peak load and thus price volatility
- Enhancement in RE system (RES) and energy efficiency
- Increase in reliability, security, and resiliency from microgrid applications in RES to improve system

In this analysis integration of wind energy system (WES), photovoltaic (PV) system and biomass energy system (BES) are carried out for the purpose of analysis to achieve the objectives.

2. Methodology and Objectives

The following objectives of the paper are achieved by using Renewable Energy Technology Screen (RETScreen) Version 4 software simulation tool. The RETScreen International Clean Energy Project Analysis Software is a unique decision support tool designed with the contribution of numerous experts from government, industry, and academia. The software can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs). The software also includes product, project, hydrology and climate databases, a detailed online user manual, and a case study. RETScreen International is getting financial support from Natural Resources Canada's (NRCan) CANMET Energy Technology Centre - Varennes. The software is developed in collaboration with a number of other government and multilateral organisations, and with technical support from a large network of experts from industry, government and academia [5].

For this purpose of simulation, weather data of various places is taken from drop down list and used for analysis purpose so that suitability of integrated RE system may be judged. The software provides simulation by Method 1 and Method 2. Second method is an extension of Method 1 providing more detail analysis. The main inputs used in the analysis are multiple technologies options from drop down list, power capacity required, initial cost, type of fuel, selection of RE system from drop down list, rate of energy export, transmission and distribution loss, rate of inflation, project life, rate of interest and debt term etc. Energy models are prepared using above mentioned input data to obtain the following outputs:

- Calculation of energy exported to grid from RE sources
- Income from energy export
- Gross and net GHG emission reduction
- GHG reduction income
- Total annual cost
- Total annual saving and income
- Financial viability including simple and equity payback
- Cumulative cash flow

3. Integration of RE systems

A large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply has been carried out by Lund (2006) using computer software namely EnergyPLAN [6]. In another paper a load balance model has been suggested to evaluate economic and environmental effects of integrating wind power into three typical generation mixtures. The results have been indicated that the system operating cost increased by 83%–280% (depending on generation mixture) at a wind penetration of 100% of peak demand and system emissions decreased by 13%–32% (depending on the generation mixture) [7]. In the present paper RE integration of WES, PV system and BES are carried out. Costs of RES per kW are taken as $ 1,900, $ 9,100 and $ 467 for WES, PV system and BES respectively. Cost of energy to be exported from the microgrid of the proposed system is taken as $ 70/MWh [5, 8]. The following combinations of integration are chosen:

- WES and PV system
- PV system and BES
- BES and WES

3.1. Integration of Wind and Photovoltaic Energy Systems

Weather data of Jaisalmer found suitable for integration of wind and PV energy systems which is used to develop energy model and cash flow curve of the integrated RES. The place is situated in the western state of Rajasthan, India at latitude of 26.9° N, longitude 70.9° E and elevation of 130 m. The daily average radiation of the place is 5.16 $kWh/m^2/d$ and average wind speed of 3.9 m/s, maximum 4.9 m/s in June and minimum 3.4 m/s in Oct. Government of India has an elaborate program to install 1000 MW PV system at a nearby place in the desert of Rajasthan Thar desert in the coming decade. The area is selected for a proposed distributed generation from integrated WES and PV system to study the feasibility of integrated system. A load demand of an area Manak Chowk of Jaisalmer is chosen, having a load of 1.47 MW, say 1.5 MW to install an integrated system of WES and PV system [9].

Before building a system with several intermittent energy sources and variable consumption, guidance on selecting the dimensions of the individual components should be obtained by simulating the system operation under the local conditions like weather, insolation, wind speed etc. In general, a key objective of such a system is to use the maximum proportion of RE as mentioned above, but other factors including the financial investment, social aspects, local infrastructure, durability etc. must also be considered.

3.1.1. Results of Performance and Emission Analysis of Integrated 750 kW Wind and 750 kW Photovoltaic Energy System at Jaisalmer

Although the behaviour of wind and PV energy systems are different, equal power capacity of 750 kW each considered shown in Figure 1. Simulation results are obtained indicating total energy export to the grid 3,285 MWh giving an income $ 229,950. The results are shown in the energy model in Table 1 achieving net GHG emission reduction 3,730 tCO_2 (tonnes of CO_2), GHG reduction income $ 74,607 giving a total annual saving and income of $ 304,557. Complete GHG emission analysis, total annual cost, and financial viability are also shown in Table 1. The detail specification, manufacture and models are suggested by the tool itself. Wind turbine 15 units of Atlantic Orienet make with Model No. AOC 15/50-23m and PV system 3000 units of Uni-Solar make with Model No. a-Si-SSR-256W are chosen from the drop down list of the software tool. Other options of wind turbines and PV systems are also available in the list which may be selected depending upon requirement of the site and load demand. Cumulative cash flow graph is illustrated in Figure 2, showing equity pay back starts after 6.9 yr when cash flow becomes positive [9, 10].

Table 1. Results of Energy Model of 1.5 MW integrated energy project of WES 750 kW and PV energy system 750 kW indicating detail of proposed case power system, GHG emission analysis and financial analysis

Proposed power case system		Financial parameters	
Technology 1	Wind turbine	**Inflation rate**	2.0 %
Power capacity	750 kW	**Project life**	20 yr
Capacity factor	30%	**Debt ratio**	70%
Manufacturer	Atlantic Orienet	**Debt interest rate**	5.00%
Model	AOC 15/50 -23m – 15 units	**Debt term**	14 yr
Electricity exported to grid	1,971 MWh	**Annual savings and income**	
Total initial costs	$ 1,384,666	**Fuel cost - base case**	$ 0
Technology 2	PV	**Electricity export income**	$ 229,950
Power capacity	750 kW	**GHG reduction income -14 yr**	$ 74,607
Manufacturer	Uni-Solar	**Total annual saving & income**	$ 304,557
Model	a-Si-SSR-		
Capacity factor	20%	**Emission analysis**	
Electricity export rate	$ 70		
Electricity exported to grid	1,314 MWh	**GHG emission propose case**	0
Country-Region	India	**GHG credits transaction fees**	2.0%
Fuel type	Coal	**Net annual GHG emission reduction**	3,730 tCO_2
GHG emission factor Excl. T&D losses	0.927 tCO_2/MWh	**Acres of forest absorbing carbon**	1,283
T&D losses	20%	**GHG reduction credit rate**	**20** $/ tCO_2
GHG emission factor Incl. T&D losses	1.159 tCO_2/MWh	**GHG reduction credit duration**	14 yr
GHG emission base case	3,806 tCO_2	**GHG reduction credit escalation duration**	2.0 %
Annual costs and debt payments		**Financial viability**	
O&M (savings) costs	$ 0	**Pre-tax IRR – equity**	16.3 %
Fuel cost - base case	$ 0	**Pre-tax IRR – assets**	2.8%
Debt payments - 10 yrs	$ 203,994	**Simple payback**	9.5 yr
Total annual costs	$ 203,994	**Equity payback**	6.9 yr

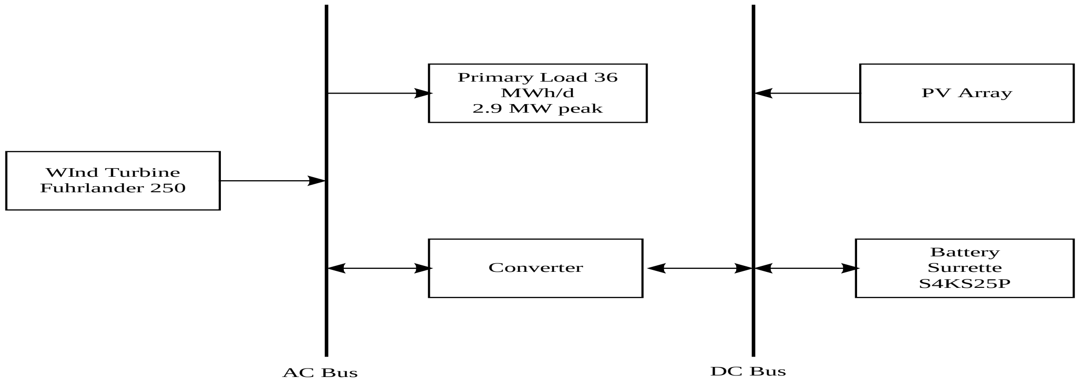

Fig. 1. Basic block diagram of integrated wind and PV energy systems

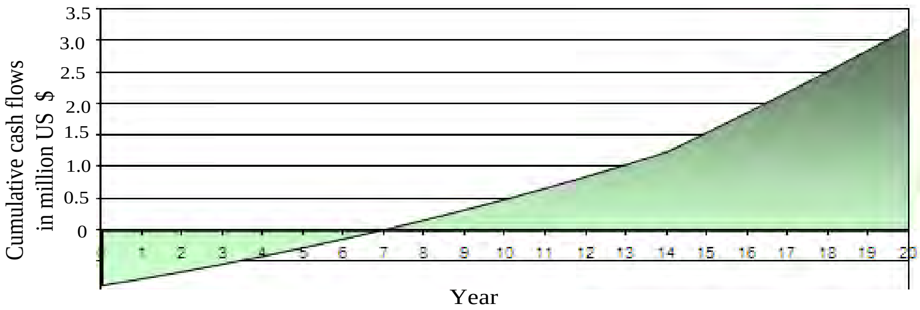

Fig. 2. Cumulative cash flows graph of integrated WES 750 kW and PV energy system 75

3.2. Integration of other RE Systems

Minambakkam, a suburb of Chennai, India is selected for a project of integrated of PV energy system and BES suitable for a comparable load demand of 1.5 MW as in the case of section 3.1. Rice is one of the main agricultural products in this area; hence availability of rice husk is sufficient to supply any biomass gasifier generating electricity. Simulation by RETScreen software is based on specific fuel consumption of rice husk 2.096 kg/kWh with heat rate of 22,200 kJ/kWh [11, 12]. Sufficient amount of solar insolation is also available at the site. The place is located at a latitude 13.0° N, longitude 80.2° E and elevation 16.0 m. The daily average solar radiation is 5.49 kWh/m^2/d with maximum 6.78 kWh/m^2/d in April and minimum 4.17 kWh/m^2/d in December and average temperature 28.8° C [13]. All these weather and agricultural data are used to develop energy model, the results of which shown in Table 2 and cash flow curve as shown in Figure 3.

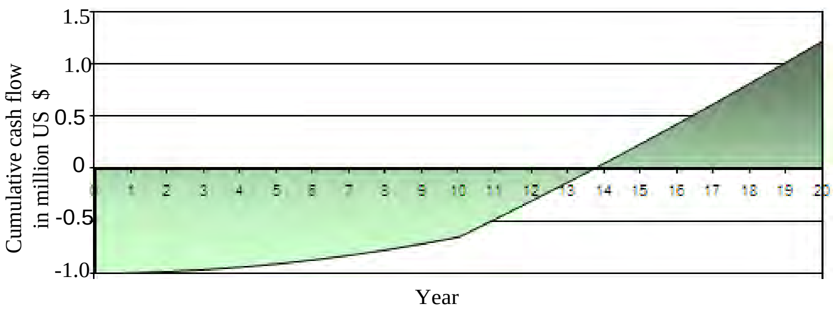

Fig. 3. Cumulative cash flows graph of integrated PV energy system 750 kW and BES 750 kW

Integration of BES and WES suitable for the same load demand of 1.5 MW is proposed to carry out at a coastal area Veraval in western Indian state of Gujrat, located at latitude 20.9° N, longitude 70.4° E at an elevation of 8 m. Mean temperature of the area is 26.6° C, average daily radiation 5.94 kWh/m^2/d and average wind speed 4.3 m/s, maximum wind speed 7.1 m/s in July and minimum 2.7 m/s in Nov. Rice is the main foodstuff of the people of Veraval; hence rice husk is available in abundance around the vicinity of the place suitable to supply rice husk based gasifier for the proposed BES. Uninterrupted flow of wind is available in the coastline area, making WES option feasible particularly during summer days, when the wind speed is high [13]. Energy model of the system prepared, the results of which are shown in Table 2 and cash flow of the project shown in Figure 4.

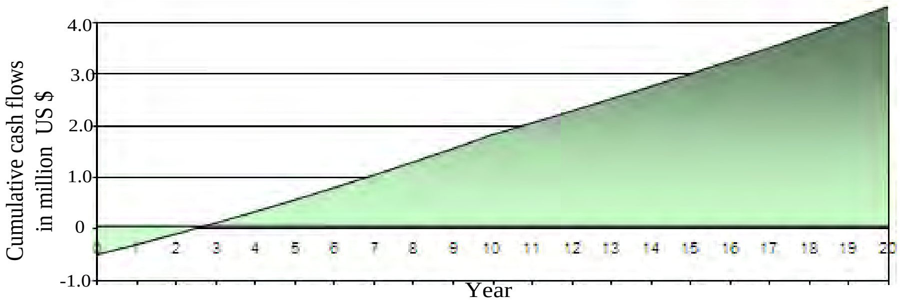

Fig. 4. Cumulative cash flows graph of integrated BES 750 kW and WES 750 kW

4. Comparative results obtained from energy models

Comparative results of analysis of integrated systems on annual basis are tabulated from the energy models data of the various integrated systems, i.e. WES 750 kW with PV energy system 750 kW, PV system 750 kW with BES 750 kW and BES 750 kW with WES 750 kW shown in Table 2.

Table 2. Comparative results of Energy Models of 1.5 MW integrated energy project of WES, PV system and BES each of 750 kW indicating detail energy generated, GHG emission analysis and financial analysis

Integration systems	WES+PV system	PV system +BES	BES+WES
Electricity generated MWh	3,285	**8,672**	8,015
Income from electricity export $	229,950	515,088	**561,078**
Total annual cost $	203,994	**677,523**	546,779
GHG emission reduction tCO_2	3,730	8,105	**8,850**
Income from GHG emission reduction $	74,607	162,092	**177,013**
Total annul saving /income $	304,557	677,180	**738,091**
Equity payback period yr	6.9	13.7	**2.7**
Feasibility/remarks	Not so feasible	Not so feasible	Most feasible

5. Conclusions and recommendations

- Maximum energy 8,672 MWh generated and exported annually from integrated PV system and BES whereas nearly half energy 3,285 MWh is generated in the case of integrated WES and PV system. Therefore, the integrated system of PV system and BES is recommended for energy generation rather than using other integrated RES of similar power rating.

- Annual energy export income $ 561,078 is highest in the case of integrated BES and WES and less than half $ 229,950 from integrated WES and PV system. The integrated system of BES and WES is economically most feasible. Hence, this system is recommended for a windy place where biomass is cheaply available.

- Total annual cost $ 677,523 is highest in integrated PV system and BES and lowest of $ 203,994 (nearly less than one third) in integrated WES and PV system. The high total annual cost is due to consumption of biomass (rice husk) used with the BES gasifier. Hence, integrated system of PV and BES not feasible to opt for generation purpose if low annual cost is the preference. Integration of WES and PV system is suggested where lesser annual cost is desirable for a windy place.

- Annual reduction in GHG emission is least of 3,730 tCO_2 in case of integrated WES and PV energy system whereas highest of 8,850 tCO_2 (nearly 2.5 times) in case of integrated BES and WES. Annual GHG emission of 8,105 tCO_2 is found in case of integrated PV system and BES. In the present scenario of the world growing air pollution, GHG emission reduction is the prime factor while considering electricity generation options. Therefore, integrated system containing BES should be given preference over other integration of RE systems without BES.

- Annual income from GHG emission reduction $ 177,013 is highest in integrated BES and WES and lowest of $ 74,607 (nearly less than half) in integrated WES and PV system. Whereas the annual income is $ 162,092 in integrated PV system and BES. The analysis results show that income from integrated systems containing BES with other RES is more than any other RE integration running without BES because of higher reduction in GHG emission. Therefore, integrated system BES with WES should to be preferred over other integrated systems to get more annual income from carbon trading.

- Total annual saving /income $ 738,091 is also maximum from integrated BES and WES and nearly less than half $ 304,557 from integrated WES and PV system. Total annual saving/income is estimated as $ 677,180 in case of integrated PV system and BES. It is found that results are in favour of integration of BES with other RES. Hence, integration of BES with WES and PV system with BES is suggested to use in any part of the world wherever biomass available.

- Equity payback period is shortest of 2.7 years in case integrated BES and WES and longest of 13.7 years (nearly more than 5 times) in case of integrated PV system and BES. A major portion of cash flow curve of integrated of PV system and BES lies in the negative side and positive cash flow starts after 13.7 years indicating non-feasibility of the system; hence this system of RE integration is not suggested to opt. Integrated BES and WES is estimated to be the best option since a major portion of cash flow curve lies in positive side and system starts giving return just after 2.7 years.

Therefore to get quickest positive cash flow, integrated system of BES and WES is recommended.

- Comparing all positive and negative aspects of combinations of integration, best system for integration is BES with WES. Moreover, this integration of RE has minimum environmental impact while generating electricity. That also provides huge income from carbon trading.

- The not-so-feasible combination of integration is PV system with BES due to high total initial annual cost. But it may be also suggested for use because of more generation, high GHG emission reduction and total annual saving. WES and PV system may be opted where less total annual cost required.

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Feasibility Study of Solar-Wind Based Standalone Hybrid System for Application in Ethiopia

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Abstract: Shortage of electric power is a serious problem in Ethiopia. As recently as the year 2009 electric power supply in the country including the capital Addis Ababa, was at best every other day for several months. Until recently, the sole power producer in the country, Ethiopian Electric Power Corporation (EEPCo) produces a total of 800 to 900 MW of power for a country with a population of about 80 million. This clearly shows as to what the shortage would look like.

In this regard, this study investigates the possibility of providing electricity from solar/wind based hybrid standalone system for remotely located people detached off the main grid line. Within the hybrid system setup PV panels, wind turbines, a bank of batteries and for a backup diesel generator is included.
The wind potential of the area has been assessed in a previously published article. The solar potential has also been investigated in another article awaiting publication. It is based on the findings of the solar and the wind energy potential that this study is carried out.

A model community of 200 families, comprising of approximately 1000 to 1200 people in total is considered for the study. A community school together with a health post is also included. The electric load comprises of lighting, water pumps and other small appliances.

For the techno-economic analysis in the feasibility study of the hybrid system the National Renewable Energy Laboratory's (NREL) HOMER software is used. Given all the necessary inputs to the software, the results showed a list of feasible electric supply systems, sorted according to their total net present cost (NPC). Cost of energy (COE in $/kW), penetration level into the renewable resources (renewable fraction), the number of liters of diesel oil used by the generator and also the generator working hours is also given out in the results table. The greenhouse gas emission level of the system is also incorporated within the results.

Furthermore, a sensitivity analysis is carried out for the major sensitive components of the hybrid system. The major sensitive components of the system recognized are the changing price of PV panels and the ever hiking price of diesel oil. From the results it is concluded that the solar energy potential is the most promising resource that can be utilized.

Keywords: *Wind Energy potential; Solar Radiation potential; Primary Load; Deferrable Load; Net Present Cost (NPC)*

1. Introduction

Power generation in Ethiopia started at the end of the 19th century, during the then king Minilik time. The first generator was used in the palace around 1906 and in 1912 the first hydropower plant at a place called Akaki, very close to the capital, Addis Ababa. Ever since, the country could produce only 814 MW (until recently) in its over 100 years long history.
Currently shortage of electric power is a serious problem in Ethiopia. As recently as the year 2009 electric power supply within Addis Ababa, the capital of the country, was at best every other day for several months. Even in the same year we are electricity supply with in the capital is intermittent.

As mentioned in previous articles [1] [2][3], the Ethiopian Electric Power Corporation (EEPCo), the only proprietor of the electric power production corporation with total management control (issue license, set tariff, supervise the generation, transmission, and distribution, sales, import export, etc.), currently produces between just over one MW of power. It is only this amount which is available for a country with a population well over 75 million. Over 95% of the resource for electricity generated is Hydropower. Although the country is endowed with enormous resource of solar energy there is no solar or wind energy contribution in the EEPCo's system.

The total countrywide coverage of the generated electricity is estimated to be some 15%. With only so small coverage, electricity supply in the deeper rural regions is unthinkable. This clearly indicates that something has to be done and the responsibility should all lie on the shoulders of the engineers within the country. The depletion of fossil fuel and the climbing up of the oil price with its involved politics, the pollution associated with the use of fossil fuel is are all left for the reader of this piece of work to consider as additional motivation.

"That the human race must finally utilize direct sun power or revert to barbarism because eventually all coal and oil will be used up. I would recommend all far-sighted engineers and inventors to work in this direction to their own profit, and the eternal welfare of the human race" Frank Shuman -1914

2. Methodology

The location under investigation is Debrezeit, 08″44′N, 39″ 02′E 1850 m. Wind and solar energy potential of the location is studied and have been given in previously published articles and a book [1][2][3]. As it is clearly shown in the references the wind energy potential is not so promising. However, the solar energy potential is absolutely usable. Figure 1 shows the monthly average wind speed at a height of 10 m. At a certain height, Z, the wind speed increases according to equation (1). It has been shown in [1] that average annual wind speeds of 3 to 4 m/s may be adequate for non-grid-connected electrical and mechanical applications such as battery charging and water pumping.

$$v(z)\cdot \ln\left(\frac{z_r}{z_0}\right) = v(z_r)\cdot \ln\left(\frac{z}{z_0}\right) \qquad (1)$$

Where: Z_r is the reference height (10 m); z_0, is the roughness length.

The solar energy potential of the location is given in figure 2. As can be seen from the figure the solar energy potential is more than 6 kWh /m^2 for almost the whole time of the year. It is only in the rainy season, July and August the potential falls to between 5 and 6 kWh/m^2. This is indeed excellent situation for working on this resource.

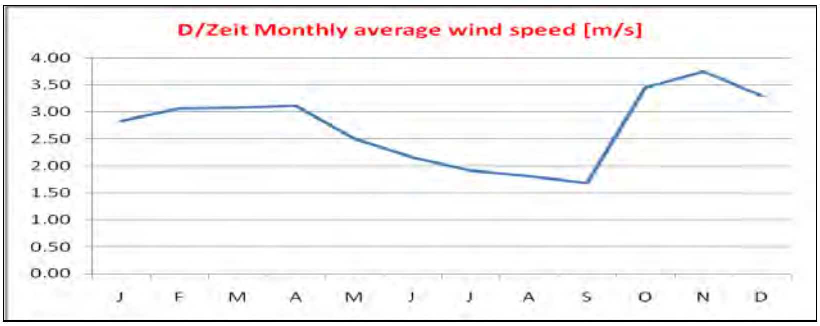


Figure 1: Monthly average wind speed

Having determined the solar and the wind energy potential energy of the location under investigation, a model community of two hundred families is considered for which the necessary basic load of electric lighting and water pumping system is suggested.

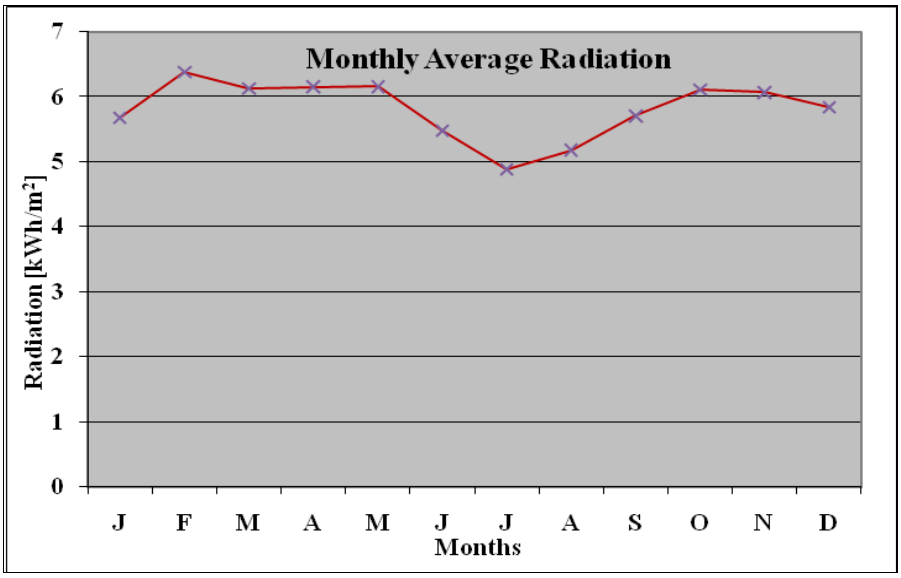


Figure 2 Monthly average daily solar radiations

HOMER software is used for the analysis. HOMER is a micropower design tool developed in 1992 to simulate and optimize stand-alone and grid-connected power systems with any combination of wind turbines, PV arrays, run-of-river hydro power, biomass power, internal combustion engine generators, micro-turbines, fuel cells, batteries, and hydrogen storage, serving both electric and thermal loads (by individual or district-heating systems) [4]. HOMER can perform a 'what-if' analysis to investigate uncertainties or changes in the input variables such as price variation of: fuel, PV panels, turbines or others in the one hand and wind speed, solar radiation, etc. on the other. The simulation results are economically and technically optimal and feasible solutions of hybrid setups listed according to their net present cost (NPC).

The net present cost (or life-cycle cost) of a component is the present value of all the costs of installing and operating that component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. HOMER calculates the net present cost of each component of the system, and of the system as a whole.[5]

3. Electric Load

As mentioned earlier, the assumed 200 family community is nothing but a model community. It is to be noted that this number can shrink or expand if need be. Five to six family members are considered in each family. Two load types are suggested: primary load, load that must be met immediately, and deferrable load, load that must be met within a certain time (exact timing is not important).

A community school and a health post are also included within the community. Electric load suggested are lighting, water pumping, radio receiver, and some clinical equipment. It is to be noted that the load suggested here is estimated by considering the poorest people in the remotest corners of the country with no access to any of the modern energy supply types, not even a kerosene lamp or a candle light. A typical daily load pattern is presented in table 1.

The primary load consists of 2 to 3 light bulbs and a radio receiver per household and also some more light bulbs for the for the community school and the health post. Limited clinical equipment such as vaccine refrigerators, communication VHF radio, microscope, and AM/FM stereo are also considered.

Table 1 Monthly average daily electrical load [kWh]

Months	Jan	Feb-May	June	July	Aug	Sep	Oct-Dec
Deferrable Load	6	6	5	4	4	5	6
primary load	139	141	141	139	139	141	141
Total Load	145	147	146	143	143	146	147

The deferrable load is mainly water pumping. Four to five family members per house hold and about 100 liters of water per day is suggested. Water Pumps of a 150 W power rating and pumping capacity of 10 liters per minute is chosen. Six pumps at six convenient locations are to be installed. Additional pump for the School and the clinic is also to be installed. A four day storage system is considered. The resulting total load is as given in Table 1.

4. The Hybrid Setup and the Findings

The hybrid system studied is one combining solar and wind energy conversion system, with diesel generator(s) and a bank of batteries included for backup purposes. Power conditioning units, such as converters, are also a part of the system. The operational concept of the hybrid system is that renewable resources are the first choice for supplying load and any excess energy produced is stored in the battery. The diesel generator is a secondary source of energy. Electronic controller circuitry is used to manage energy supply and load demand. A schematic diagram of the standalone hybrid power supply system sought is shown in figure 3.

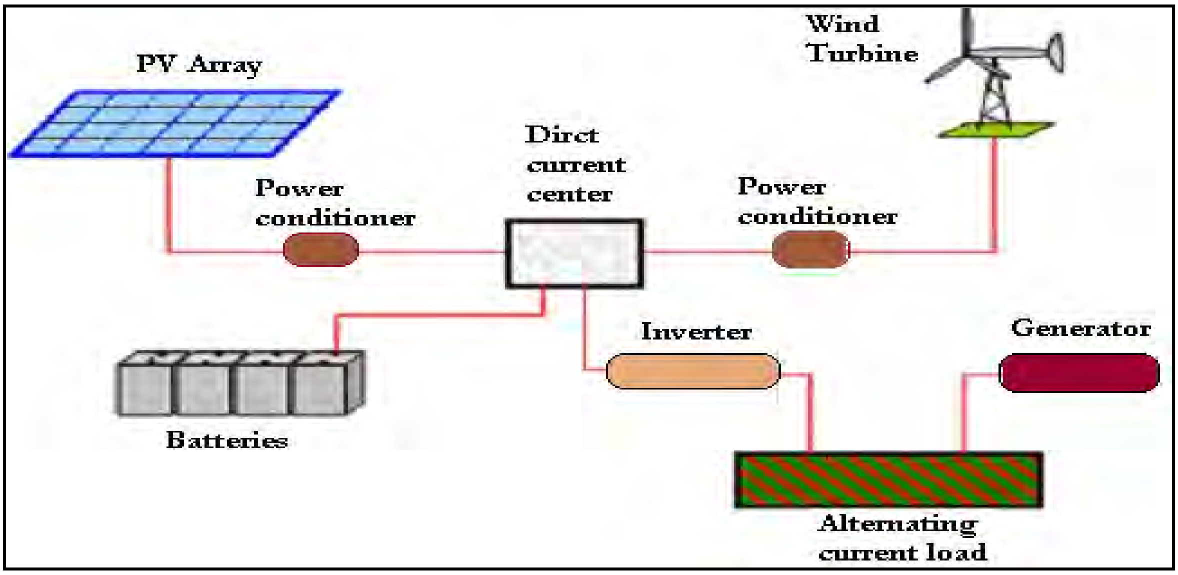


Figure 3: Schematic diagram for the standalone hybrid power supply system

HOMER requires input information in order to analyze the system and to give the feasible solutions. The main input to the software is the load. After carefully determining the hourly community electric load for both the primary and the deferrable load types the monthly average of the daily load is supplied to the software. The load profiles are shown in figure 4 and figure 5.

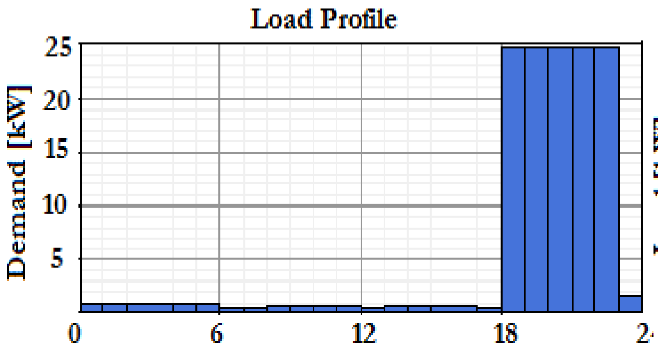


Figure 4 Primary load profile

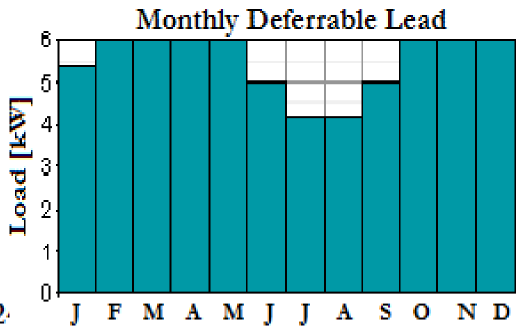


Figure 5 Deferrable load profile

Additional data supplied to the software is summarized in table 2.

Table 2 Input data to HOMER

	PV	Wind Turbine G20	Diesel Generator	Battery (Surrette 6CS25P)	Convertor
Size (kW)	1	20	44	1156 Ah	1
Capital ($)	1200-6000	45,000	11,000	833	700
Replacement cost ($)	1200-6000	30,000	7,000	555	700
O & M cost ($/yr)	0	900	0.4 ($/hr)	15	0
Sizes considered (kW)	0, 5, 10, 15, 20, 30, 50, 70, 100		0, 44, 88		0, 20, 40, 60, 80, 100
Quantities considered		0, 1, 2, 3		0, 40, 60, 80, 100, 200	
Life time	25 yrs	25 yrs	40,000 hrs	9,645 kWh	15 yrs

5. Results

Having fed the necessary input data given in the earlier section to the software the software is run. The resulting list of optimal combinations of realizable setups obtained is given in both overall and categorized forms. Table3 shows extracted part of the long list from the complete overall table. The extraction is based on the contribution made by renewable resources in the realizable set-ups.

As can be seen in the table the first row contains a system with no contribution (0 %) from the renewable resources. The next row contains a PV-Gen-battery-Converter set-up. For just a 16.7 % increase in total NPC over the first set-up ($201,609 to $235,177), the percentage contribution made by renewables increased from 0 to 58 %. This can be an attractive solution for implementation. Of course, there is no wind turbine involved in the system; the wind energy potential at this location is quite low, as can be seen from figure 4-19 and also from previous investigation [1].

Table 3 Extracts from the overall optimization results list

PV(kW)	Wind Turbine G20	Diesel Generator (kW)	Battery	Converter (kW)	Dispatch strategy	Initial capital	Total NPC	COE ($/kWh)	Renewable fraction	Diesel (L)	Generator (hrs)
		44	40	20	CC	$ 58,320	$ 201,609	0.322	0	18623	1785
20		44	40	20	LF	$ 130,320	$ 235,177	0.376	0.58	12078	1909
15	1	44	40	20	LF	$ 157,320	$ 276,081	0.441	0.53	12550	1947
20		44	80	20	LF	$ 163,640	$ 276,560	0.442	0.62	10617	1729
30		44	40	20	CC	$ 166,320	$ 278,443	0.445	0.66	13037	2127
30		44	60	40	LF	$ 196,980	$ 279,851	0.448	0.77	7048	1062
20	1	44	40	20	LF	$ 175,320	$ 285,862	0.457	0.62	11339	1811
30		44	80	40	LF	$ 213,640	$ 290,597	0.465	0.83	4883	716
20	1	44	60	20	LF	$ 191,980	$ 305,266	0.488	0.64	10417	1701
30		44	100	40	LF	$ 230,300	$310,604	0.497	0.85	4053	590

Figure 6 shows the monthly average electrical production and table 4 the overall system report.

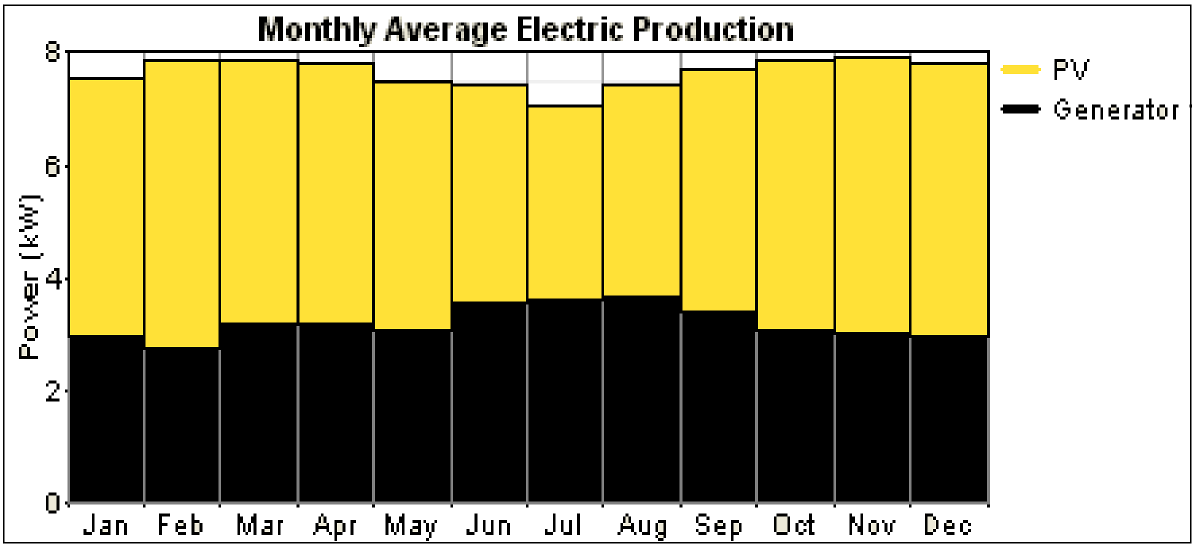


Figure 6: Electricity production for a 58 % penetration of the renewable

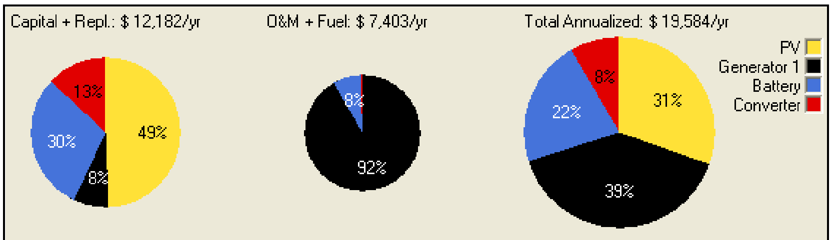
The maximum contribution by renewables, 85 %, is achieved by the set-up given in the last row of the table. For this set-up the NPC is $310,604, which is a 32 % increase in the total NPC over the setup with a renewable contribution of 58 %. This setup can also be seen as an alternative for implementation despite the higher cost. It is understood that a system is considered as renewable system if the renewable contribution is about 27% or above. Hence, if the renewable future is to be given its merits then this system will be the option. It should be noted that this set-up once again does not include a wind turbine as the wind potential of the location is minimal.

Table 4 System report for the 58 % renewable penetration

System architecture		**Sensitivity case**	
PV Array	20 kW	Solar Data	5. 81 kWh/m^2/d
Wind turbine		Wind Data	2.51 m/s
Gen.	44 kW	Diesel Price	0.5 $/L
Battery	40 Surrette 6CS25P	PV Capital Cost Multiplier	0.6
Inverter	20 kW	PV Replacement Cost Multiplier	0.6
Rectifier	20 kW		

Annual electric production (kWh/yr)			**Annual electric energy consumption (kWh/yr)**			**Emissions (kg/yr)**	
PV array	38,823	58%	AC primary load	50,772	97%	CO2	31,806
Wind turbine			Defferable load	1,306	3%	CO	78.5
Generator	28,152	42%	Total	52,077	100%	Unburned HC	8.7
Excess electricity	5,591					Particulate matter	5.92
			Cost summary				
Unmet load	0		Total NPC	$ 235,177		SO2	63.9
Capacity shortage	0		Cost of energy	0. 376 $/kWh		NOx	701

The cost breakdown for the set-up of 58% penetration of the renewable supported by a pie-chart, is also given in figure 7.



Component	Initial Capital ($)	Annualized Capital ($/yr)	Annualized Replacement ($/yr)	Annual O&M ($/yr)	Annual Fuel ($/yr)	Total Annualized ($/yr)
PV Array	72,000	5,996	0	0	0	5,996
Generator 1	11,000	916	57	764	6,039	7,776
Battery	33,320	2,775	907	600	0	4,282
Converter	14,000	1,166	365	0	0	1,531
Totals	130,320	10,852	1,329	1,364	6,039	19,584

Figure 7 Cost summary for the 58 % renewable resource contribution

The sensitivity analysis given in figure 8 shows the PV capital cost multiplier against diesel price. The net present cost of the most cost effective set-ups for a particular set of diesel and PV price is shown.

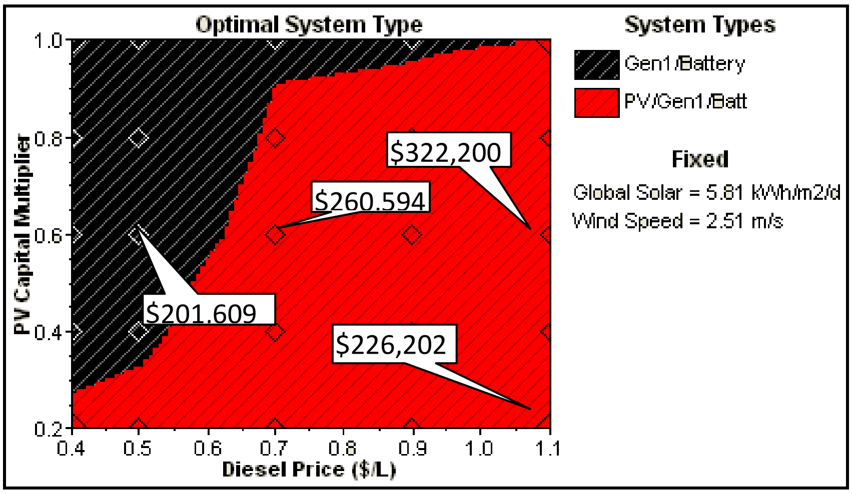


Figure 8 Sensitivity of PV cost to diesel price

6. Discussion and/or Conclusion

The feasibility study for the hybrid system is based on the findings of the wind and solar energy potentials at the particular locations. From the results, the wind energy potential of this site, Debrezeit, is not attractive enough for independent wind farm applications. However, it can be concluded that the potential in some cases could be a viable option if integrated into other energy conversion systems such as PV, diesel generator and battery. The results of this study can be considered as applicable to a significant size of the regions in the country having similar climatic conditions.

Regarding the solar energy it is definitively conclusive that there is abundant resource. The feasibility study, which is based on the findings of the two potential showed a list of possible feasible set-ups according to their Net Present Cost (NPC). The level of the renewable resource penetration can be said is closely tied with the net present cost. The choice as to which feasible system to pick from the list is linked to the choice of whether to consider the renewable resource or the net present cost. This decision is left to the policy makers of the country. However, as in the quotation given in the Introduction part Engineers shoed persistently press the policy makers to consider the utilization of the renewable resource.

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Analysis of the training metrics of ANNs and linear MCP models used for wind power density estimation at a candidate site

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Abstract: In order to estimate the amount of electricity that can be produced by a potential wind farm it is important to know how the wind resource performs at the site where it is to be installed. Of fundamental importance in an analysis of the wind resource is the wind speed parameter. Understanding how this parameter behaves over periods of time that cover ten or more years (long-term) is vital for an accurate estimation that will span the working life of the wind installation. However, in most cases there is insufficient data available about the candidate site to enable a long-term study.

In this work, the long-term wind power density at a candidate site is estimated through the use of a Measure-Correlate-Predict (MCP) algorithm and an Artificial Neural Network model (ANN). To evaluate the accuracy of the estimations different metrics are used, with a comparison of the results obtained for each of them .

The mean hourly wind speeds and directions obtained from twenty-two weather stations located on different islands in the Canary Archipelago (Spain) are used for this study.

Among the conclusions that are reached is that the use of one or another metric (or combination of metrics) in the wind power density estimation process can lead to differing interpretations and/or conclusions. For this reason, it is important that the most appropriate metric (or set of metrics) is chosen at each moment for the study that is being carried out.

Keywords: *Wind Power Density, Short-Term estimation, Long-Term estimation, Artificial Neural Networks, Measure Correlate Predict*

1. Introduction

The wind speed at any given site varies from one year to another [1]. For this reason, the long-term performance of the wind resource (10 years or more) needs to be known as accurately as possible to enable precise estimation of the power output of a wind farm over its working life [2-4]. In most cases there is insufficient data available about the candidate site to carry out long-term analyses. As a general rule, the information available about the wind resource at a candidate site only covers short periods of time (not more than one year).

In order to estimate the long-term wind speed at a candidate site, a number of authors have used long-term wind data obtained from reference stations in combination with estimation models. The traditional Measure Correlate Predict (MCP) algorithms [5-7] and methods which use Machine Learning [8-12] are the most commonly used techniques to generate the models in the estimation processes. The former generally use a single reference station to generate the model. With some exceptions, most of the MCP methods use linear regression algorithms to characterise the relationship between the wind speeds at the candidate and reference sites. Two different methods will be used in this paper. One employs the theory of Artificial Neural Networks (ANNs), and the other a traditional MCP linear regression algorithm.

The ANNs used in this paper were comprised of three layer networks with feedforward connections. More specifically, multilayer perceptron topologies (MLPs) were used [13]. A single hidden layer with 15 neurons was employed so as not to increase the training time. This architecture has demonstrated its ability to satisfactorily approximate any continuous transformation [13].

The models used to carry out the aforementioned estimations are trained, validated and tested using the available short-term (one year) wind data from reference and candidate weather stations. Using the model thereby obtained and the observed long-term reference station wind data, the candidate station long-term wind data can be estimated. In order to evaluate the performance of the models generated during the test stage of the study, different authors use a wide variety of metrics. Some of these metrics use the ratios between the mean observed and estimated values for different parameters of the wind resource [6,10], Eq. (1), while others [9,11,12] use point-to-point metrics such as, for example, the coefficient of correlation (CC) between the estimated and observed wind speeds, Eq. (2), and the Mean Absolute Percentage Error (MAPE), Eq. (3).

$$Ratio = \frac{\frac{1}{n}\sum_{i=1}^{n} E_i}{\frac{1}{n}\sum_{i=1}^{n} O_i} \tag{1}$$

$$CC = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(E_i - \overline{E}\right)}{\sqrt{\left[\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2\right] \times \left[\sum_{i=1}^{n}\left(E_i - \overline{E}\right)^2\right]}} \tag{2}$$

$$MAPE = \frac{100}{n}\sum_{i=1}^{n}\frac{\left|O_i - E_i\right|}{O_i} \tag{3}$$

where E_i are the estimated data; O_i , are the observed or measured data and *n* is the number of data.

2. Meteorological data used

The meteorological data used in this paper correspond to the mean hourly wind speed and directions of twenty-two weather stations located in six of the seven islands that make up the Canary Archipelago (Spain).
The data series used were provided by the State Meteorological Agency (Spanish initials: AEMET) of the Ministry of the Environment and Rural and Marine Environs of the Spanish Government and by the Canary Islands Technological Institute (Spanish initials: ITC).
The available wind data are as follows:

- Six (6) weather stations with 10 years of available wind data (1999-2008)
- Five (5) weather stations with data available for the year 2002.
- Eleven (11) weather stations with data available for the year 2006.

3. Methodology

The methodology employed in the analysis undertaken in this paper consisted of: the generation of models for short-term (one year) estimation and the generation of models for long-term (ten years or more) estimation. The first type of model generation used data from all twenty-two weather stations, while the second (long-term) type used only those stations for which meteorological data was available for a ten year period (six weather stations).

As many models (cases) were generated for the short-term study as possible combinations, taking as the starting point one station as reference station and another as candidate station. In this way, 55 combinations were generated for the year 2002 and 136 for 2006, making a total of 191 different cases. On the same basis, and using the six weather stations for which ten years worth of data were available, a total number of 15 cases were generated for the long-term study.

Following is an explanation of the different baseline scenarios used in the study.

Scenario A): Estimation of the short-term wind data using ANNs.

The models are generated from the known wind data for the reference and candidate stations (one year). The data available for the reference and candidate stations is randomly divided for use in the training, validation and test stages in respective proportions of 60%, 20% and 20%.

Different networks or estimation models are generated using the data from the training and validation stages. Using these models and the test data for the reference station (which is not used in the generation of the model), data estimation is performed for the candidate station. The estimated data is then compared with the observed data to generate the different metrics used in the analysis.

The wind speed and direction of the reference station (input weather station) are used as input parameters of the neural network. The candidate station (target weather station) wind speed is used as the output parameter (Fig. 1).

Scenario B): Short-term estimation using an MCP method

A simple linear regression between the wind speed of the reference and candidate stations is used for the MCP method. Wind direction is considered in the generation of the models, with the parameters of the model calculated for twelve direction bins of 30º. A simple validation is carried out to evaluate the quality of the models. That is, 20% of the data is reserved as a test subset, which is not used in the construction of the model. The remaining 80% is used for training. The data is randomly allocated to these two groups.

Scenario C): Long-term estimation using ANNs

Only the six weather stations for which data is available for a ten year period are used in the generation of the different networks or models in the long-term estimation study. One of the available years (in this case 2008) is used for generation of the network. All the data for the year is randomly allocated to two sub-groups (80% to training and 20% to validation). As in the case of Scenario A), the different models or networks are generated using this information. The candidate station long-term data is estimated using these models and the data corresponding to the other years of the reference station. By comparing the estimated data and the observed long-term data at the candidate station, the different metrics to be used in the analysis of the results are calculated.

Scenario D): Long-term estimation using an MCP method

The same stations are used as in Scenario C), as well as the same reference year. The models are generated in the same way as in Scenario B), except that in this case 100% of the year's data is used in the construction of the models. Once the parameters of the model have been calculated, the long-term candidate station data is estimated using the data from the remaining years of the reference station.

Matlab software (the MathWorks, Inc) was used to implement the different scenarios.

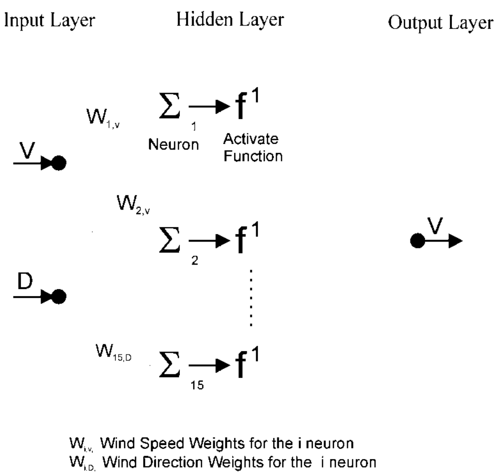

Fig. 1. ANN Schematic diagram with wind speed (V) and wind direction (D) of a reference weather station as input signals, and wind speed (V) of a candidate (target) station as output signal.

4. Analysis of Results.

Figure 2 shows the results obtained for the mean wind speed ratio in the case of Scenarios A) and B). This comparison is performed by representing on the x-axis the existing coefficients of correlation R, Eq. (4), between the wind speeds measured at the reference and candidate stations.

$$R = \frac{\sum_{i=1}^{n}\left(Vr_i - \overline{Vr}\right)\left(Vc_i - \overline{Vc}\right)}{\sqrt{\left[\sum_{i=1}^{n}\left(Vr_i - \overline{Vr}\right)^2\right] \times \left[\sum_{i=1}^{n}\left(Vc_i - \overline{Vc}\right)^2\right]}} \quad (4)$$

where Vr_i and Vc_i are the measured wind speeds at the reference and candidate weather stations, respectively. $\overline{Vr}$ and $\overline{Vc}$ are the mean wind speeds at the reference and candidate weather stations.

Based on Figure 2, and for the cases studied, the following conclusions were reached: a) the ratio between the estimated and observed mean wind speed is independent of the existing coefficient of correlation, R, between the mean wind speeds at the reference and candidate stations. This becomes more noticeable for coefficients of correlation greater than 0.4. b) for cases where the coefficient of correlation is less than 0.4, the dispersion in the results obtained for the different cases analysed is relatively high (in the range between 0.82 and 0.99). For coefficients of correlation higher than 0.4, the results are concentrated principally between the values 0.95 and 1.01.

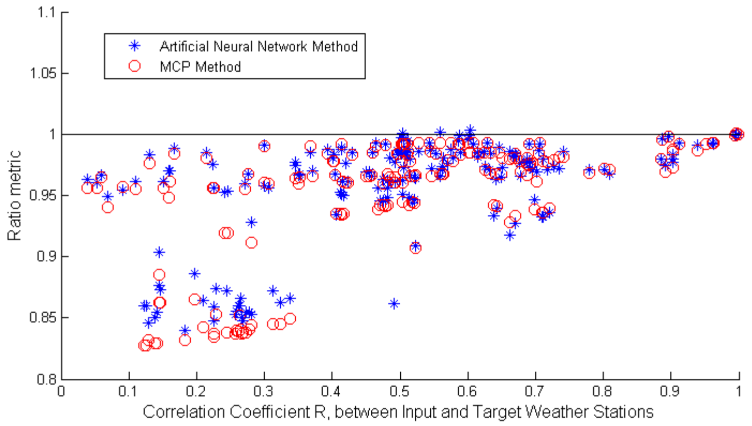

Fig. 2. Variability of the ratio of the mean wind speed with the correlation coefficient between reference (input) and candidate (target) weather station wind speed. Scenarios A) and B).

In the same analysis, but using the Mean Absolute Relative Error (MARE) point-to-point calculation metric for the wind speed, S. Velázquez et al. [11] found that this was dependent on the coefficient of correlation, R, between the wind speeds at the reference and candidate stations.

Figure 3 shows the results for the wind power density ratio, for the different cases studied in Scenarios A) and B). Unlike the previous results, obtained for the mean wind speed ratio, the mean wind power density ratio does depend on R, Eq. (4).

The wind power density P_i, or power per unit of area perpendicular to the direction from which the wind is blowing, is given by Eq. (5). Where ρ_i is expressed in kg m^{-3} and V_i is expressed in m s^{-1}, P_i is obtained in W m^{-2}. P_i, which depends on the air density ρ_i and on the wind speed v_i, is the basic unit for measuring the power contained in the wind.

$$P_i = \frac{1}{2}\rho_i V_i^3 \qquad (5)$$

If the results obtained in Fig. 2 and Fig. 3 are compared it can be observed in many cases that, though a good result is obtained for the mean wind speed ratio (values close to 1), the same cannot be said for the mean wind power density ratio. This can be seen, for example, in the results in the range of coefficients of correlation between 0.4 and 0.8. In the case of the mean wind speed ratio, these values are generally between 0.95 and 1.01, while for the mean wind power density ratio the results are between 0.5 and 0.8. It can be deduced from this analysis that a good result in the mean wind speed ratio is not always equivalent to a good result in the estimation of the wind power density.

The coefficient of correlation, CC, between the estimated and observed wind speeds at the candidate site, Eq. (2), depends on the existing coefficient of correlation, R, between the wind speeds at the reference and candidate stations, Eq. (4) [11]. So, the higher CC is, the closer to 1 will be the mean wind power density ratio.

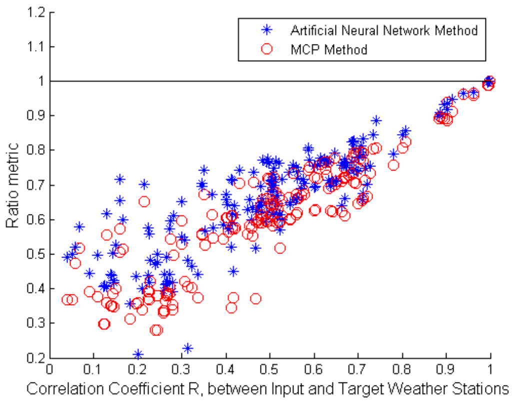

Fig. 3. Variability of the ratio of the mean wind power density with the correlation coefficient, R, between reference (input) and candidate (target) weather station wind speed. Scenarios A) and B).

Figure 4 show the results obtained in the 15 cases analysed in Scenario C) for the mean wind speed ratio metric and the mean wind power density ratio metric. Also shown, for each case, is the coefficient of correlation, R.

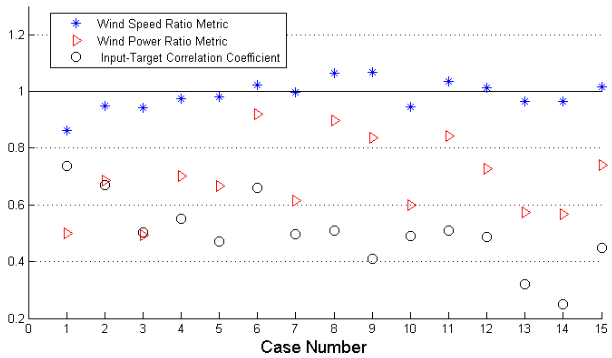

Fig. 4. Results for the ratio of the mean wind speed and ratio of the mean wind power density (long-term). Scenario C).

The basic conclusions obtained from the results for Scenario C) are the same as for Scenarios A) and B). The values, for example, in cases 7, 12 and 15, of 0.9959, 1.0132, and 1.0165, respectively, for the mean wind speed ratio are close to the target value of 1. However, the results in the same cases for the mean wind power density ratio are, respectively, 0.6141, 0.7272 and 0.7392, some way off the target value of 1.

If a point-to-point calculation metric like the Mean Absolute Percentage Error (MAPE) is used for the same Scenarios C) and D), then the results shown in Figures 5 and 6 are obtained.

If Figures 4 and 5 are compared, cases such as case 1 are observed which, while displaying the worst result for the mean wind speed ratio, has the third best result for the MAPE-based analysis. Meanwhile, case 7 gives a mean wind speed ratio of 0.9959 (the best of the results for this metric), which is practically equal to the target value, but has one of the worst results for the MAPE metric of wind speed, with values of 55.90% and 56.41% with respect to the

observed value depending on whether the estimation is conducted using ANNs or MCP methods, respectively. Identical conclusions are obtained if the ratio of the mean wind power density, Fig. 4, is compared with the MAPE metric of wind power density, Fig. 6.

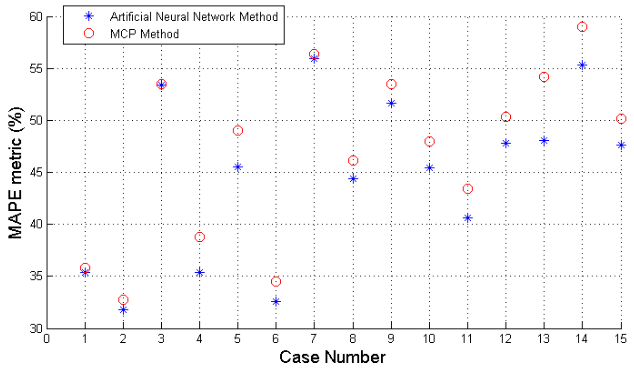

Fig. 5. Results for the MAPE metric of the wind speed. Scenarios C) and D).

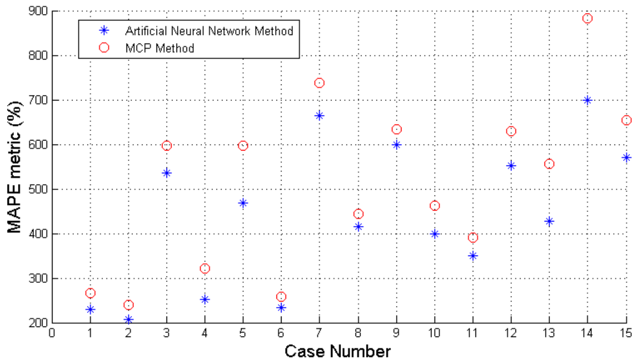

Fig. 6. Results for the MAPE metric of wind power density. Scenarios C) and D).

It can also be concluded from Figures 4 to 6 that the errors calculated when using point-to-point calculation metrics are much higher than when using metrics such as the ratios between the mean values of the entire data series.

5. Conclusions

The most important conclusions that have been reached in this paper are as follows:

a) The results of the metric of the ratio between mean estimated and observed wind speeds are independent of the coefficient of correlation between the reference and candidate wind speeds, Eq. (4). This is not the case with the metric of the ratio of the mean wind power density which is dependent on this coefficient of correlation.

b) In the estimation of short and/or long-term wind power density, the ratios between the mean values of the observed and estimated parameters, Eq. (1) are, on their own, not good indicators for decision-taking in analyses of the estimation of the wind resource, since values close to the target value of 1 in the ratio of the mean wind speed are not always equivalent to good results in the estimation of the wind power density, Figs. 4-6.

If the above metrics are considered for use in analysis of the performance of the estimation models, additional metrics should also be used such as the coefficient of correlation, CC, between the estimated and observed values of the wind speed. This metric takes into account the combined performance over time of the estimated and observed values.

c) The interpretations that can be made when using metrics such as the ratio between the mean values of parameters and point-to-point calculation metrics such as the MAPE, are very different. Case 7, for example (Fig. 4), with a mean wind speed ratio close to 1, gives a relative error (MAPE), with respect to the wind speed, higher than 55%, Fig. 5.

d) When the objective is the estimation of the wind power density for a subsequent point-to-point calculation (as is, for example, an hourly calculation), metrics like the MAPE and the CC are considered to be better indicators when it comes to analysing the accuracy of the models.

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Using Electric Water Heaters (EWHs) for Power Balancing and Frequency Control in PV-Diesel Hybrid Mini-Grids

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Abstract: Electricity is usually supplied by diesel generators in remote communities at costs that can reach up to $1.50 per kWh in northern Canada. At these costs, several renewable energy sources (RESs) such as wind and photovoltaic (PV) can be cost effective to meet part of the energy needs. Their main drawback, being fluctuating and intermittent, can be compensated with either storage units, which are costly, and/or by adapting the electrical power consumption (load) to the availability of RESs. Electric water heaters (EWHs) are good candidates for demand side management (DMS) because of their relatively high power ratings and intrinsic thermal energy storage capabilities. The average power consumed by an EWH is strongly related to the set point temperature (*Td*) and to the hot water draw (*Wd*). A 5.5 kW, 50 gallon EWH is modeled in MATLAB-Simulink and a typical 24-hour water draw profile is used to estimate the potential range of power variation offered by an EWH for power balancing purposes. Besides, a strategy for controlling the power consumed by the EWH, by means of *Td*, using a grid frequency versus temperature/power droop characteristic is proposed. In this way, the EWH can be used for power balancing and for assisting with the mini-grid frequency control.

Keywords: *Diesel hybrid system, electric water heater, power balancing, frequency regulation*

Nomenclature

t_{on} *time period that EWH is ON* .... h
t_{off} *time period that EWH is OFF* .... h
T total operation cycle of EWH .... h
Tin incoming water temperature .... °F
Ta ambient air temperature outside tank .... °F
Td reference temperature for the EWH .... °F
T_H *temperature of water in tank* .... °F
ρ *density of water* .... lb/gal
C thermal capacity of water the tank .... BTU/°F
B thermal capacity of water usage .... BTU/°F
Q energy input rate .... Btu/h
Wd average water draws per hour .... gal/h
Cp specific heat of water .... BTU/lb. °F
SA surface area of tank .... ft^2
U stand-by heat loss coefficient .... Btu/°F. h. ft^2
$P_{EWH\ average}$ *power consumed by EWH* .... kW

1. Introduction

Diesel generators sets (gensets) are a relatively expensive way to produce electricity in remote areas when connection the main grid is not feasible. Renewable energy sources (RESs) such as wind and photovoltaic (PV) are an attractive solution to reduce cost of electricity in these systems. They are environmentally friendly and their incorporation into diesel based mini-grids is relatively simple [1] for low penetration levels. They are usually controlled as passive units, injecting as much of intermittent and fluctuating power as possible, while the grid forming unit(s), usually gensets, have to match the power generated and consumed in the system [2]. This is not an easy task considering that remote communities are characterized by highly variable loads with the peak load as high as 5 to 10 times the average load. What is more, gensets should not operate at low load conditions (~0.3-0.4 pu), due to maintenance problems in the diesel engine, and should provide spinning reserve for cases of sudden load surges or renewable generation reduction [3]. It should be noted that diesel gensets are usually Operated in parallel with frequency x power droop characteristics what facilitates active power dispatch. Besides, operation with variable frequency conveys the message of surplus

(higher frequencies) or shortage (lower frequencies) of active power in systems with non-dispatchable renewable sources.
Power balance issues can be overcome with energy storage units but this is a relatively costly solution [4]. Alternatively one can use controllable loads to help with the power balancing and frequency regulation in a diesel hybrid mini-grid. Due to their relatively large time constants, thermal loads such as electric water heaters (EWH) present an energy storage characteristic and are good candidates for power balancing and frequency control [5].
The use of EWHs in load side demand control was introduced in 1934 by Detroit Edison. Timers were employed to cut off energy flow to EWHs during peak periods for four hours [6]. Later, many other control strategies were developed.

This paper discusses the use of EWHs to help balance the active power and assist with the frequency regulation in diesel hybrid mini-grids. A model of 5.5kW-50gal EWH is implemented in Matlab/SIMULIINK in order to observe the impact of varying the set point temperature (*Td*) on the power consumed by the EWH supplying a typical residential water draw (*Wd*) profile. Analytical equations are derived and used for estimating how much power an EWH can take or drop during each hour of the day, by varying *Td*, while keeping the hot water temperature (T_H) within acceptable values.

2. Methodology

2.1. Electric water heater (EWH) model:

The following first-order differential equation, which represents the energy flow in an electric water heater [7], was used to implement a simple model of an EWH.

$$C\frac{dT_H}{dt} = U\,SA(Ta - T_H) + Wd\,\rho C(Tin - T_H) + Q \tag{1}$$

The first part at the right side represents the heat losses to the ambient, the second the heat needed to heat the inlet cold water, and the last one is the input heat energy from the resistive element of the EWH.
By integrating both sides one gets

$$T_H = \frac{1}{\tau}\int (R'GTa + R'BTin - T_H + R'Q)dt \tag{2}$$

Where $G = U\,SA$, $B = Wd\,\rho C$, $R' = 1/(G + B)$ and $\tau = R'C$

By implementing (2) in Matlab/SIMULINK one can see the variation of the temperature of the hot water in the tank (T_H) for various conditions. The heating element of the EWH is turned ON and OFF so as to keep T_H within a tolerance band (+/- Δ) of *Td*. When the heating element of the EWH is ON, T_H rises until it reaches (*Td*+Δ). Then the heating element is turned OFF and T_H decreases until it reaches (Td-Δ), when the heating element is turned ON again. In this study, the rated power of the EWH (P_{rated}) is assumed to be 5.5 kW and *Td* for the base case (Td_b) is set at 120 °F with Δ equal to 2.5 °F. The 24-hour hot water draw (*Wd*) profile used in this paper refers to the hourly profile proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [8]. The other main parameters used in the simulations are shown in Table 1.

In this study, the following assumptions are made:

- The hot water temperature in the entire tank is the same.
- The ambient and the inlet water temperature (*Ta* and *Tin*) are constant during the day.
- The variation of *Td* does not affect *Wd*.

The variation of T_H for one day is shown in Fig. 1(a) using the ASHRAE *Wd* schedule shown in Fig. 1(b). The instantaneous power consumed by the EWH is shown in Fig. 1(c). A simulation (time) step of 0.0001 h was considered.

Table 1. Main EWH parameters

Q(Btu/h)	*ρ*(Ib./gal)	*V*(gal)	*C*(BTU/°F)	*Ta*(°F)	*Tin*(°F)	*G*(Btu/ °F.h)
18771.5	8.34	50	417	67.5	60	3.6

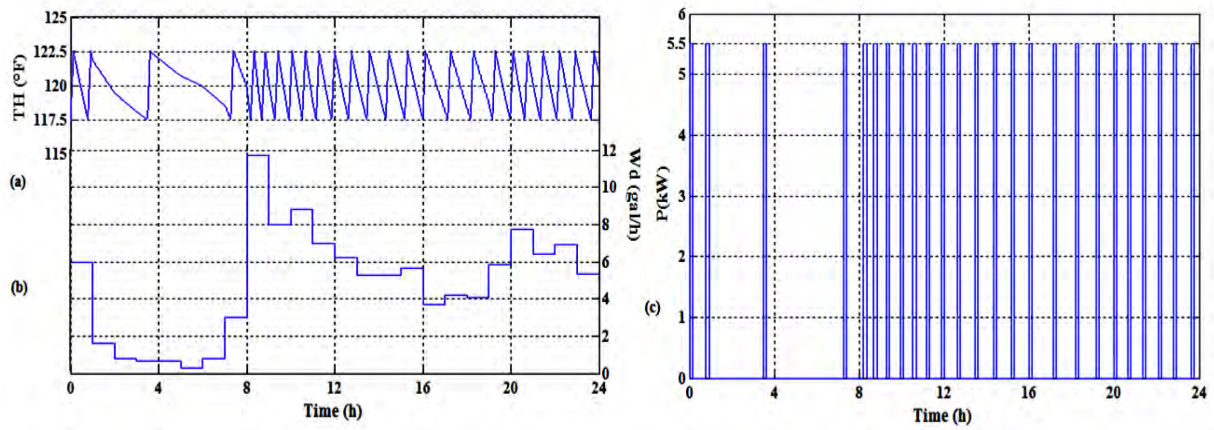


Fig. 1: (a) Variation of T_H (°F). (b) Wd schedule (gal/h). (c) EWH power consumption (kW).

One can see from Fig. 1(c) that t_{on} and t_{off} and the operation period ($T = t_{on} + t_{off}$) of the EWH during the day are not constant. t_{off}, in particular, varies significantly with *Wd*. Table 2 shows the maximum and minimum values of t_{on}, t_{off} and *T* during the one day period considered.

Table 2. Maximum and minimum on, off and operation period of the EWH.

$t_{on-\max}$ (h)	$t_{on-\min}$ (h)	$t_{off-\max}$ (h)	$t_{off-\min}$ (h)	$T_{\max}$ (h)	$T_{\min}$ (h)
0.1639	0.1143	3.6571	0.3453	3.7714	0.5092

2.2. *Mathematical analysis:*

An equation that describes how T_H varies in time can be obtained by solving Eq. (1) as

$$T_H(t) = T_H(t_0)e^{-(1/\tau)(t-t_0)} + \left(R'GTa + R'BTin + R'Q\right)[1 - e^{-(1/\tau)(t-t_0)}] \quad (3)$$

With the appropriate modifications, it can be used for obtaining expressions to calculate t_{on} and t_{off}. However, exponential equations are not very convenient to use. Alternatively, one can derive linear expressions for t_{on} and t_{off}. This can be done by replacing dT_H by T_{high}-T_{low} (T_{low} - T_{high}) in Eq. (1) when the EWH is ON (OFF) and *dt* by t_{on} (t_{off}). Besides, T_H is assumed equal to *Td* in order to calculate the average heat losses to the ambient and due to inlet cold water replacing the water drawn from the tank. In this case

$$t_{on} = \frac{C\,(T_{high} - T_{low})}{G\,(Ta - Td) + \rho\,Cp\,Wd\,(Tin - Td) + Q} \tag{4}$$

$$t_{off} = \frac{C\,(T_{high} - T_{low})}{G\,(Td - Ta) + \rho\,Cp\,Wd\,(Td - Tin)} \tag{5}$$

With Eq. (4) and (5) one can calculate the operation period of the EWH ($T = t_{on} + t_{off}$) and the average power consumed by the EWH in that operation period ($P_{EWH} = D\,P_{rated}$), where

$$D = \frac{t_{on}}{T} = \frac{G\,(Td - Ta) + Wd\,(Td - Tin)\,\rho\,Cp}{Q} \tag{6}$$

The value of *Wd* for the above equations should be the average water draw for the period under consideration (*T*). As shown in Table 2, for T_{high}-T_{low}=2Δ and with Δ = 2.5 °F, t_{on} is always smaller than 1h what allows the use of the hourly ASHRAE *Wd* schedule for validating Eq. (4). By comparing the values of t_{on} obtained with eq. (4) with those of the simulations one sees that the error were smaller than 0.01%. On the other hand, t_{off} varies more with *Wd* and can be larger than 1 h, usually for low values of *Wd*. In this case, an average value for *Wd* valid for that duration needs to be considered.

The values of *D* obtained from (6), which are equivalent to P_{EWH} in pu, are shown in Table 3 for different values of *Wd* and *Td*. There one sees that P_{EWH} at *Td* = 140 °F is around twice that at *Td* = 100 °F for all values of *Wd*. Besides, operation at low values of *Wd*, limits significantly the variation of P_{EWH} one can get by varying *Td*. Thus, in these cases, the EWH will be less effective as a means for balancing active power in the electric system.

Table 3. Variation of P_{EWH} (pu) with Wd and Td.

Wd(gal/h) / *Td*(°F)	0.25	0.75	1.5	3	6	9	12
100	0.0107	0.0196	0.0329	0.0595	0.1129	0.1662	0.2195
108	0.0131	0.0238	0.0398	0.0717	0.1357	0.1997	0.2637
116	0.0155	0.028	0.0466	0.0839	0.1586	0.2332	0.3079
124	0.0179	0.0322	0.0535	0.0961	0.1814	0.2667	0.3521
132	0.0204	0.0364	0.0604	0.1083	0.2043	0.3003	0.3962
140	0.0228	0.0406	0.0672	0.1205	0.2272	0.3338	0.4404

One important aspect when designing the control scheme of a given system is to identify the sensitivity of a quantity of interest to variations in some of its key parameters. This can be done by means of partial derivatives. For *D*, and consequently P_{EWH}, these key parameters are *Td*, taken here as the control parameter, and *Wd*, assumed as a disturbance in the system. From Eq. (6) one can get

$$\Delta P_{EWH}(pu) = \Delta D = \frac{\partial D}{\partial Td}\Delta Td + \frac{\partial D}{\partial Wd}\Delta Wd = \frac{G + Wd\,\rho\,Cp}{Q}\Delta Td + \frac{(Td - Tin)\,\rho\,Cp}{Q}\Delta Wd \tag{7}$$

For the case under consideration assuming that *Wd* is constant

$$\Delta P_{EWH}(pu) = \Delta D = \frac{3.6 + 8.34Wd}{18771.5}\Delta Td \tag{8}$$

This equation is very useful when one wishes to compute by how much one should change *Td*, for the EWH operating with a given value of *Wd*, in order to change P_{EWH} by a certain value in steady-state. The limit values for P_{EWH} and *Td* are those shown in Table 3.

Another important aspect of the operation of an EWH for active power balancing is the amount of power it can drop or take under transient conditions. Since the EWH operates in an ON/OFF mode, its instantaneous power consumption is either rated or zero. This cannot be changed. However, one can during transient condition values for t_{on} and t_{off} significantly larger than those obtained for steady-state conditions.

Let's consider first the case where the EWH should take additional load. From Fig. 1(a) one sees that T_H increases almost linearly when the EWH is ON and t_{on} is the time required for T_H to increase by 2Δ, 5 °F in this study, when *Td* remains constant. As shown in (4), t_{on} increases as *Wd* increases but it does not vary significantly with *Wd* since *Q* is the dominant element in the denominator of (4). If *Td* is suddenly increased by a value larger than the tolerance band ($\Delta Td > 2\Delta$), the EWH will be turned ON immediately and remain ON until the value of T_H increases by at least ΔTd. Based on this, one can estimate that the increase in t_{on} during transient conditions, with respect to the previous value in steady state, for a given ΔTd on average, for $T_H = Td$, as

$$\Delta t_{on}(\%) = \frac{\Delta Td + \Delta}{2\Delta} \tag{9}$$

Table 4 shows the maximum values of t_{on} that one can have during each time of the day, assuming the ASHRAE *Wd* schedule, as one changes *Td* from an initial value, either 120 °F or 100 °F, to 140 °F. Td_b = 120 °F is the base case, when one does not expect the need to take or drop power during the next few hours. However, if one knows that there will be a need to take as much load as possible, due to a typical surge in production of wind power or due to a decrease in the regular electric load in the system, then one could operate with *Td* = 100 °F.

Table 4. t_{on_max} for different values of initial Td using the ASHRAE Wd schedule. Case #1 (Td=120°F, ΔTd=20°F, Δt_{on}=4.5.) Case#2 (Td=100°F, ΔTd=40°F, Δt_{on}=8.5).

Time (h)	0	1	2	3	4	5	6	7	8	9	10	11
Wd(gal/h)	6.0	1.6	0.8	0.7	0.7	0.3	0.8	3.0	11.7	8.0	8.8	7.0
ton(h), Case1	0.646	0.537	0.522	0.519	0.519	0.512	0.522	0.568	0.876	0.712	0.743	0.677
ton(h), Case2	1.221	1.016	0.986	0.981	0.981	0.966	0.986	1.074	1.656	1.346	1.403	1.280
Time(h)	12	13	14	15	16	17	18	19	20	21	22	23
Wd(gal/h)	6.25	5.30	5.30	5.65	3.70	4.20	4.10	5.85	7.73	6.38	6.90	5.30
ton(h), Case1	0.654	0.626	0.626	0.636	0.585	0.597	0.595	0.642	0.702	0.658	0.674	0.627
ton(h), Case2	1.236	1.183	1.183	1.202	1.105	1.128	1.124	1.213	1.327	1.244	1.274	1.185

An useful expression for Δt_{off} cannot be obtained in a similar way because the curve for T_H decreasing does not resemble a straight line. Nonetheless, one knows that t_{off} is usually long enough for power balancing operation. Therefore, in this case, one can define a worst case conditions (*Wd* =11.7 gal/h) for which t_{off_min} = 2.3337 (4.4081) h when *Td* = 120(140) °F.

2.3. Temperature Control Using Frequency Droop

Droop control is a well-known technique used for operation and power sharing of power generators connected in parallel. The relationship between frequency and power can be described by

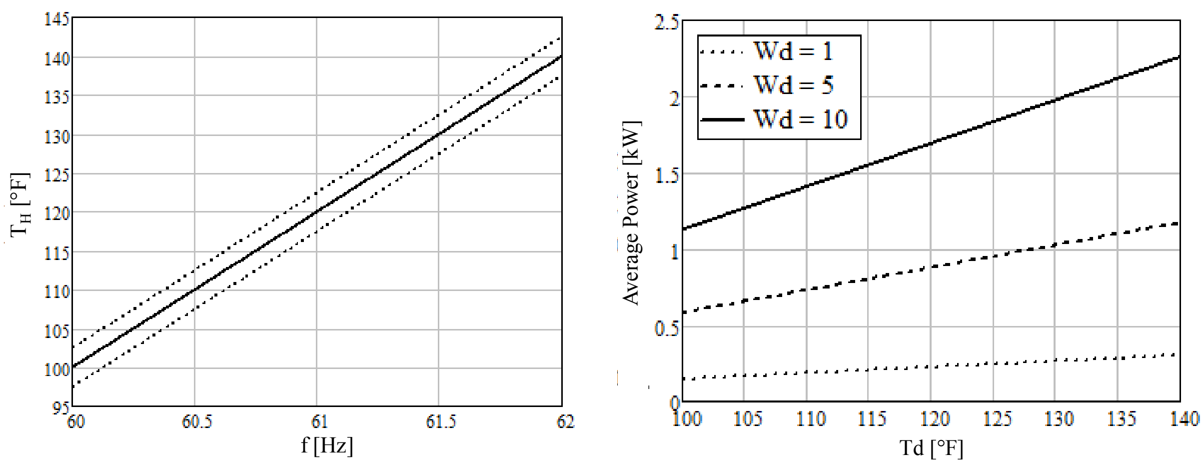
$$P_g = s_p(f_{nl} - f) \tag{9}$$

Where P_g is the output power of the generator (kW) s_P is the slope of the curve (kW/Hz), f_{nl} is the no-load frequency of the generator (Hz) and f is the operating frequency of the system (Hz) [3].

As the actual loading of the genset is proportional to the frequency, it is proposed that the power consumed by the EWH to be controlled by means of the *Td*, using the frequency versus temperature droop function

$$Td = Td_b + m(f - f_c) \tag{10}$$

Where m is a slope factor equivalent to s_p and f_c is the center frequency (Hz). *Td* is equal to half its total excursion. Fig. 2 (a) shows the frequency x temperature droop function with m = 20 °F/Hz, Td_b=120°F, and f_c = 61 Hz. The value of T_H will vary within *Td* ±Δ as shown with the dotted lines. The action of droop is limited to when *Td* is within acceptable limits of temperature; in this case it was limited between 100 °F and 140 °F. From Eq. (9), when the load increases, the frequency of the generator decreases. This frequency reduction will cause *Td* in the EWH to decrease, while when the generator load decrease the frequency will increase making *Td* increase. Varying *Td* during steady and transient condition will affect the average power consumption, as can be seen on Fig 2 (b) for different values of *Wd*, for the EWH described on Section 2.1. Varying *Td* between 140° F and 100 °F would result in a 1.13 kW variation in the average power consumed. However for periods of lower water draw (*Wd* ~ 1 gal/h) this variation is limited to 0.15 kW, which makes this control strategy sensitive to the water draw condition. It is important to note that have been reported in the literature that the electricity consumption is directly related to water consumption [9], what makes the effect on peak load shaving improved with this strategy.



(a) (b)

Fig. 2: (a) Frequency x temperature droop variation (b) Average power consumption variation with Td for different average water draw.

3. Results

A mini-grid with a genset feeding a network with 20 houses in a single phase connection where only two of the three outputs of the genset are used is presented in [3] and is used in this paper to evaluate the impact of the frequency x temperature droop control in the loading of the generator and grid frequency. The genset is rated at 95kW on a three phase basis, however in practice it means that only about 2/3 of the generator power is available. The droop parameter of the genset are s_p = 29.4 kW/Hz and f_{nl} = 62.3 Hz.

A residential load profile for a house without EWH based on [10] was scaled to have a daily energy consumption of 20 kWh and used as reference for all 20 houses to determine the 24 h load profile of the mini-grid. Fig. 3 (a) presents the single house load profile used and the power consumption profile of the EWH with *Td* = 120 °F. The *Wd* schedule considered was the one presented in Fig. 1 (b). Two cases are considered, first the EWH operates with constant *Td*, base case, and the second one using the frequency x temperature droop strategy (Tdroop) with *m* = 20 °F/Hz and f_c = 61 Hz. Fig. 3 (b) presents the genset load for each hour of the day. The load variation is reduced with the droop approach. The peak load from this day decreases from 56 kW to 52 kW, while in the lower load region, the load increases from 8.3 kW to 9.5 kW. This small difference in the low load region is due to the fact that varying *Td* for controlling the power is sensitive to the water profile that during that period was low. Fig. 4 presents the frequency variation regarding the change in the genset load (a) and the variation on *Td* due to the frequency droop implemented.

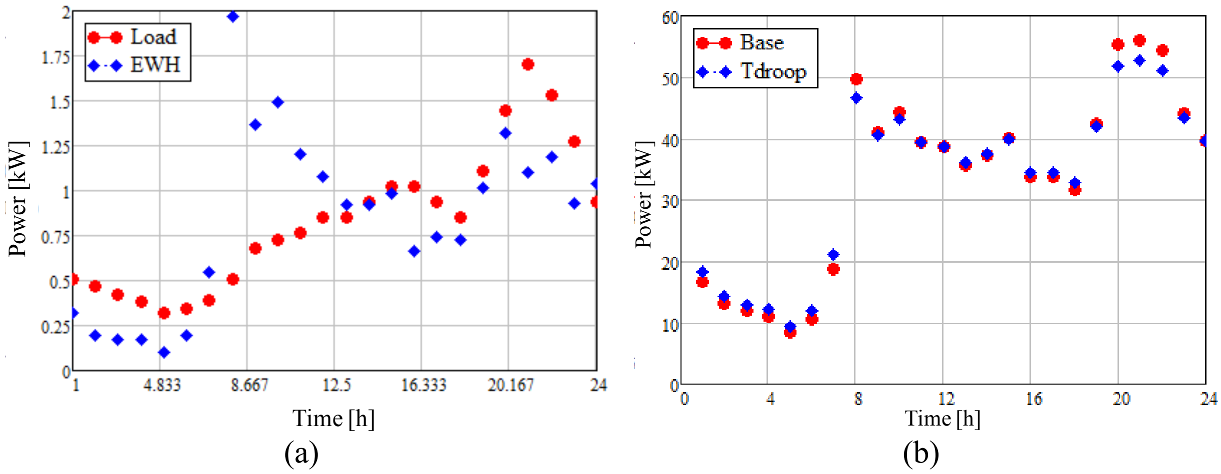
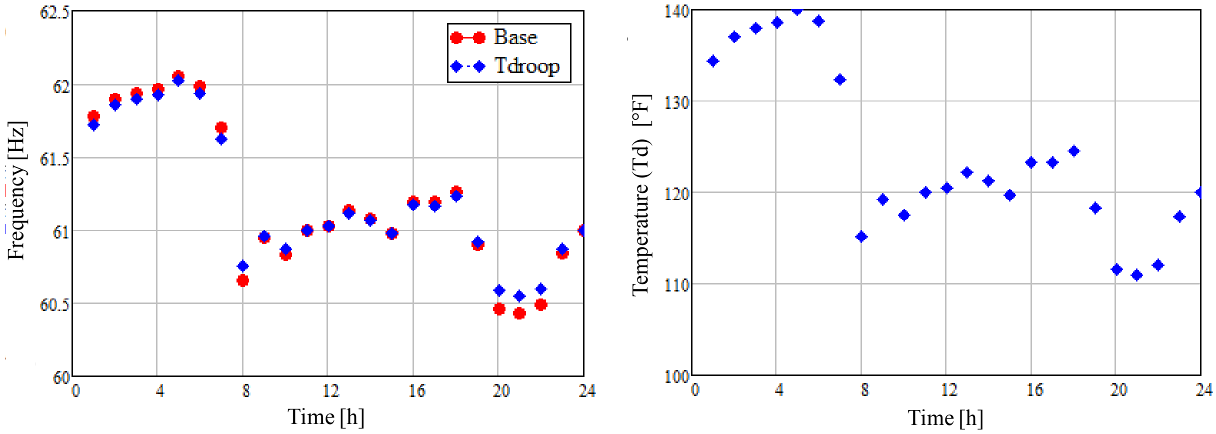


Fig. 3. (a)Load Profile and EWH Power Profile for Td = 120° F and (b) Genset power.



(a) (b)

Fig. 4. (a) Minigrid frequency and (b) individual EWH Td during the 24 h case study.

4. Conclusions

This paper presented EWHs as candidates for DMS due to the fact that the average power consumed is strongly related to the set point temperature (*Td*) and to the hot water draw (*Wd*). A mathematical model was obtained for the EWH. It was proposed a strategy for controlling the power consumed by the EWH, by means of *Td*, using a frequency versus temperature droop characteristic. A 5.5 kW, 50 gallon EWH was modeled in MATLAB-Simulink and a typical 24-hour water draw profile was used to estimate the steady state performance in a 95 kW diesel based mini-grid. Results showed that with the proposed control strategy power variations in the mini-grid can be reduced; however it is strongly dependent on the values of water draw from the houses.

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Impacts of large-scale solar and wind power production on the balance of the Swedish power system

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Abstract: Higher targets for renewable energy and current trends in wind power and photovoltaics (PV) suggest that future power systems will include large amounts of renewable and variable power generation. Integration of large-scale variable power generation changes the balance and operation of power systems, including scheduling of conventional generation units, transmission and use of balancing power. In this paper the Swedish power system is studied with the energy system optimisation model MODEST in a number of scenarios involving different combinations of large-scale solar and wind power. The model includes a representation of the Swedish district-heating systems to determine the effects on combined heat and power (CHP) operation. It is found that when renewable power generation is added to the present system, utilisation of investments in CHP plants is reduced due to an increased electricity surplus that favours use of heat pumps for district heating. At high penetration levels of both solar and wind power, water is spilled from hydropower reserves.

Keywords: *Solar power, Wind power, Power system, Optimisation*

1. Introduction

According to the EU directive on renewable energy, 20 % of the energy use within the union is to be covered by renewable energy sources by 2020 [1]. An important part of this goal is to transform the power system to include more renewable electricity generation. The power source most likely to reach substantial integration levels within this time frame is wind power. Although wind power currently covers 4.8 % of the total electricity demand within the EU, penetration levels in some individual countries are higher, for example Denmark (19 %), Portugal (15 %), Spain (14 %) and Ireland (11 %) [2]. Solar power generation, mainly from grid-connected photovoltaics (PV), is also increasing worldwide, although the contribution is smaller than for wind power. In Germany, the country with the highest solar power penetration, PV electricity covers 1-2 % of the national electricity demand [3]. However, if current developments continue, combined with decreasing costs for solar cells, a future expansion of solar power does not seem unlikely. The EU directive on energy efficiency in buildings, which states that all new buildings must be nearly zero energy buildings by 2020, also suggests a future widespread integration of on-site solar technologies [4].

Solar and wind power are both *variable* power sources, which means that the output varies both systematically and randomly on different time scales. The power generation can be forecast to some extent, but not controlled. In the case of wind power, the variation is due to moving weather fronts. Solar power has a more predictable seasonal and diurnal pattern, although the output during daytime can be heavily fluctuating due to variations in cloudiness. Variable power sources have a number of impacts on the balance, operation and reliability of power systems. The hour-to-hour varying production pattern alters scheduling of other generation units in the system and affects transmission between geographic areas. Furthermore, power generation that deviates from the forecast must be handled by system reserves. Depending on the power system, an increase in the penetration level of variable power sources has to be met by some increase in reserve requirements. For large-scale wind power it has been estimated that an increased penetration that corresponds to 10 % of the total annual demand increases the reserve requirements by 2-8 % of rated wind power capacity [5].

An important aspect is how addition of volumes generated by wind and solar power affects scheduling of other generation units and the total system balance. In this paper, the impacts of a large-scale integration of solar and wind power on the balance of the Swedish power system, a high-latitude and hydro-dominated system, is investigated. For example, how is scheduling of other generation units affected and how do electricity exports and imports and CO_2 emissions change?

A model of the Swedish power system was built in the MODEST optimisation model [6]. The model encompasses and optimises the whole chain of energy flows from sources to end-uses. An aggregated but detailed representation of the total Swedish generation capacity, including nuclear power, hydropower, combined heat and power plants, *etc.*, is included and the time resolution captures important fluctuations in demands and renewable power generation. The Swedish district heating systems are also explicitly represented to capture the effects on CHP operation. Solar and wind power are integrated in different scenarios as additions to the existing system. In these scenarios, it is recognised that wind power will most likely be integrated on a large scale before solar power.

The rest of the paper is structured as follows. Section 2 presents an overview of the applied methodology, including the optimisation model and the parameters and data used. Section 3 presents the results from the different studied scenarios. These results are discussed in Section 4 and some conclusions are drawn in Section 5.

2. Methodology

Energy system modelling enables important properties of a real system to be varied in a controlled environment. Using a validated model with a realistic performance, the impact of future changes to the system can be estimated. With an optimisation model, the best performance of a system under certain conditions is found. This section describes the applied optimisation model of the Swedish power and district heating systems. It also presents the studied scenarios for solar and wind power integration.

2.1. The MODEST power system and district-heating model

MODEST (Model for Optimisation of Dynamic Energy Systems with Time-dependent components and boundary conditions) uses linear programming to optimise the energy flows of a system to supply demands while minimising the total cost. In MODEST, an energy system is modelled as a set of nodes interconnected by energy flows. For each node and flow, a set of characteristics can be defined to relate, direct and constrain the flows. Typical such characteristics in a MODEST model are energy balances, dimensioning of maximum outputs for energy conversion and limitations of supplies. A cost can be associated with each flow and node, reflecting for example fuel costs.

Using MODEST, an energy system model of the Swedish power system was created. In the model, energy flows from resources (water and fuels) via generation units to distribution systems and finally to demand nodes representing the national electricity and district heating loads. For electricity, there is also an exchange with Nordic and continental European electricity markets. A flowchart showing the energy flows and nodes of the model is provided in Fig. 1. In the model, time is represented by a ‘quasi-dynamical’ time division, with a variable resolution that is more fine-grained for peak-load or peak-production periods. The time division is adapted to capture the relevant variability in solar and wind power generation.

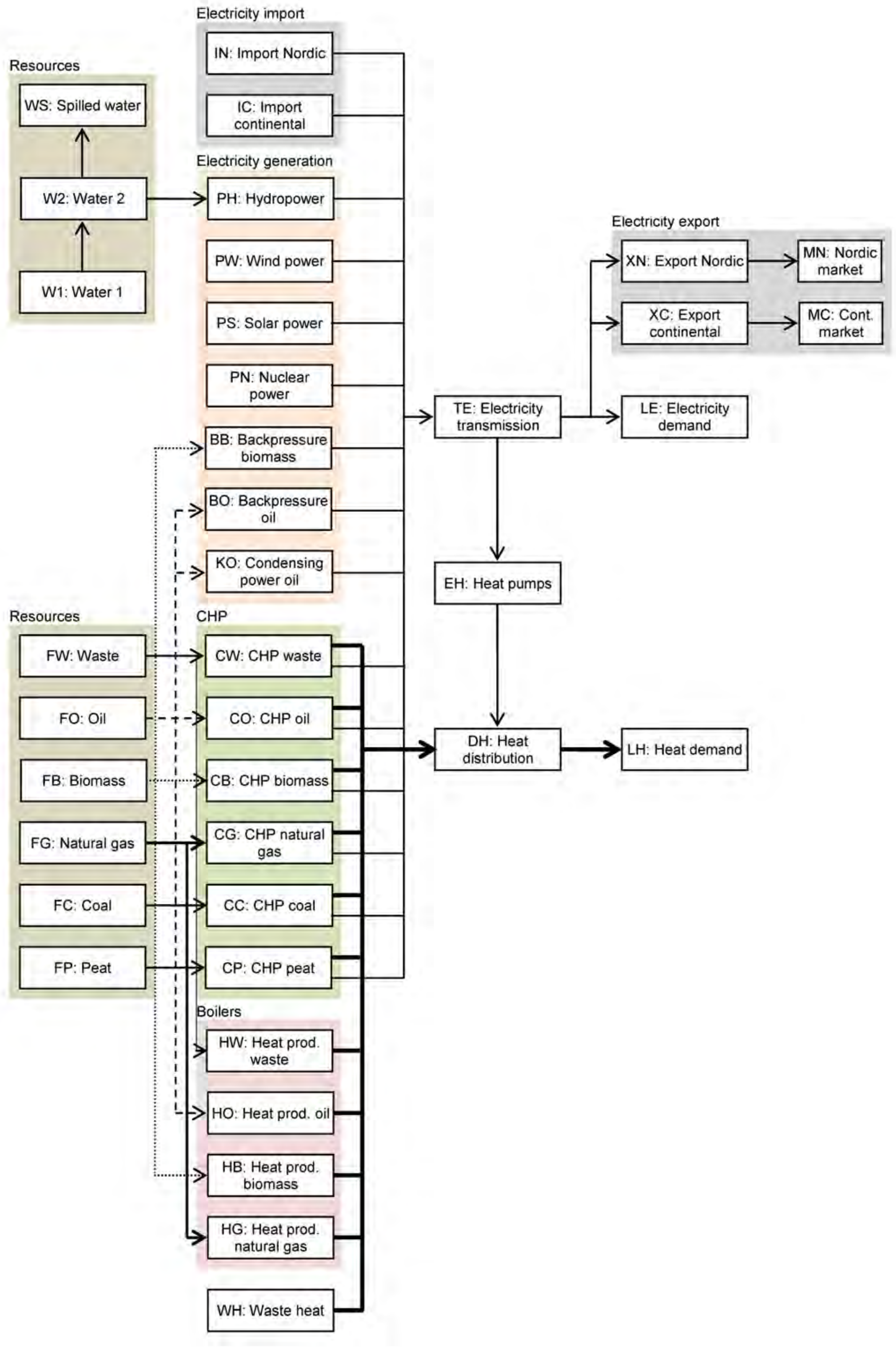

Fig. 1. Flowchart showing the nodes and energy flows in the MODEST model of the Swedish power and district-heating systems.

2.2. Studied scenarios

Two scenarios are studied. Scenario A represents today's system while Scenario B involves large-scale solar and wind power integration. In the latter scenario it is assumed that 30 TWh of wind power generation annually has been added to the existing system, which increases the total generation capacity of the system and turns the Swedish power system into a net producer of electricity. In three cases (B2-B4) besides the base case of today's solar power (B1), solar power is added to the system in 10 TWh steps, up to 30 TWh. In the most extreme scenario (B4), 60 TWh of renewable power generation are added, which is almost equal to the total current nuclear power generation. The main questions are how large volumes of electricity from plants with practically no running costs entering the system alter the scheduling of other power plants within the country, if the mix for heat production changes, how net exports and imports change and how CO_2 emissions are affected.

2.3. Input data

Model parameter values were chosen to make the model correspond to today's power system, with the year 2008 chosen as a representative year. All data were collected with the aim of reproducing the system performance of this year. Data for system parameters such as capacities, conversion efficiencies, resource limitations, prices, emission factors, *etc.*, were collected from a variety of sources, including different statistics sources, authorities' reports and business reports. Some data, which were still considered sufficiently up-to-date were collected from a previous national-level MODEST study. Data for estimating the variable components in the system were obtained from empirical time series with an hourly resolution. Some variable components are electricity and heat loads, solar and wind power generation and electricity market prices. Electricity prices were collected from NordPool and EEX spot market data, solar power data from a previous study of large-scale solar power variability in Sweden, wind power data from a database with modelled wind power data based on a scenario for widespread wind power in Sweden, electricity demand from NordPool's power system data and heat demand data scaled up from heat load data for a local district-heating system. All data series are from 2008 except the wind power and solar power data, which are from 1999, a representative year in terms of annual availability of solar irradiation and wind energy. All of these data are reported in detail in [7].

3. Results

The results of the energy system optimisations for the studied scenarios are shown in Fig. 2 and Fig. 3. Fig. 2 shows the energy balances for scenarios A and B. The impacts on the electricity and district heating production and the fuel use are visualised, as well as occasionally spilled energy, electricity imports and exports and CO_2 emissions. Fig. 3 shows duration graphs for district heating in scenario A and in the extreme case B4. The bold lines in the latter figure represent the district heating demand and show the different demand levels sorted in decreasing order. The step length corresponds to the length of each individual time period in the model. The other curves show plant outputs in the time periods.

As can be seen in Fig. 2 for the electricity production, the total production increases gradually in scenario B due to integration of wind and solar (B2-B4) power. This has no significant effect on the other parts of the electricity mix, apart from in case B4, where there is a small decrease in hydropower production. This is because some water has to be spilled as the capacity for electricity export is reached. This can also be seen in the graph for spilled energy. In the heat production mix, there is an incrementally larger contribution from heat pumps. This is because it is occasionally feasible to use excess electricity in the system for heating, compared to other more costly alternatives. This is generally on the expense of heat-only production, but in B4 also of CHP. As seen in the graph for fuel use, the total use of fuels decreases accordingly, mainly biofuel but in all cases also oil as compared to scenario A. From the heat duration curve in Fig. 3 (case B4) it can be seen that the heat pumps, which in scenario A are exclusively used at high loads, are now feasible to use even at lower loads.

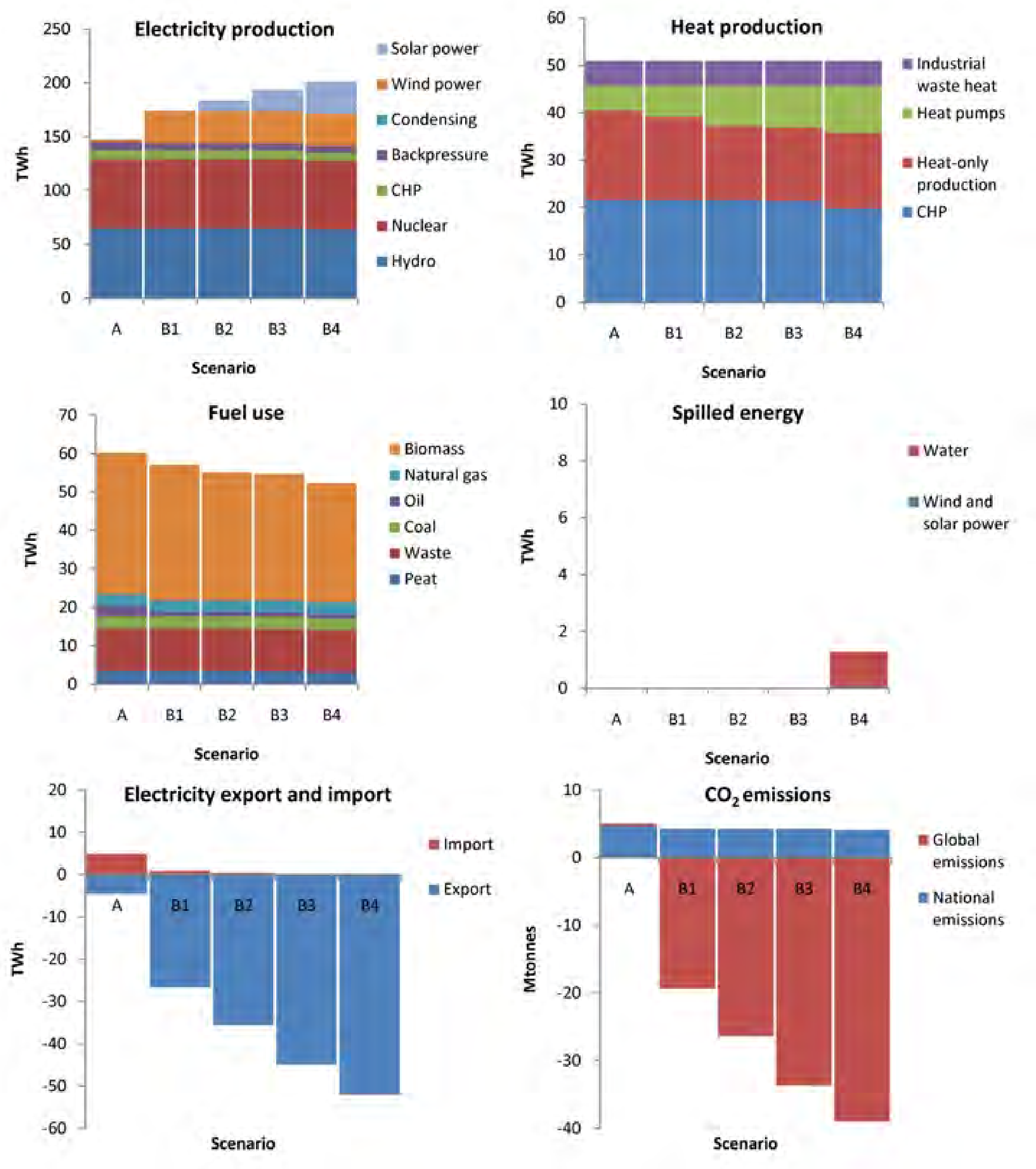

Fig. 2. Energy system characteristics in Scenarios A (base scenario) and B (addition of wind power) with cases 1-4 (different solar power integration levels).

Electricity exports increase due to the excess generation (Fig. 2), while imports decrease due to wind and solar electricity replacing imported electricity. This is reflected in the CO_2 emissions: emissions are reduced in power systems abroad due to export of electricity, which is assumed to replace coal-fired marginal electricity production. National emissions, resulting from fuel combustion in the studied system, and global emissions, being emissions caused or replaced by electricity exchange with continental Europe, are shown separately in Fig. 2. The reduction of global emissions vastly exceeds the local emissions.

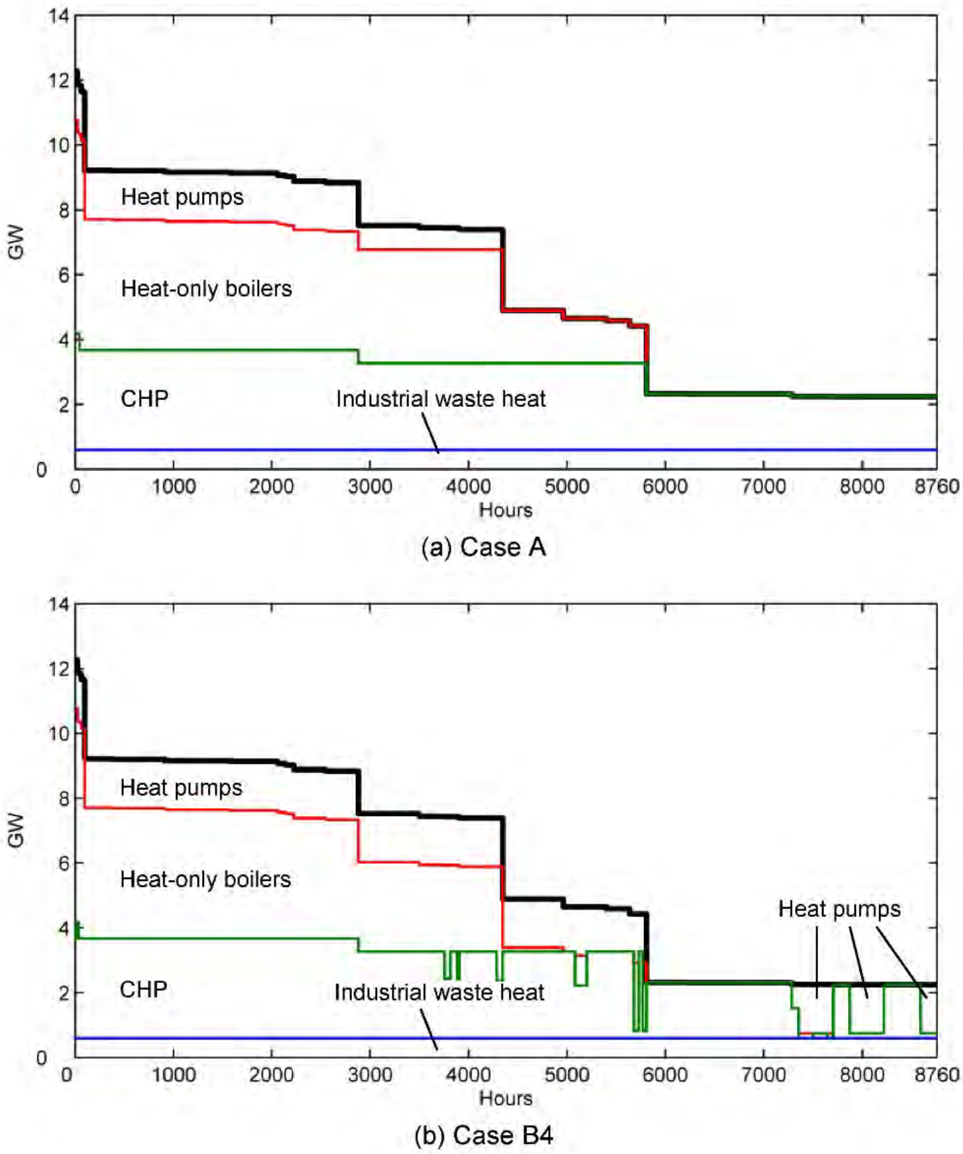

Fig. 3. Duration curves for the district heating demand (solid bold staircase line) and contribution of different types of heat production meeting this demand.

4. Discussion

The major impact on the district heating system in scenario B is biomass-fuelled CHP being replaced by heat pumps. This is perhaps a questionable system solution because investments in CHP plants are utilised to a lesser degree. From an overall systems perspective it may seem more reasonable to use CHP in Sweden where the heat can be utilised in district heating systems and to install solar cells in countries with less district heating and a higher and less seasonally fluctuating insolation. However, on a liberalised electricity market, if solar cells become cost-effective, a large-scale integration is possible and would be something that district heating utilities would have to adapt to. With a large surplus generation from renewables, the electricity prices would occasionally be very low, which would make it reasonable to decrease CHP production because of the low revenues from sold electricity. At the same time the low electricity prices would make electric heating, at least with heat pumps, cost-effective. It is important to note that neither competition with CHP, nor other impacts such as water spillage, pose any definitive limits to the integration of solar and wind power. In general, integration of variable power generation is not primarily restricted by any fundamental technological limits but is rather determined by economic trade-offs, depending on the balance between demand and generation locally and in neighbouring areas, transmission capacities, hydropower control and spillage [8].

Some limitations of the studied scenarios, which are based on today's power and district heating systems, have impacts on the results. For example, the increased use of heat pumps occurs when transmission capacities restrict the possibilities for electricity export. Therefore, increased transmission capacity to neighbouring countries would make it possible to export the electricity instead of using it for electric heating. An increased transmission capacity would probably accompany an extensive integration of renewable power generation. However, if solar and wind power penetration levels increase in other countries, its variability will to some extent be correlated to the variability of the Swedish plants. A production surplus in neighbouring countries would therefore reduce the possibilities for exports, despite a higher transmission capacity. Additional scenarios that take this into account would be needed for further studies.

Another possibility that should be included in future scenarios is load management, which could help absorbing solar and wind power variability. Increased use of heat pumps could be seen as one type of load management, as it occasionally increases the electricity demand. Other types of demand response should be included as well. Another possible feature of the future power system is a changed electricity demand due to a large-scale introduction of electric vehicles. These could also introduce additional storage capacity to the system. A large-scale change to the district heating load is also possible, following energy efficiency measures in the built environment, which could possibly change the basis for the CHP production. But district heating may, on the other hand, also serve new purposes, such as industrial heat demand, absorption cooling and washing machines, which reduce seasonal demand variations and improve conditions for CHP production. Global warming and its effects on the climate could also be taken into account. For example, precipitation will probably increase in Sweden [9], which improves the hydropower ability to balance variable power generation. All of these possibilities should be included in further research.

Some more fundamental limitations of the applied model should also be mentioned. The variability of combined solar and wind power is described in detail, but not the short time-scale fluctuations that determine the instantaneous utilisation of reserve capacity. Moreover, hydropower control is modelled in an aggregated form and does not consider individual rivers where the flows between hydropower plants may be coupled. Another simplification is that bottlenecks in transmission capacity within the Swedish power system are not included. Combined, these simplifications may overestimate the flexibility of the power system. In reality, it would be possible e.g. for water spillage to occur for lower penetration levels of renewable power generation than the ones in case B4.

5. Conclusions

The energy system optimisation model MODEST has been used to study the Swedish power and district-heating systems with large-scale renewable power integration. It was found that incremental amounts of solar and wind power added to the existing system do not cause any spilled energy until they reach the levels in the most extreme case where solar and wind power each produce 30 TWh annually. However, the large-scale renewable power integration reduces utilisation of investments in CHP plants due to an increased use of heat pumps and, as a consequence, leads to reduced use of biofuels for district heating. A major proportion of the added generation capacity produces a surplus that is exported. Further research should include scenarios for the major influential system components and parameters, such as domestic and foreign transmission capacity.

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Sustainable working media selection for renewable energy technologies

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Abstract: The sustainable working media selection is one of the most important stages in renewable energy technologies. The compromise among such properties as contribution to greenhouse effect, flammability, toxicity, thermodynamic behaviour, performance specifications, and the others defines a sustainable decision. The aim of present work is to apply a fuzzy set methodology providing sustainability among thermodynamic, economic, and environmental requirements. The organic Rankine cycle (ORC) for the class of working fluids based on the hydrofluoroethers (HFE) is considered to demonstrate a proposed approach. To select new working fluids, which have no information on thermodynamic behavior, artificial neural networks (ANN) approach is offered to forecast the ORC energy efficiency. The ANN correlations for coefficient of performance (COP) and pressure ratio (output) as functions of critical temperature, critical pressure and normal boiling temperature (input) are built via REFPROP database. The validation set has been used to estimate the ORC energy efficiency without of thermodynamic property calculations. The accuracy of ANN prediction for the cycle performances does not exceed 4% relative to the training set values. The Bellman – Zadeh model as the intersection of membership functions (fuzzy criteria mappings) is applied to sustainable selection of working media.

Keywords: *Working Fluids, Organic Rankine Cycle, Coefficient of Performance, Artificial Neural Networks*

Nomenclature

COP	*coefficient of performance…………………*	*Z*	*compressibility factor……………………...*
K	*generalized criterion……………………..*	*μ*	*membership function………………………..*
K_i	*local criterion……………………..*	*ρ*	*density………………………………. kg·m⁻³*
M	*molar mass……………… ………g·mole⁻¹*	*Ψ*	*flammability index…………………………..*
n_i	*number of atomic species (i)*		*Subscripts*
p	*pressure………………………………MPa*	*C*	*critical*
RD	*relative deviation……………………….%*	*B*	*boiling*
T	*temperature…………………………….K*	*opt*	*optimum*
		th	*thermodynamic*

The paradigm of sustainable development considers an integrated solution of the ecological, economic, social and cultural problems arising from the design of technical systems. The transformation of renewable energy sources into mechanical work mainly is based on the application of the Rankine cycle. The Rankine cycle working on organic substances, the Organic Rankine Cycle, has found wide application as renewable energy technologies (RET). There are many criteria of efficiency of RET and the extreme values are desirable to reach for each ones taken separately. Usually, three main goals are involved in the design process: thermodynamic, economic and environmental. The problem of prospective working media selection is closely connected with modern technologies based on the concept of sustainable development. To utilize low potential heat source, the ORC working fluids should possess normal boiling temperature below 350 K, practically vertical right boundary curve in the temperature – entropy diagram, high heat of evaporation, high density and comprehensible operational qualities. The selection of working fluids with desirable combination of such properties as contribution to greenhouse effect, flammability, toxicity, thermodynamic behavior, performance specifications, and the others is one of the most important stages in RET simulation and design. Working fluid selection problem has been tackled using achievements of molecular theory, engineering experience and experimental studies [1] - [4]. Clearly, a working fluid that combines all the desirable properties and has no undesirable properties does not exist.

1. Sustainable ORC working fluids selection

The aim of present work is to include a fuzzy set methodology in order to meet thermodynamic, economic, and environmental goals for working fluid selection in the ORC. To solve this problem, achievements of information technologies and the molecular theory, technical experience and experimental data are used. There is a multitude of efficiency criteria and the attainment of the extreme for each of them is the ultimate goal of the design. Usually a compromise among three basic criteria – energy, economic and ecological is considered. The generalized criterion of efficiency for all system as a whole is represented by a vector $\boldsymbol{K}$, which includes local criteria $\boldsymbol{K_i}$ that reflect the set of requirements to ORC working fluids by the consumer.

1.1. Tailored working fluid concept

We consider here only such criteria, which are linked by certain relations R to the properties of working fluids P, i.e. the system defined by a three-tuple { K, R, P }. The relation R is a kind of technological operator and its structure can be determined via the equations of mass, momentum and energy balance, supplemented with the characteristic equation of state. It is usually impossible to estimate the performance attributes of refrigeration system from target properties (physical, chemical, ecological, and etc) correlated with molecular structure following to fundamental principles only. So, we need to enlist restricted experimental information to define real properties P via their model properties M (X). The set of model parameters X, as a mapping of the experimental data containing the observed properties P, gains in importance as information characteristics of substance by which its property behavior can be restored. A physical meaning is no less important for the vector X and should map the working fluid characteristics on the molecular level to select a proper molecular configuration. This is very convenient when one needs to be able to predict the properties of any molecular structure. The working fluid selection problem can be mathematically formulated as the multi-criteria optimization problem: to find

$$\boldsymbol{Opt\ K}\ [K_1\ (X), K_2(X), \ldots, Kn(X)], X \in X_P \qquad (1)$$

We assume that $K_j(X) = \| \boldsymbol{P_j}, M_j(X) \|$ is a "distance" between the desired (ideal) efficiency of system $\boldsymbol{P_j}$ and its real model $\boldsymbol{M_j}$. For thermodynamic criterion, K_{th} the value $\boldsymbol{P_j}$ corresponds to the theoretical maximum of the efficiency objective function, e.g. efficiency of the Carnot cycle. Solution of multi-criteria problem is a finding of compromise among all criteria and constraints and can be formulated as follows: to construct the function

$$\boldsymbol{K} = K_1 \cap K_2 \cap \ldots \cap K_n . \qquad (2)$$

The formal solution of problem is added up to determination of the optimum vector $\boldsymbol{X_{opt}}$ of such kind that $|\boldsymbol{K}\ (\boldsymbol{X_{opt}})| \succ |\boldsymbol{K}\ (\boldsymbol{X})|$ for any $\boldsymbol{X} \neq \boldsymbol{X_{opt}}$ where $\succ$ is preference sign. The model parameters $\boldsymbol{X_{opt}}$ identify a trade-off decision possessing to desired efficiency criteria. In our case the model parameters ***Xopt*** identify an optimum working medium having the desired complex of properties (*"tailored" working fluid*). Critical or/and fixed parameters of working fluids are typical examples of the information characteristics of substance linked with its molecular structure.

Attainment of the optimum decision corresponds to the compromise among various criteria and displays the quality of engineering decisions. Criteria of sustainable development cannot be formulated on a strict mathematical basis and always have subjective character. The several approaches for finding the compromise between local criteria and constructions of generalized criterion function were offered. For example, in traditional thermodynamics analysis, the concept exergy or exergy-ecological costs is introduced for monetary and power values. Additive convolution of power (*COP*) and ecological (Global Warming Potential – *GWP*) parameters of efficiency has been offered for the analysis of refrigerating systems in TEWI criterion [4]. A weak point of such approaches is the implicit assumption about conformity of the economic (ecological) and energy efficiency objectives that contradicts a real situation. Finding the compromise actually is a non-trivial decision-making problem and cannot be formalized. There are some ways of transformation of vector criterion in scalar which were discussed earlier [5], [6].

1.2. Multicriteria making decision

Design objectives usually contradict with each other, so that is difficult to provide sustainable solution, which simultaneously satisfies both of them. Meaningful analysis of this ill-structured situation should include uncertainty conception. For the multicriteria problems the local criteria usually have a different physical meaning, and consequently, incomparable dimensions. It complicates the solution of a multicriteria problem and makes it necessary to introduce the procedure of normalizing criteria or making these criteria dimensionless. There is no unique method for the criteria normalizing and a choice of method depends on statement of problem having subjective nature. In the present study, a next sequence of decision-making steps is applied [6].

- Determination of the Pareto optimum (or compromise, or trade off) set $\boldsymbol{X_P}$ as the formal solution of multicriteria problem to minimize uncertainty sources;
- Fuzzification of goals as well as constraints to represent an ill-structured situation;
- Informal selection of convolution scheme to transform a vector criterion into scalar combination of vector components.

Sustainable decision is defined by the Bellman and Zadeh model [7] as the intersection of all local fuzzy criteria and is represented by its membership function μi(X) as follows:

$$\mu_C(X) = \mu_1(X) \cap \mu_2(X) \ldots \cap \mu_n(X)),\ i = 1,2,\ldots,n; \quad X \in X_P \qquad (3)$$

The membership function of the objectives and constraints can be chosen linear or nonlinear depending on the context of problem. One of possible fuzzy convolution schemes is presented below.

– Initial approximation ***X***-vector is chosen. Maximum (minimum) values for each criterion K_i are established via scalar maximization (minimization). Results are denoted as “ideal” points $\{ X_j^0, j = 1 \ldots m \}$.

– Maximum and minimum boundaries for criteria are defined:

$$K_i^{min} = \min_j K_j(X_j^0) = K_i(X_i^0),\ i = 1 \ldots n;\ K_i^{max} = \max_j K_j(X_j^0),\ i = 1 \ldots n. \qquad (4)$$

– The membership functions are assumed for all fuzzy goals as follows

$$\mu_{Ki}(X) = \begin{cases} 0, & \text{if } K_i(X) > K_i^{max} \\ \dfrac{K_i^{max} - K_i}{K_i^{max} - K_i^{min}} & \text{if } K_i^{min} < K_i \le K_i^{max}, \\ 1, & \text{if } K_i(X) \le K_i^{min} \end{cases} \qquad (5)$$

A final decision is determined as the intersection of all fuzzy criteria represented by its membership functions. This problem is reduced to the standard nonlinear programming problem.

1.3. Cycle configurations

Three main configurations of ORC are considered (Fig. 1) for typical working fluids R717, R123, and cyclohexane. The modeling of characteristics of the ORC is based on the First and Second Laws of thermodynamics and described elsewhere [8].

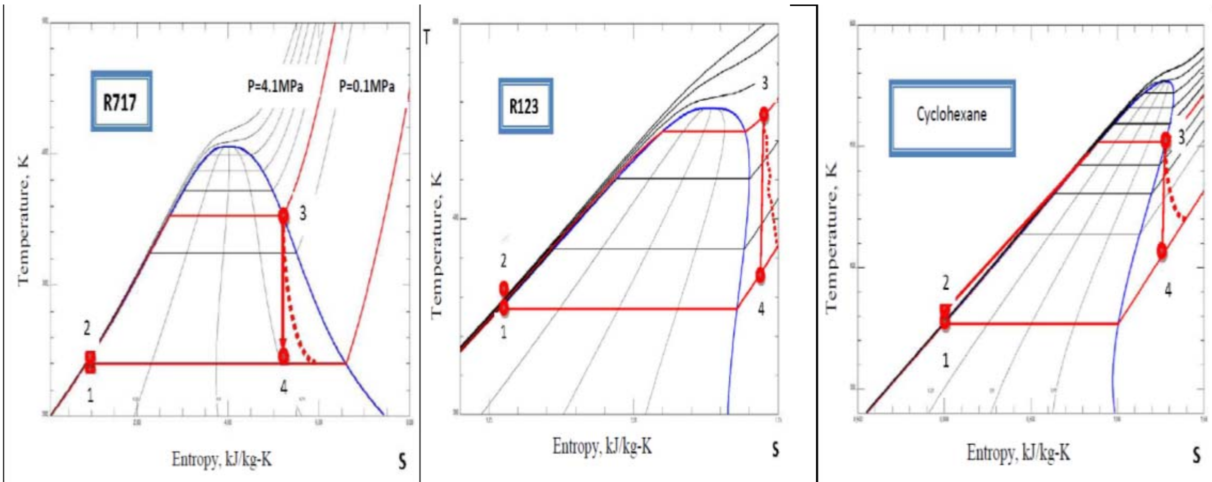

Fig. 1. ORC cycle configurations for different working fluids

2. ORC energy efficiency appraisal via artificial neural networks

Thermodynamic behavior of one-component substances in gas and liquid phases has identical topological structure similar to the cubic equations of state. The reliable quantitative description of a thermodynamic surface can be achieved via similarity theory. From this point of view, critical temperature – T_C and pressure – P_C together with normal boiling temperature – T_B are the most rational parameters which provide correct description of thermodynamic surfaces near the saturation curve.

2.1. Construction of ANN correlations. Results and discussion

To select the ORC working fluid with better properties we need preliminary estimating thermodynamic properties and assessment of different efficiency criteria. To evaluate the cycle performance data the artificial neural networks capable to recognize complex input – output relationships is applied. At first step the training set was used to calculate the main cycle characteristics. In Table 1 temperature boundaries (T_3, T_4) and a range of admissible pressures (*Pmin, Pmax*) which characterize the operating conditions for ORC configurations are given.

ANN represents the mathematical tool which during training allows establishing dependences between input data and target characteristics of any complexity. The purpose of training is to find factors of communications between neurons, which define abilities of a neural network to allocation of the latent relationships between input and output values. After training, the network becomes capable to forecast new data on the basis of the limited sample of known interrelations between input and output values. In this case, we aspire on the basis of the known information on the input T_C, P_C and T_B for restricted set of known substances which are connected by complex relationships with output value – *COP*, to predict energy efficiency of the Rankine cycle for little-studied working fluids only from critical parameters and normal boiling temperature. The ANN correlations for COP (output) as function of critical temperature, critical pressure and normal boiling temperature (input) are built on the REFPROP 8.0 database [9]. The training set consists of 15 components (R134a, R123, R1270, R717, R600a, R290, R245fa, R245ca, R236fa, R227ea, R142b, R125, R113, R22, R32).

Table 1. COP comparison for the organic Rankine cycle with ANN calculations

Working fluid	*Cycle Type*	T_{C}, ^0C	P_{C}, *MPa*	T_{B}, ^0C	T_{3}, ^0C	T_{4}, ^0C	P_{min}, *MPa*	P_{max}, *MPa*	*COP, %,[8]*	*COP, %, ANN*	*RD, %*
R32	A	78.11	57.8	-51.7	31.3	30.0	19.3	20.0	0.36	0.38	-4.5
R32	B	78.11	57.8	-51.7	100.0	97.7	19.3	20.0	0.42	0.44	-4.3
R125	A	66.18	36.3	-48.1	40.1	30.0	15.6	20.0	2.32	2.38	-2.3
R125	B	66.18	36.3	-48.1	100.0	91.9	15.6	20.0	2.36	2.36	0.1
RE125	A	81.34	33.5	-35	100.0	79.0	10.1	20.0	5.77	6.02	-4.3
R134a	A	101.0	40.6	-26.1	67.7	30.0	7.7	20.0	7.74	7.73	0.1
RE134	C	147.1	42.3	5.5	100.0	41.0	2.5	16.6	12.56	12.48	0.7
R143a	A	72.73	37.6	-47.2	43.6	30.0	14.4	20.0	3.14	3.08	1.9
R143a	B	72.73	37.6	-47.2	100.0	87.3	14.4	20.0	3.31	2.98	10.0
R152a	A	113.5	44.9	-24	72.6	30.0	6.8	20.0	8.82	8.78	0.4
R152a	B	113.5	44.9	-24	100.0	53.8	6.9	20.0	9.22	9.27	-0.5
RE170	A	126.8	52.4	-24.8	75.1	30.0	6.7	20.0	9.38	9.29	0.9
RE170	B	126.8	52.4	-24.8	100.0	53.0	6.7	20.0	9.68	9.84	-1.6
R218	C	71.89	26.8	-36.8	58.9	33.6	10.0	20.0	5.22	5.22	0.0
R227ea	C	101.7	29.3	-16.4	83.8	44.2	5.3	20.0	9.20	9.22	-0.2
R236ea	C	139.2	34.1	6.19	100.0	53.9	2.4	15.7	12.02	12.16	-1.1
R245ca	C	174.4	39.2	25.1	100.0	53.7	1.2	9.3	12.79	12.96	-1.3
R236fa	C	125.5	32.0	-1.4	100.0	48.6	3.2	19.3	11.63	11.55	0.6
R245fa	C	154.0	36.4	15.1	100.0	50.7	1.8	12.7	12.52	12.51	0.1
RE245mc	C	133.6	28.9	5.59	100.0	54.5	2.4	14.9	11.84	11.82	0.2
RC270	A	124.6	54.9	-31.5	100.0	41.6	8.2	20.0	8.86	8.62	2.7
R290	A	96.65	42.5	-42.1	57.1	30.0	10.7	20.0	5.91	5.91	-0.1
R290	B	96.65	42.5	-42.1	100.0	76.0	10.7	20.0	6.11	6.18	-1.2
RC318	C	115.2	27.8	-6	98.9	54.7	3.6	20.0	10.97	10.69	2.6
RE347mc	C	164.5	24.8	34.23	100.0	56.4	3.6	20.0	11.72	11.22	4.3
R600	C	152.0	38.0	-0.5	100.0	48.4	2.8	15.3	12.58	12.53	0.4
R600a	C	135.0	36.5	-11.7	100.0	45.3	4.0	20.0	12.12	12.11	0.1
R601	C	196.5	33.7	27.8	100.0	57.7	0.8	5.9	12.91	12.87	0.3
R601a	C	187.7	33.9	36.1	100.0	58.4	1.1	7.2	12.75	12.75	-0.0
R1270	A	92.42	46.7	-47.7	48.5	30.0	13.1	20.0	4.28	4.28	-0.1
R1270	B	92.42	46.7	-47.7	100.0	81.2	13.1	20.0	4.53	4.16	8.2
C5F12	C	148.8	20.4	29	100.0	72.7	1.04	7.6	10.49	10.49	0.0
CF3I	A	123.3	39.5	-21.9	85.2	30.0	5.6	20.0	10.63	10.68	-0.5
CF3I	B	123.3	39.5	-21.9	100.0	39.6	5.6	20.0	10.93	10.93	-0.0
n-hexane	C	234.7	30.1	341.8	100.0	61.9	0.2	2.5	13.00	13.00	0.0

The construction of ANN includes the following sequence of actions: a choice of initial data for training; a choice of architecture of a network; dialogue selection of ANN parameters; process of training; check of adequacy of training (validation); and forecasting. Calculations were performed in Matlab Neural Network Toolbox environment (**http:**//www.mathworks.com). The back propagation algorithm has been used for ANN training. Output values in the initial sample were calculated for various configurations of cycles based on thermodynamic properties as reported in [8]. As input values the given T_C, P_C and T_B are used. The various architectures of neural networks with different neuron numbers and activation functions in the first and second layers were considered. The third layer of a network always contains one neuron with linear active function.

For configuration A two hidden layers were used. The first contained two neurons and the second – one. As activation function the hyperbolic tangent was used. The training sample data for working fluids R125, R143a, R32 and R1270 were chosen. Testing was done for R152a, CF3I, and RE170. Check of adequacy was done for R290 and R134a. Results are listed in Table 1.

For configuration B two hidden layers were used. The first contained five neurons and the second – one. As activation function the hyperbolic tangent was used. As training sample data for working fluids R125, R143a, R152a, and RC270 were used. Testing was performed for RE125, R1270 CF3I and RE170. Check for adequacy was considered for R32 and R290. Results are listed in Table 1.

Construction of an artificial neural network for a configuration C coincides with architecture of a network for a configuration B. Training sample included the following working fluids: R218, R236fa, RE245mc, C_5F_{12}, R600, R601a, and n-hexane. Testing was done on the set of substances: R227ea, R236ea, RE134, R245fa RE347mcc, R601, and final verification accordingly for RC318, R600a, and R245ca.

Results of COP calculation for different ORC configurations are given in Table 1. Deviations of "experimental" values of COP [8] from calculated by means of the trained artificial neural network are within the error of calculations via the multi-constant equations of state [10] – [12]. Appreciable deviations of a relative error (more than 5 %) are observed for low COP values that have no principal meaning because we are interested by the working fluids with the maximal power efficiency.

The organic Rankine cycle for the class of working fluids based on the hydrofluoroethers (HFE) is considered to demonstrate a proposed approach. Critical properties of HFEs were taken from Ambrose *et al* [13]. Flammability indices correlated to atomic species by simple ratio of fluoride (n_F) and hydrogen (n_H) atoms $\Psi = n_F/(n_F+n_H)$ are given in Table 2. The normal boiling points for HFEs were restored from Murata *et al*. correlations [14]. Temperature boundaries were taken for configuration A in range 300…315K.

To select the trade-off working fluid the membership functions (5) for energy efficiency (μ_{COP}) and ecological safety (μ_{GWP}) as function of critical parameters were calculated at following assumptions: $COP^{max} = COP^{Carnot}$; $COP^{min} = 3.64$ and $GWP^{max} = 500; GWP^{min} = 0.$ Flammability index ($\Psi > 0.7$) was considered as constraint. Intersection of membership functions defines the compromise solution for each HFEs under consideration. Final decision is chosen after comparison of compromise solutions with flammability index.

The *COP* comparison among the ORC with HFE working fluids (Table 2) shows the maximum value 4.1% for $C_5H_2F_6O_2$ and minimum *COP* – 3.6% for C_2HF_5O. The energy efficiency of HFE – $C_5H_2F_6O_2$ looks more attractive among widespread industrial HFEs: HFE-125 (CF_3OCF_2H), HFE-134 (CHF_2OCHF_2) HFE-143a (CF_3OCH_3), HFE-227me ($CF_3OCFHCF_3$), HFE-245mf ($CF_3CH_2OCF_2H$), HFE-245mc($CF_3CF_2OCH_3$),HFE-254pc ($CHF_2CF_2OCH_3$), HFE-356mec ($CF_3CHFCF_2OCH_3$), HFE-356mff ($CF_3CH_2OCH_2CF_3$), HFE-7000 (HFE-347mcc) (n- $C_3F_7OCH_3$), HFE-7100 (HFE-449mccc) ($C_4F_9OCH_3$), (HFE-

449mccc) ($C_4F_9OCH_3$), and HFE-7200 (HFE-569mccc) ($C_4F_9OC_2H_5$). The $C_5H_2F_6O_2$ flammability index is also appropriate ($\Psi = 0.75$) but near limiting value 0.7.

Table 2. Critical parameters, COP, and flammability index for hydrofluoroethers

Working fluids	*M, gmole^{-1}*	*T_c, K*	*p_c, MPa*	*ρ_c, g cm^{-3}*	*Z_C*	*Ψ*	*COP,%*
C_2HF_5O	136.021	354.49	3.35	0.579	0.267	0.83	3.64
$C_2H_2F_4O$	118.030	420.25	4.23	0.529	0.270	0.67	3.94
$C_2H_3F_3O$	100.040	498.50	4.82	0.485	0.240	0.50	3.94
C_3F_6O	166.022	361.90	3.06	0.610	0.277	1.00	3.64
$C_3F_8O_2$	220.018	372.40	2.33	0.610	0.271	1.00	3.65
C_3HF_7O	186.028	387.80	2.62	0.550	0.275	0.88	3.75
$C_3H_2F_6O$	168.038	428.90	3.04	0.553	0.269	0.75	3.94
$C_3H_3F_5O$	150.047	462.03	3.54	0.553	0.259	0.63	3.94
$C_3H_3F_5O$	150.047	406.82	2.89	0.500	0.256	0.63	3.92
$C_3H_5F_3O$	114.066	449.05	3.51	0.412	0.260	0.38	3.94
C_4F_8O	216.029	400.00	2.69	0.680	0.257	1.00	3.89
$C_4F_{10}O$	254.026	391.70	1.87	0.630	0.232	1.00	3.75
$C_4HF_7O_2$	214.038	452.88	2.87	0.597	0.273	0.88	3.94
$C_4HF_7O_2$	214.038	435.06	2.65	0.569	0.275	0.88	3.94
C_4HF_9O	236.036	412.63	2.26	0.499	0.311	0.90	3.93
$C_4H_2F_8O$	218.045	421.60	2.33	0.533	0.272	0.80	3.94
$C_4H_2F_8O$	218.045	444.63	2.57	0.581	0.261	0.80	3.94
$C_4H_2F_8O_2$	234.045	449.81	2.41	0.571	0.265	0.80	3.94
$C_4H_3F_5O$	162.058	455.03	2.91	0.486	0.258	0.63	3.94
$C_4H_3F_7O$	200.055	455.10	2.77	0.576	0.255	0.70	3.94
$C_4H_3F_7O$	200.055	437.60	2.48	0.530	0.257	0.70	3.94
$C_4H_3F_7O$	200.055	433.21	2.55	0.542	0.261	0.70	3.94
$C_4H_3F_7O$	200.055	463.89	2.71	0.541	0.260	0.70	3.96
$C_4H_4F_6O$	182.064	459.60	2.70	0.481	0.267	0.60	3.95
$C_4H_4F_6O$	182.064	476.31	2.78	0.500	0.256	0.60	4.03
$C_4H_5F_5O$	164.074	431.13	2.53	0.448	0.258	0.50	3.94
$C_5F_{10}O$	266.037	427.00	1.90	0.600	0.237	1.00	3.82
$C_5H_2F_6O_2$	208.059	485.10	2.77	0.720	0.198	0.75	4.11
$C_5H_2F_{10}O$	268.053	447.40	2.14	0.582	0.265	0.83	3.84
$C_5H_3F_7O$	212.066	476.55	2.58	0.538	0.256	0.70	4.03
$C_5H_3F_7O$	212.066	467.64	2.52	0.518	0.266	0.70	4.00
$C_5H_3F_9O$	250.062	475.74	2.23	0.563	0.251	0.75	3.90
$C_5H_3F_9O$	250.062	462.72	2.37	0.558	0.276	0.75	3.93
$C_5H_3F_9O$	250.062	473.01	2.24	0.550	0.259	0.75	3.90
$C_5H_5F_5O$	176.085	475.54	2.64	0.494	0.238	0.50	4.05
$C_5H_5F_7O$	214.081	481.54	2.38	0.497	0.256	0.58	3.92
$C_6H_3F_9O$	262.073	498.97	2.20	0.520	0.267	0.75	3.82
$C_6H_3F_{11}O$	300.070	486.48	1.95	0.567	0.255	0.79	3.89
$C_6H_5F_9O$	264.089	482.02	1.98	0.518	0.251	0.64	3.90

2.1. Conclusions

Fuzzy set approach is powerful tool to finding of compromise among energy efficiency, environmental constraints and economic indices of working media in conceptual RET design. In this work, criteria of sustainable development for renewable energy technologies of transformation low potential sources of heat into work on the basis of the ORC were developed. For search of new working fluids, which have no information on thermodynamic behavior, ANN approach is proposed to forecast energy efficiency of the Rankine cycle. On the basis of the limited data about critical parameters and normal boiling temperature of substances for various configurations of cycles, the values of COP are determined without the calculation of thermodynamic properties.

This study is one of first attempts to apply methodology of tailored substances to selecting optimum working fluid for ORC. Construction of ANN correlations between information characteristics of working fluids and criteria of efficiency of Rankine cycle narrows the area of compromise search in the space of competitive economic, environmental and technological criteria.

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Interactions between selected energy use and production characteristics of German manufacturing plants

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Abstract: This paper analyzes the interactions between a number of key energy characteristics of German industrial plants in 2006, using an exceptionally rich dataset comprising more than 44 000 plants. Already by using basic descriptive statistical techniques we find that larger energy users tend to use energy less efficiently. This correlation is particularly prevalent in sectors with high energy intensity. We identify an energy mix effect as the main driver of this interrelation, since larger energy consumers tend to use less electricity in relation to other fuels, and electricity can be deployed more efficiently. The energy mix effect is also one of the reasons behind a negative correlation between energy intensity and the emission factor. From the correlation between plant-level energy intensity and gross output, we infer on the existence of increasing and decreasing returns to energy. We identify increasing returns to energy in most sectors, but decreasing returns to energy in some of the particularly energy intensive sectors.

Keywords: *Energy intensity, Emission factor, Manufacturing, Microdata*

1. Introduction

The industry sector[1] is a major energy consumer and it is receiving growing attention from researchers and politicians, who see it as a prominent battle ground in the fight against climate change, resource scarcity and energy insecurity. According to IEA data for 2006 [1][2], the German industrial sector Germany is responsible for 22 % of total final energy use and 15 % of CO_2 emissions. As the industry sector is fundamental for economic growth and employment in most countries, politicians are reluctant to cut industrial energy use by limiting the overall size of the industry sector. Consequently, policy initiatives mostly aim at boosting industrial energy efficiency and reducing the average carbon factor of energy inputs. Recent examples of policies in Germany include, amongst others, the "Heat-Power Cogeneration Act", the Ecological Tax Reform and the "Large Combustion Plant Directive". The effectiveness of such measures, however, is limited by economic and technological restrictions inherent to the industry sector, and a thorough understanding of these restrictions is vital for policy design. In particular, energy intensity[2] and total energy use are not independent of each other. Several effects link a plant's level of energy use and energy intensity.[3] Conceptually, these effects can result in either a positive or a negative correlation between the two measures.

For example, if the amount of energy needed to produce the last unit of output decreases with rising energy use, larger energy users would on average use energy more efficiently. Such *increasing returns to energy* would imply a negative correlation between energy intensity and energy use. Conversely, in the case of *decreasing returns to energy*, the amount of energy

[1] We define the industry sector as the mining, quarrying and manufacturing sectors with ISIC codes C and D.
[2] We use energy intensity as an inverse measure of energy efficiency and calculate it as the ratio between total energy use (in kWh) of a plant and gross output (in 1000 EUR) of a plant. The use of gross output instead of value added which accounts for inputs is dictated by data availability. See Petrick et al. [3] for further discussion of this issue.
[3] The existing literature on the interaction between energy use and energy intensity as well as their determinants is widely ramified. Since a comprehensive review of the existing literature is beyond the scope of this paper, the reader is referred to the excellent review by Gillingham et al. [4] and the references given therein.

needed for the last unit of output increases with rising output, and energy intensity and total energy use would be positively correlated. Note that in both cases a correlation between energy intensity and output is also implied. In the first case, a (ceteris paribus) concave demand function for energy implies a negative correlation between energy intensity and output, while in the second case the demand function is convex and energy intensity and output are positively correlated.[4] In either case the effect of returns to energy can be distorted by an *energy mix effect*. We hypothesize that with rising overall energy use, the composition of plants' energy mixes changes and, in particular, the share of primary fuels, such as natural gas or coal, rises at the cost of the share of electricity and other processed fuels. Since electricity can be used more efficiently than primary fuels (with regards to output per used kilowatt hour), overall energy intensity is (ceteris paribus) expected to decrease with a rising electricity share and thus to increase with a rising fuel use due to the energy mix effect.

Apart from the interaction between total energy use and energy intensity, we analyze the link between energy use, energy intensity and the plant-specific emission factor, i.e. the ratio between CO_2 emissions (in t) and energy used (in kWh). At first glance it appears that exceptionally efficient energy users also try to minimize their carbon footprint (in part in response to policy) since plants with advanced technology are more likely to be both efficient and clean. At second glance, however, the energy mix effect might distort this picture; because the carbon factor of electricity is high due to conversion losses. The energy mix effect could thus lower the emission factor with increasing energy use and increasing energy intensity. To combine the interactions between efficiency of energy use and the carbon factor, we complement this part of the analysis with findings about a plant's carbon intensity, defined as the ratio of CO_2 emissions per gross output (in g/1000 EUR).[5]

In this paper we analyze the impact of returns to energy and energy mix effects on the link between energy use and energy intensity by measuring the net correlation between energy use and energy intensity. We also analyze the link between energy and carbon intensities as well as the plant specific emission factor in order to answer the question whether more efficient

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[4] To understand why increasing returns to energy imply a negative interrelation between output and energy, consider a production function that abstracts from all other production factors. Such a production function *y=f(e)*, where *y* is the output und and *e* is the production factor energy, exhibits increasing returns to energy if it is convex. The implied factor demand function *e=g(y)* is the inverse of the production function and concave, i.e. the second derivative is negative. From the factor demand function, energy intensity (denoted *eint*) can be derived as a function of output:

$$\text{eint} = \frac{g(y)}{y} \tag{1}$$

The sign of the derivative of *eint* with respect to *y* depends on the sign of the difference between marginal productivity and average productivity:

$$\frac{d\,\text{eint}}{dy} > 0 \quad \Leftrightarrow \quad g'(y) - \frac{g(y)}{y} > 0 \tag{2}$$

Since the second derivative of the factor demand function is negative, average factor demand will always be larger than marginal factor demand – which is exactly the intuition of increasing returns to energy (we assume that the Inada conditions hold). Thus, in the case of increasing returns to energy, the interrelation between energy intensity and output should be negative. In the case of decreasing returns to energy, the implied factor demand function would be convex, and the same argument (with exchanged sign) would hold – in the case of decreasing returns to energy, the interrelation between energy intensity and output should be positive.

[5] The same caveat as in the case of energy intensity applies, cf. footnote 2.

plants are also cleaner. To get a better picture of the differences between sectors, we present results not only at the aggregate level, but also for selected sectors of particular interest.

2. Data and Methodology

This paper is part of a research project that uses an exceptionally rich dataset, parts of which have only recently been made available by a research data centre of the German Official Statistics. The "AFiD panels"[6] are a collection of microdatasets comprising observations at the plant and enterprise level for various sectors, including industry. For this paper we use the panel "Industrial Plants" [5] in combination with an energy use module [6]. The combined dataset contains annual observations for up to 68 000 industrial plants per year from 1995 to 2006. In this paper we concentrate on the most recent cross section and use 2006 data, comprising 44 080 plants. An important feature of the data at hand is that it is based on a mandatory survey that each plant with more than 20 employees is required to answer. Thus, the degree of representativeness of our dataset is exceptionally high.[7] A more detailed description including a list of all variables included in the datasets as well as information on the underlying statistics can be found in Petrick et al. [3].[8]

To analyze the interrelation between the energy and production characteristics, we use basic correlation analysis. We calculate Spearman's rank correlation coefficients for all plants in the dataset as well as for selected sectors that are particularly interesting with regards to their energy use patterns. We use Spearman's correlation coefficient instead of Pearson's in order to minimize sensitivity to outliers. However, results based on Pearson's correlation coefficient can be obtained from the authors on request.

3. Results

To study the link between total energy use and energy intensity as well as the underlying mechanisms, we begin with the aggregate effect. For the German industry as a whole we find a strong and significant positive correlation between energy use and energy intensity (Table 1). This implies a negative correlation between energy use and energy efficiency which could be explained either by decreasing returns to energy for energy or by a fuel mix effect.

At the aggregate level, it is not clear whether this correlation is driven mainly by differences between plants or between sectors. Since energy intensive sectors like the cement, glass and ceramics, paper or metal manufacturing industries are responsible for the lion's share of overall energy consumption, plants in these sectors are also large energy users. This is confirmed by Petrick et al. [3], who isolated the heterogeneity between different sectors by calculating the correlation between the sector medians of total energy use and energy intensity.[9] To control for cross-sectoral heterogeneity in this paper, we compute correlation measures within sectors (see Figure 1). We find that energy intensity and total energy use of plants are positively correlated also within sectors. The correlation is particularly strong in sectors that are highly energy intensive, like the paper and pulp, glass and ceramics, mineral

[6] AFiD: "Amtliche Firmendaten für Deutschland", English: Official Firm Data for Germany.

[7] In the process of data cleansing we drop plants with an annual turnover below 10 000 EUR and those that reported an electricity consumption of zero. In 2006, 3 586 out of 47 666 plants were dropped.

[8] Presentation of results is limited by the legal requirement to preserve the confidentiality of data on individual plants. For this reason, all research output has to be approved by staff at the research data centre before publication.

[9] Aiming to get results that are robust towards large differences between different plants of different sectors is one reason why we use Spearman's rank correlation coefficient instead of Pearson's correlation coefficient.

processing (incl. cement) or iron and steel sectors. Since energy use and carbon emissions (and also energy intensity and carbon intensity) are highly correlated, we also find a positive correlation between carbon emissions and energy intensity, as well as between carbon intensity and energy use (Table 1).

Table 1. Spearman's rank correlation coefficients for selected variables at the plant level (2006 data).

	Energy use (kWh)	Energy intensity (kWh/1 000 EUR)	CO_2 emissions (t)	Carbon intensity (g/1 000 EUR)	Emission factor (g CO_2/kWh)	Share of electricity in total energy use (%)
Energy intensity (kWh/1 000 EUR)	0.60					
CO_2 emissions (t)	> 0.9	0.58				
Carbon intensity (g/1 000 EUR)	0.59	> 0.9	0.61			
Emission factor (g CO_2/kWh)	-0.15	-0.20	-0.02	-0.01		
Share of electricity in total energy use (%)	-0.14	-0.21	(-0.01)	-0.03	> 0.9	
Gross Output (1 000 EUR)	0.68	-0.09	0.69	-0.08	(-0.01)	-0.01

Own calculations. In cases of ">0.9" the exact value is not available to ensure confidentiality of the data. Coefficients in brackets are not significant at the 1 % level.

While increasing returns to energy should allow larger plants to use energy more efficiently, this is obviously not the case in the data, either because there are no increasing returns to energy or because increasing returns to energy are outweighed by a counteracting fuel mix effect, as described in section 1. To shed more light on this issue, we study the correlation between energy intensity and gross output. Aggregated across all sectors, we find a statistically significant but very weak positive correlation. This picture becomes more diverse as we look at the correlation in specific sectors (Figure 1). In energy intensive sectors, namely in the paper and pulp, glass and ceramics, mineral processing as well as iron and steel sectors, correlation between energy intensity and gross output is positive, indicating decreasing returns to energy. Notable exceptions among the energy intensive sectors are the mining, quarrying, chemicals as well as the non-ferrous metals and foundries sectors. In most other sectors energy intensity and gross output are negatively correlated, indicating increasing returns to energy. Nevertheless, since the correlation coefficient does not usually exceed 0.25 in absolute value and the correlation between energy intensity and gross output is only a rough indicator, the impact of increasing or decreasing returns to energy seems to be limited.

Apart from increasing and decreasing returns to energy, we earlier identified an energy mix effect as another potential driver linking energy use and energy intensity. As the negative correlation between the share of electricity in the energy mix and total energy use of a plant illustrates, excessive energy users tend to use relatively little electricity but rely more on other fuels (Table 1 and Figure 1). Natural gas is especially important as an alternative; in certain cases also coal (e.g. in the iron and steel sector, the mineral products sectors or the mining and quarrying sectors) or renewables like biomass (the pulp and paper sectors are one example; cf. Petrick et al. [3]). Since electricity is already a highly processed fuel, it can be employed very efficiently – energy intensity and the electricity share in a plant's fuel mix are negatively correlated, both at an aggregated and mostly also at the sectoral level (Figure 1). Note that the correlation coefficients for electricity share and energy intensity as well as for the electricity share and total energy use are much larger than the correlation coefficient for energy intensity and gross output, in most sectors and at the aggregate level. From this we infer that the strong positive correlation between energy use and energy intensity found at the sectoral and aggregate level is mainly driven by the energy mix effect: with rising overall energy use the share of electricity in a plant's fuel mix decreases. Since electricity can be used rather efficiently, overall energy intensity is expected to rise accordingly.

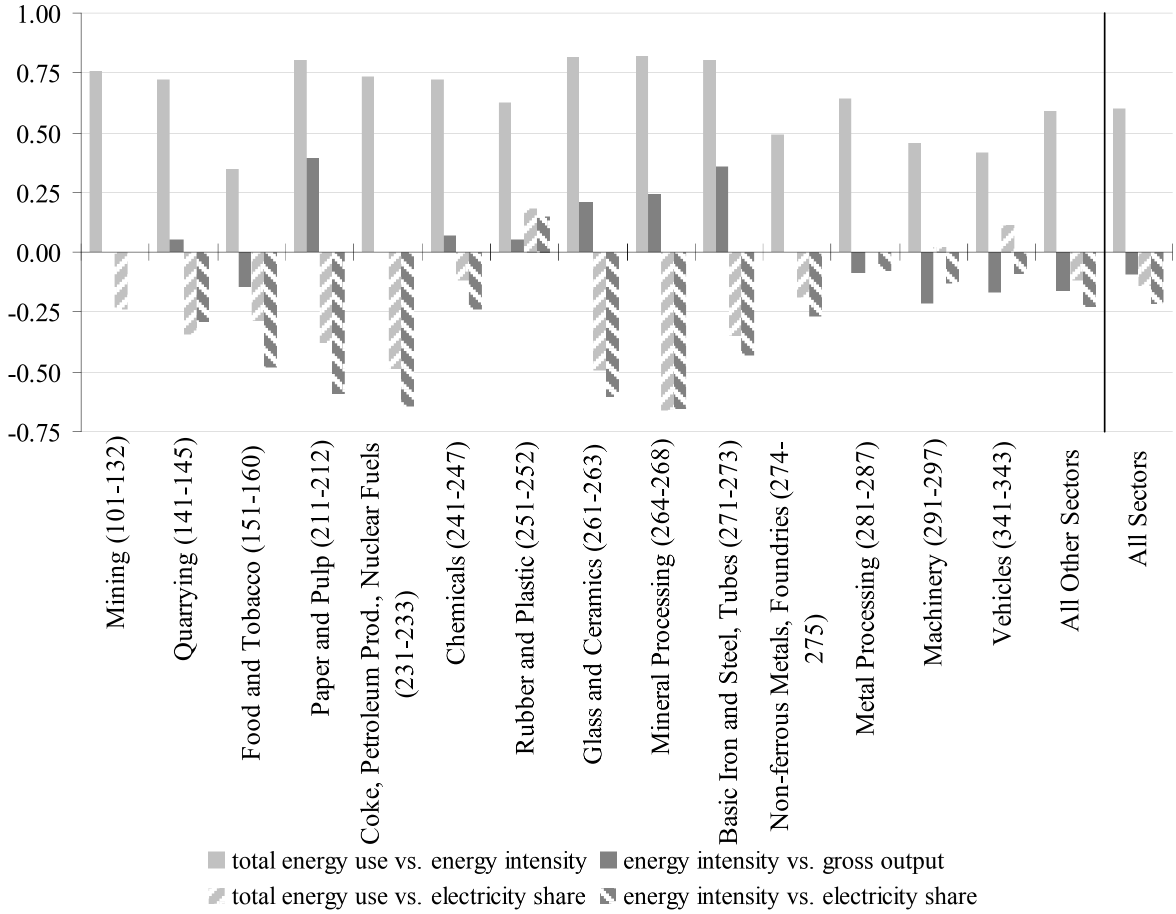

Figure 1. Spearman's rank correlation coefficients between selected variables within sectors (2006). Only coefficients that are significant at the 1 %-level are shown. The three-digit sector identifiers refer to the corresponding ISIC codes.

Apart from the link between total energy use and energy intensity, we also analyze the mechanisms linking energy use – and thus energy intensity – and the emission factor. The emission factor (or carbon factor) is the ratio of emitted CO_2 from fuel combustion per unit of energy (in g CO_2/kWh). We find a statistically significant negative correlation between emission factor and energy use as well as energy intensity (Table 1). The link between energy intensity and emission factor stands out in particular. Contrary to intuition, more energy efficient plants actually use a dirtier fuel mix in the sense of a higher carbon factor. This result not only holds for all sectors in general, but also for most individual sectors, especially for the energy intensive ones, with the exception of the rubber and plastics sector (Figure 2).

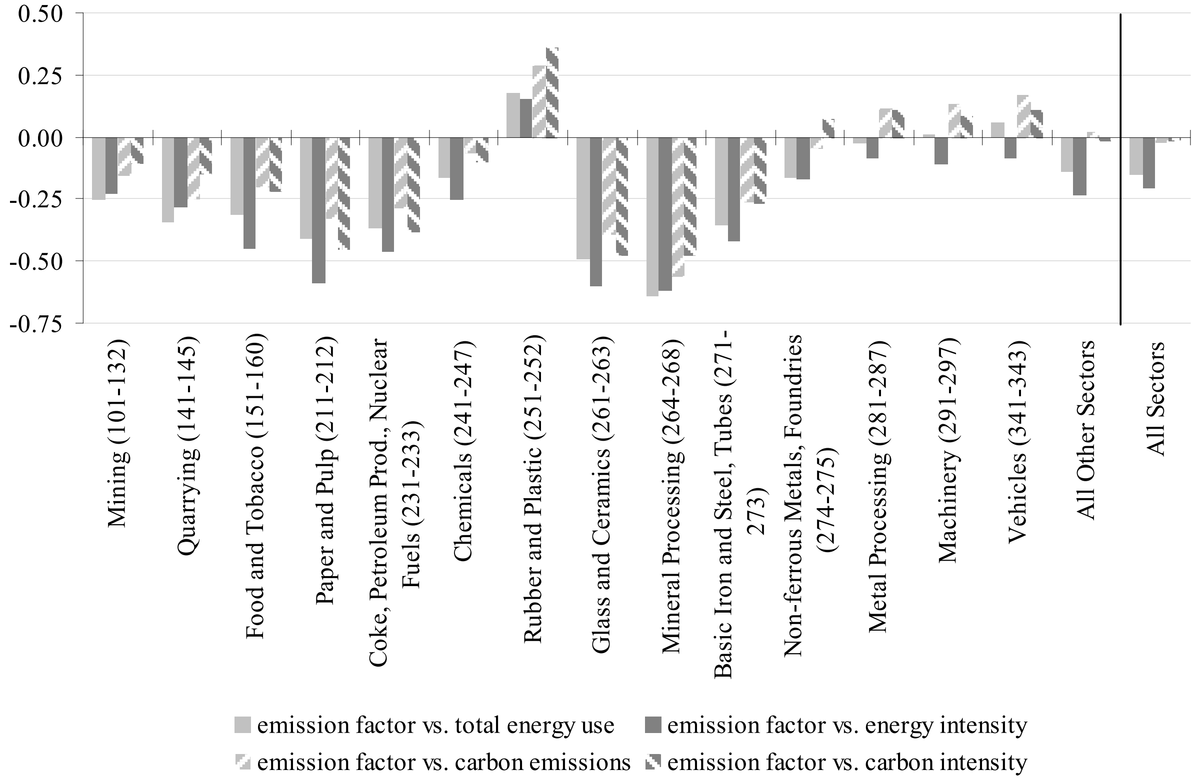

Figure 2: Spearman's rank correlation coefficients between emission factor and selected variables within sectors (2006). Only coefficients that are significant at the 1 %-level are shown. The three-digit sector identifiers refer to the corresponding ISIC codes.

To understand this paradox, it is vital to understand the role of electricity. As mentioned before, electricity can be used very efficiently, but at the same time its emission factor is high due to conversion losses in the energy conversion sector. In fact, the 2006 carbon factor for electricity was 2.9 times the carbon factor of natural gas and still 1.7 times the carbon factor of hard coal.[10] Consequently, a production technology that uses a lot of electricity may be very energy efficient, but since the carbon factor of electricity is very high, the carbon efficiency advantage of that technology may be smaller than the energy efficiency advantage relative to a technology less intensive in electricity. These two opposing effects also account for a low correlation between the emission factor and carbon intensity for some sectors and for the aggregate of all sectors (Figure 2). Some particularly energy intensive sectors, like the glass and ceramics sector, the mineral processing sector or the paper and pulp sector, are exceptional here. In these cases energy intensity and emission factor are especially highly correlated, implying that the energy efficiency advantage of using electricity is particularly large (cf. also the correlation between energy intensity and electricity share for these sectors from Figure 1). In fact, it is large enough to outweigh the carbon factor disadvantage, leading to the paradoxical situation of a high emission factor together with low carbon intensity.

[10] The carbon factor of electricity in 2006 was 585 g per kWh. It is calculated for the average German electricity mix as the ratio of all direct CO_2 emissions from fossil fuel combustion divided by the available electricity supply. Thus, different emission factors for the primary fuels used by the power plants are accounted for, but indirect emissions through production and transport of the primary fuels are not accounted for (own calculations on the basis of AGEB [7] and Umweltbundesamt [8]).

The same argument explains why larger energy consumers have lower emission factors, both across and within sectors. Since plants that use more energy tend to rely less on electricity, they do not have to shoulder the burden of conversion losses in their specific emission factor. At the same time, their energy intensity tends to be higher. The two effects partly offset each other and the effect of the emissions factor on total CO_2 emissions is small, although still negative, with the same aforementioned exceptions (Figure 2).

4. Discussion and Conclusions

In this paper we use new microdata on 44 000 industrial plants to analyze the use of energy in industrial production in Germany. Our dataset allows for the analysis of plant-level energy use and emission patterns with extraordinary detail, accuracy and representativeness. Since the dataset also includes information on the plants' monetary gross output, we are able to draw conclusions not only about the level, but also about the productivity of industrial energy use in Europe's largest economy.

We find that energy use and energy intensity are positively correlated, both at the aggregate level and within specific sectors, i.e. larger energy users tend to use energy less efficiently. This correlation is especially high for sectors with high energy intensity. We identify an energy mix effect as the main driver of this interrelation, since larger energy consumers tend to use less electricity in relation to other fuels, and electricity can be deployed more efficiently. Increasing and decreasing returns to energy are of less importance and not uniform across sectors. By means of the correlation between energy intensity and gross output, we identify increasing returns to energy in most sectors, but decreasing returns to energy in some of the particularly energy intensive sectors. The energy mix effect is also one reason for a negative correlation between energy intensity and the emission factor, since energy efficient plants tend to use more electricity, which has a comparably high emission factor. The efficiency advantage of electricity is outweighed by a carbon factor disadvantage, at least for industry as a whole.[11]

Our paper sheds light on the crucial role of electricity. Despite the fact that electricity is often seen as a climate friendly alternative in industrial production in the public discussion, we find that the carbon burden from conversion inefficiency in the power producing sector usually leads to higher emissions in end use. Nonetheless, it would be hasty to discard the emission saving potential of electricity in industrial final energy use in future policies because the emission factor of electricity is decreasing over time (Figure 3). In 1995, the emission factor of electricity was 694 g CO_2/kWh, i.e. 110 g more than in 2006. Once the share of low-carbon fuels and renewables in electricity generation is sufficiently high, their emission-reducing effect might outweigh the detrimental effect of conversion losses. Technological progress is also working in favor of electricity, enhancing not only end use efficiency but also conversion efficiency in the power sector. This adds to the many other arguments for using electricity in the industrial sector, such as the high flexibility of use, resilience towards supply insecurities because of substitutability of primary fuels and ease of handling.

On balance, this paper has shown that the plant-level energy mix, energy intensity and level of energy use are not independent of each other. Hence, it is important to take into account the energy mix when designing policy measures targeted at reducing energy intensity.

[11] A note of caution is advised with regard to the methodology. We focus on absolute correlations that should not be interpreted as causal relationships. Analysis of partial correlations, e.g. via regression analysis, is left as a task for future research.

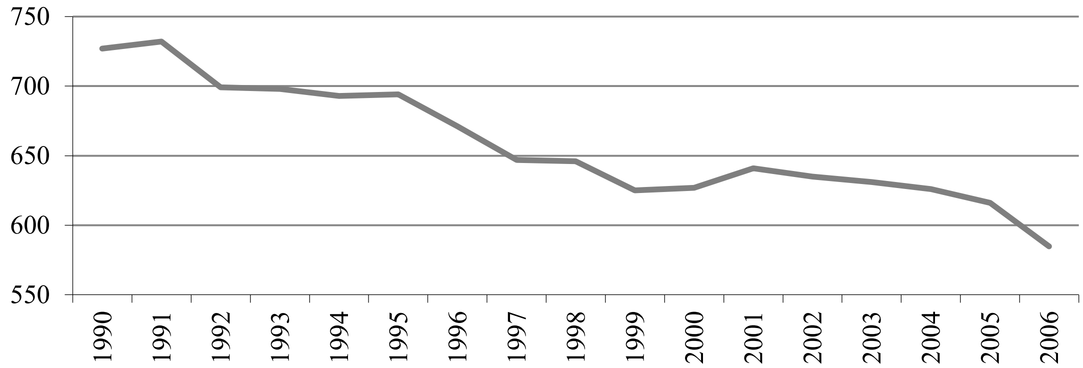

Figure 3: Development of average emission factor of electricity in the German public grid (in g CO_2/ kWh). Source: 1995-2005:Umweltbundesamt [9], 2006: own calculations based on the same source.

Acknowledgements

We would like to thank Alexander Vogel of the research data centre in Kiel for running the estimation code and performing the confidentiality checks. The staff of the research data center of the Statistical Offices of the Länder made the data provision possible. Ulrich Wagner gratefully acknowledges financial support from the Spanish Ministry for Science and Innovation under grant SEJ2007-62908.

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Robin Hood and Donkey Principles: renewable energy proposals for Ghana

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Abstract: This study proposes a reliable way of distribution and transfer of electricity cost to both the urban and rural consumers in Ghana. While the Robin Hood principles borrows the essence of the strategy used in this model by a British folklore character by the same name, in providing resources for the deprived and in this context an equitable demand and supply of electricity. The Donkey principle highlights the strategic billing policy used in Ghana, which suggests that urban communities should carry some of the cost burden of energy used by rural communities. The study aims at promoting strategies and educating the public on realistic solutions to the energy crisis. In Ghana, people in the rural communities lacks credit to afford almost any form of renewable energy system due to irregular source of income, although the bulk of consumables (agro based) are produced by them. Infrastructure in some rural communities is inadequate. In contrast, majority of the urban dwellers have access to credit and spend a reasonable amount of their earnings on electricity primarily focused on business and leisure. The study also addresses cost, motive, frequency and reasons for acquiring and using a secondary source of energy (SSE). The results of the study suggest a more just and equal system of distribution and billing of electricity cost.

Keywords: *Robin Hood, Donkey, Secondary Source of Energy (SSE), Distribution, Ghana*

1. Introduction

Rapid increase in population and increased material consumption always has its toll on the general resources of any given economy. Energy seen as the bedrock of every society is vital for a growing economy to flourish. In Ghana, many rural sectors do not have access to electricity[1, 4, and 8]. The government often spread out the hope of embarking on an extensive electrification project. However, lack of capacity, quality planning and sound framework always turns up to become the "Achilles´ heel" in economic development and environmental sustainability. For those rural areas that are accessible to the national electricity grid, lack of technical and economic capacity undermines the efficiency and reliability of systems; these are plagued with unauthorized excessive power failures making it impossible for the citizens in these communities to be able to utilize the full potential of the energy to increase productivity.

Over the years, there have been advocacy for a solar home solution (SHS) for the rural communities of developing countries. As thoughtful as some of these arguments and proposed models might sound, they most often than not miss the point in their generalization of systematically unproven panacea for the entire energy situation in all rural communities in developing countries. These experts end up re-grouping at the *theory-formulation* table to either revise their theories or come up with newer perceived solutions convinced that it would work the next time round.

For instance, Srinivasan[7] proposed pre-payment system as a way to curb SHS acquisition defaults as well as enhance the degree of acquisition in the rural communities. As laudable as the proposal is, it seems to ignore or did not anticipate some factors that have direct or indirect influence in such systems. To date, many energy service providers in developing countries have battled the complex nature of the process of prepayment and its collection system, thus meriting a careful scrutiny. It is noteworthy to examine some of the impacting factors, which include but not limited to a country´s infrastructure (*accessibility to internet and related mobile service that are essential support systems for pre-payment mode as well as reliable banking and financial institutions willing to provide credit for the needy*), economic and social configuration, per-capita income with special emphasis on individual/household income, the reliability of such income and its purchasing power as well as levels and classifications of such income and its determinants in developing countries. Moreover, administrative logistics and its bottlenecks which includes cost of personnel to inaccessible rural communities' makes pre-payment difficult and inaccessible for many people.

2. Definitions and Limitations

The social background of the principle: In most developing countries, the urban communities enjoy a relatively large percentage of the national cake in the forms of basic amenities and infrastructures like roads, access to good drinking water, affordable housing, and a reasonable access to modern health care unlike their rural counterparts. The situation compounds with an ongoing problem in that most of the rural communities have to contend and be content with an under-developed agro-based industry. This agro-based industry lacks proper incentives to help them add value to their produce. Inadequate infrastructure in the context of storage facilities as well as good transport network exposes these rural dwellers to opportunist intermediaries who offer to take their produce at less than the realistic market price. Consequently, rural economic development often stalls since they lack enough compensation for their hard work resulting in their inability to save some of their earnings – thus the typical cyclical nature of poverty.

The Robin Hood principle: This principle denotes taking from the rich and giving to the poor thus becoming a proposed model recommended by this study to help policy makers to resolve energy distribution for both urban and rural sectors of the Ghanaian economy[2, 3]. The concept of 'taking' in the principle denotes 1) weaning the urban dwellers off the main grid to help allocate the excess capacity to the rural areas. The urban dwellers are then encouraged to 2) adapt to renewable energy systems. Since there are few industrial activities in the rural areas and the need of the energy are simple, the benefits of this proposal become sound because the rural communities get the needed opportunity to develop the agro-base sector, creating jobs and mitigating the rural – urban migration influx. The Robin Hood principle also presumably suggests that most urban dwellers are in better position to afford renewable energy arguably due to access to credits and loans from financial institutions[6].

The Donkey principle: Donkeys have the potential of easily carrying 20 to 30 percent of their own body weight and thus suitable as beast of burden; other use of donkeys includes farming and transportation. Donkeys have the tendency to resist any form of force or intimidation if for whatever reason they consider submitting to such demand to be dangerous to them[9]. The Donkey principle is an allegory used in promoting the practicality and transparency required to ensure a fair billing system of electricity usage. The Donkey principle is coined from a billing policy in Ghana, where a government directive through levies makes it possible for corporate firms and urban communities to carry some of the cost burden of the electricity used by the poor rural communities. The same policy suggests that the extra cost paid by the urban citizens covers rural electrification projects as well as setting up streetlights at strategic locations across the country. Since the core idea is to promote social fairness, the noble assumption will be for the administrative aspects including methods for collecting, managing, monitoring and executing that the required projects are made public. On the contrary, everything concerning rural electrification and other related projects are usually activities initiated under cloak and dagger. Giving power to the people in essence should include some measure of openness and this usually aims at building trust. The people paying these monies often feels cheated since there is no formal accountability from the authorities that are supposed to be in charge of providing this vital service for the nation. Thus, the donkey theorem recommend a clear-cut system, where an institution is set up to monitor and report all the monies accumulated from this strategic billing as well as give a clear framework and timeline as to how the monies are disbursed for the projects that they are collected for.

Social responsibility: The adoption of a photovoltaic system often reduces pollution. Thus photovoltaic system promises clean sources of energy especially the reduction of carbon emission. The conventional energy systems on the other hand, use other types of fuel (*gas, diesel, petroleum products and wood*) in generating energy, thus depleting the natural resources and causing environmental harm. For these reasons, adapting green energy sources promotes social responsibility.

For this study, the term ***energy*** refers to both conventional and renewable systems for generating or providing electricity.

Secondary source of energy from this point cited as SSE; is the sum total of all sources of energy and light generating systems readily available to end user both in the urban and rural communities. The list includes but not limited to candles, kerosene lamps, torch and flash lights, generators.

Distribution of photovoltaic energy identifies all the efforts made to deploy the technology to the end user. The processes involved in the distribution details down to where and how to make the photovoltaic technology available to the end user. These include profiling of end users energy needs, packaging, transportation and installation among others.[6]

Ghana is a West African country with a population of about 24 million with an approximately 1.9 percent population growth rate. Ghana´s electricity production and consumption and exports as at the year 2007 were 6.7 billion kWh (kilowatt hours), 5.7 billion kWh and 2.49 billion kWh respectively. Since the demand of energy outweighs it supply, availability and accessibility to alternative sources of energy would be preferred by the over 9.2 million citizens in Ghana without electricity[6].

This research does not take into consideration issues like the per-capita income of the rural-urban population. Nevertheless, it mentions the minimum income of the people in Ghana and figures out the percent of such income that goes to energy consumption. Furthermore, there were practically no individual volunteers ready to divulge their actual income as well as the percentage they spend on SSE. In addition, there proved to be virtually no relevant secondary sources of reference in relation to this parameter. Information gathered and used to develop the principles, is primarily based on covert questions asked under friendly atmosphere and mainly through acquaintance, which involves among others some speculative responds and pure approximations. Furthermore, omitted in this research, justifiably for future study, is the mechanism to map up a profitability ratio of how much savings is actually attainable from the use of renewable energy systems.

The study does not include any discussion on the potential of a feed in tariff system, since Ghana, as a developing country, has not yet implemented a full-scale de-regulated energy system. Feed in tariff would have required an economic system to have a pure privatization of its energy industry as well as market-regulated prices of energy. This study is designed to serve as part of a series of proposals (1. *diffusion of photovoltaic technology for developing countries and 2. financing alternatives for renewable energy systems for renewable energy systems*) intended to act as a ´wakeup call´ and support for the energy regulatory bodies in Ghana (Ministry for Energy, Ghana Energy Commission, etc).

This paper attempts to answer the following questions:

How can the Robin Hood (RH) theorem be applied to disseminate energy to rural and urban communities and what benefits can be derived from it?

How can policy makers adopt and adapt the Donkey theorem; in helping reduce cost burden of especially low-income earners in the rural communities?

The primary objective of this study is to develop and justify a proposal on an efficient energy distribution protocol as well as flexible billing system, with the aim of helping especially the energy administrators of Ghana to re-structure the current energy policies and justify the proposed principles. Although the principles proposed would have their own specific set of limitations, the findings of this study could serve as a preliminary framework for further studies in addition to its potential for future replication in other developing economies faced with similar energy crisis.

3. Methodology

To help promote and justify the adoption of the Robin Hood and Donkey principles, this paper discusses types of SSE available and in use. Knowledge about the cost, purpose, frequency and reasons for purchasing and using a particular SSE by both rural and urban communities would help address a realistic payment plan for renewable energy systems such as photovoltaic or SHS. It is noteworthy that, the idea of availability, affordability and reliability of the renewable energy systems was part of the focus group discussion that helped generate simple questions for the interview[6]. For each of the SSE under consideration, a random sample size of 5 - 10 retail outlets at different towns in different regions (*Accra municipalities and Tema all in the Greater Accra region, Cape Coast, Apam, Winneba all in the Central region, Takoradi in the Western region and Kumasi in the Ashanti region*) responded favorably to the interview. The questions used to derive at the objective were simple and given in the local language - Akan, similar questions were used for the different form of secondary energy source. The questions were as follows:

1. What type of SSE do you prefer and why?
2. What triggers the purchase of a SSE?
3. How often is the purchase of an SSE made?
4. What are the main uses of any specific SSE?

4. Results

Table 1 below, represents a summary result of the study. When the question on an individual or household preference of a SSE was asked, the answers varied greatly. Two main reasons were identified - *the household income* and *the purpose for which the secondary energy is needed*. In Ghana, the current minimum income effective February 2010 is 3.11 Ghana cedis, a 17 percent increment from the previous level of 2.65 Ghana cedis[5]. The assumption is that, a household had to carefully consider their net income and consider as to how much of such income could be set aside for such emergencies related to power outages very prominent in the life of a Ghanaian. Although the purpose was clear and easy to understand, the issue of household income proved to be very difficult to ascertain. This is due to the fact that, most Ghanaians are reluctant to reveal how much they actually earn for two main reasons: reluctance to expose themselves to rigorous scrutiny if found to be hiding some other source of household income as well as fear of being over taxed. Furthermore, Ghana´s gross domestic product (GDP) as at January, 2011 is estimated at $ 38.24 billion with an average per capita income of $ 1,600. It is important to mention that, GDP is not the only viable index to adeptly measure the collective household's decision on energy consumption[6,10]. The household income of the urban dwellers in Ghana varied heavily based on academic qualification and the nature of work under consideration. Meanwhile, an extrapolation of the lowest to the highest income levels based on the minimum wage is considered. The monthly income level within the urban dwellers ranged from as low as 50 euro to about 2,000 euro per month (approx. 100 - 4000 GHc). Upon this finding, one can easily assume the type of SSE affordable to the people. Based on this premise the conclusion is that, the higher the income the more expensive the type of SSE considered.

Nevertheless, the frequency of power outages per location would also easily affect the type of SSE adopted despite the price factor. A typical situation in the urban communities of Ghana is found in numerous high and low capacity generators and rechargeable lamps in contrast with those living in the poorer communities using candles, kerosene lamps, flash light, low priced rechargeable lamps as well as low capacity car batteries. Future field studies aims at unraveling aspects of the aforementioned points to help present a model for calculating the percentage of household income used on any specific secondary source of energy.

As to the reasons for the need of a SSE, the findings revealed yet two more underlining motives: *what triggered the purchase and why the particular purchase*. The finding concludes that *regular power outage, brownout and inaccessibility to grid* were the main triggers. Power outage affects both rural and urban dwellers that have access to the national grid. For this reason, lack of electricity supply appears to be the major cause for the need of a SSE. Moreover, there are situations whereby there is power, yet with insufficient voltage (brownout) to power basic devices like TV and refrigerators among others. For the aforementioned reasons, the need of a reliable SSE increases at such times. At the extreme end of the situation are sections of both the urban and rural dwellers that do not have power at all due to inaccessibility to the national grid. The situation leads such citizens without any other choice than a SSE, thus the need of these sources becomes a daily concern. There are so many people who are into petty trading especially at night selling almost anything from a home cooked meal to simple household items like toilet tissues.

Apparently, these household and petty traders' resort to the purchase of specific types of secondary energy source most suitable for varied needs. Popular among such purchase includes candles, portable flashlights and generator to take care of immediate household needs or to power such facilities used for petty trading, thus answering the underlining motive on why a particular secondary source of energy is purchased. The positive aspect of this is that the energy is sometimes acquired and used for productive activities that generates income other than merely using it for relaxation or recreational activities like watching television or listening to the radio. Nonetheless, these two underlining reasons are applicable to both urban and rural people.

A probe into the uses of a SSE also varies greatly based on the type of SSE available to the user. Candles are primary needed for lighting, batteries for powering radios and lamps, whereas car batteries are used to power TV sets and other smaller appliances. Generators are on the other hand really used for various needs based on their capacities. Therefore, the issue of usage type and rate enormously triggers the purchase of any of these SSE.

The situation in the rural communities is relatively different compared to the urban dwellers. Within the rural communities, the main source of income comes from peasant farming generated from seasonal sales of crops. The study established that some rural citizens' livelihood is highly dependent on their farming activities with virtually no source of extra or other income to save. It therefore leads to yet a more positive conclusion that, their need of a SSE highly varies. The basis for the usage of both primary (conventional) and SSE is for powering lights, radios, TV sets and in some circumstances refrigerators. In view of the fact that most food stuffs come from the rural areas the implications was obvious: Most rural communities are instrumental in serving one of the basic necessities in life: sustenance. It is thus socially justifiable if some of their energy needs are met and supplementary financed by people in the urban communities. Nevertheless, the donkey principle tries to emphasize the need for transparency in all the activities for which such extra levies are collected, thus justifying the extra load they have to carry on behalf of the rural communities.

Table 1. Secondary sources of energy production in Ghana

Source of energy	**Fuel**	**Capacity**	**Usage**	**Price Range (GHC*)**	**Consumer Category**
Candle	Paraffin	Unknown	Light	.20 - .50	The product is available to both rural and urban communities.
Lamps/Torch/ Flash Lights	Kerosene and Dry cell batteries	1 – 9 Volts	Light	.50 - 3	The product is available to both rural and urban communities.
Car Battery		12 – 24 Volts	Light, Radio, Television	50 – 200 depending on brand and ampere	Higher percentage by some rural communities
Generator	Petrol / Diesel	2-7.5 Kva[1]	General household appliances including fridge and other portable equipments	590	Urban households and small and medium sized enterprise (SMEs)

*c. 1 dollar = 1.5 GHC as at 1st March 2010, *GHC – Ghana Cedis, [1]Kva – kilovolt-ampere*

5. Conclusions

Considering these parameters and the configuration of energy usage give a glimpse into reasons why political decisions and state-based activities are needed for a reasonable distribution and billing of energy systems in the country. It is noteworthy to mention that people often adopt and adapt different forms of energy systems due to desperation and the unreliability of the national grid. Although the purpose for using these SSE might not often be seen or directed to productive activities, it was observed that the bottom line of the quest for acquiring such systems is for the end user to have their peace of mind.

Interestingly, the research discovered a different sense of sharing. During an earlier focus group discussion leading to this supplementary research, one of the participants explained an interesting scenario involving how generators are used in the country; this was confirmed by others present. Apparently, households who own generators developed their own distributed energy solution, in that they share excess capacity of their system with their neighbor for a small fee. Although the original objective was to avoid being a nuisance to one's neighbor due to the noise made by generators, the individual/household have found a mutual way to share both the pain and gain from this specific energy system.

Evidently, the study helps in identifying certain shortcomings of the SSE discussed and it was applicable to both the urban and rural dwellers. The disadvantages were as follows:

1. Variable cost factors (*regularity of refueling and recharging car batteries etc*)
2. Environmental pollution and unfriendliness (*noise from generators, burning of fuels, disposal of batteries etc*)
3. The unreliability of supply

From the aforementioned points, it is apparent that following the Robin Hood principle in electricity distribution has the inherent possibility in bringing an end or reducing immensely the purchase of SSE like candles, generators, batteries etc. This is possible since the diverted energy weaned from the urban to the rural communities will help improve the agro-base industry by helping them to add value to its production and distribution cycle. Furthermore, these SSE that is erratic at best, with seemingly shorter life span cannot be compared to a lasting solution (photovoltaic or any renewable energy systems) which in itself could promote tremendous amount of savings on energy over a realistic period. Since patronizing tendencies are rampant in developing countries whose government, NGO, and other advocates tend to propose, build and launch laudable but limited energy programs to the few only to repeat the phenomenon at their political whims, makes consideration to the Robin Hood theorem a paramount issue. It is obvious that giving power to the people promotes individual and social responsibility as well as fosters a conscious effort to building a viable platform for economic development and growth.

Furthermore, the Donkey principle suggests that urban dwellers should carry some of the burden of energy costs of the rural communities. Moreover, policy makers should promote transparency and to implement policies that uphold trust among the people. Since taxpayers' money is involved, accountability goes a long way to foster mutual understanding of the direction and developmental objective of the authorities. The principle also suggests an educational platform where all parties involved (policy makers, service providers, households and individuals) gain access to relevant information by any medium available to not only be aware but also be concern about the needs of the people and how to serve them better.

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Energy efficiency optimization algorithm for roadway illumination using ARM7TDMI architecture

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Abstract: This paper presents an algorithm developed in C language that aims to help roadway illumination designers to create an illumination system that meets the standard's limits with minimum electrical energy consuming. As a secondary function, the program allows the user to get approximate luminance and illuminance values for a specific system without field measuring. The algorithm was created to fit into a hardware prototype based in ARM7TDMI architecture, with no need for complicated and heavy software running in PC machines. The main system variables regarded by the optimization function are pole height (H) and pole spacing (S), putting the luminaries as far from each other as possible, in order to use the minimum power per km. Through calculation of the system's luminance, the algorithm starts with S and H in their maximum values, decreasing every loop, subtracting the results from the standard limit (NBR5101-Brazil, CIE 118, EN 13201 or other standard loaded into the program) seeking for zero. Once the zero is found, the H and S values are put on a LCD or USB port, as algorithm results.

Keywords: *Roadway illumination algorithm, ARM application, Illumination energy efficiency*

Nomenclature

L	*roadway average luminance*	cd/m^2
E	*roadway average illuminance*	*lux*
H	*pole height*	*m*
S	*pole spacing*	*m*
I	*luminous intensity*	*cd*
Ir	*relative luminous intensity*	*cd/klm*
φ	*luminary luminous flux*	*lm*
ψ	*Luminary azimuth angle*	°
θ	*Vertical luminary angle*	°
β	*Horizontal observer angle*	°
P_a	*active power*	*W*
W	*roadway wideness*	*m*
U_o	*overall uniformity*	
n	*lanes number*	
P_r	*distance relative power*	*kW/km*

1. Introduction

One of the main problems in developing countries regarding electrical energy waste is the roadway illumination design, as the majority is over or under dimensioned, using old technology luminaries and with pole height and spacing in such values that the standard's limits are rarely achieve, which increase car accidents and criminality rate and decreasing the system's efficiency [1,2].

In order to develop a new roadway illumination system or evaluate an existing one, simulation software (Dialux, Lumisoft, Calculux) are used to calculate the main parameters required by standards such as NBR 5101, CIE 115, CIE 180, EN 13201 and others, running in PC platforms.

Another way to evaluate an existing illumination system is by field measuring, which implies in marking the grid on the ground level and taking an illuminance or luminance measure for each grid point, demanding time and a roadway free of traffic [2-4].

Therefore, facing these problems, the hypotheses of a small, low cost, device which could run an algorithm to simulated the main parameters needed to evaluate a roadway illumination system (in case of an existing system) or calculate how far away the poles could be spaced in order to consume less power (in case of a new system), was tested. It is important for the algorithm to be autonomous, that is, no computer aid.

2. Methodology

The main result variable for the algorithm implemented is P_r which is directly connected with energy consuming, therefore, it has to be as low as possible and still allows lighting parameters to meet the chosen standard's limits. For that to happen, the space between poles (S) is loaded with 50m and decreased gradually until the required value is reached. The same is done to the luminary height (H), as presented in Fig. 1.

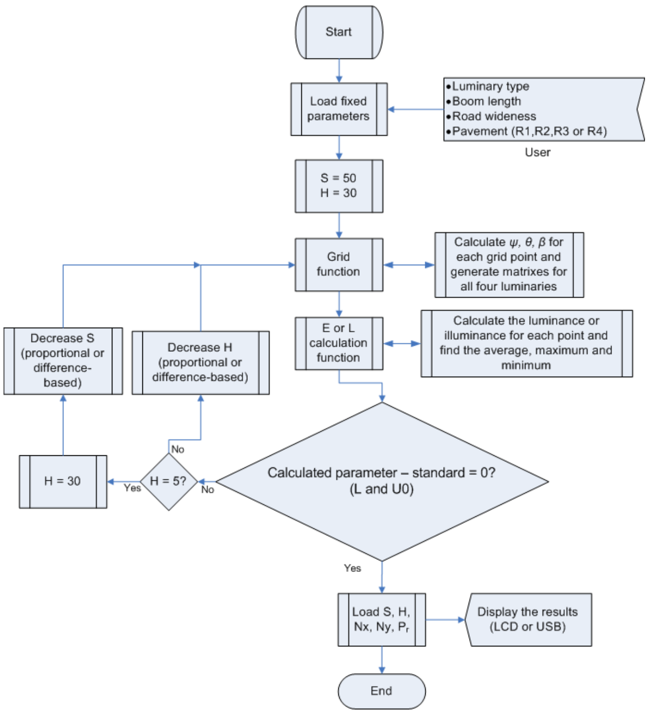

Fig.1 Block diagram of the optimization algorithm.

2.1. Hardware

The first thing to choose in the hardware design is the microcontroller where the algorithm will be running. The ARM7TDMI architecture, more precisely the Analog Device's microcontroller ADUC7026, was chosen by its processing capability of 32bits, low clock frequency (32.768kHz) with high internal speed (41MHz), the I/O pin quantity (ADCs, DACs, GPIOs) and the flash memory space of 62kB and the long multiplication and thumb mode support, allowing the process to run much faster than 16bits architecture or even standard ARM7 devices.

The hardware must have a display capable of reporting to the user of the algorithm variable results, such as: E, L, Emin, Emax, Lmin, Lmax, U_o, H, S, number of grid columns, number of grid rows and the active power consumed by kilometer (P_r).

2.2. Virtual grid creation

To calculate the system main parameters, a grid must be created on the roadway, between two luminaries with interference of, at least, one luminary after and one later, with rows spacing 1m maximum from each other and columns spacing 5m maximum [2,3], as shown in Fig. 2, where S_x is the space between grid points on a line parallel to the curb line and S_y is the space between grid points on a line orthogonal to the curb line. It was stated the symbol N_x for the total number of rows (x axis) and N_y for the total number of columns (y axis).

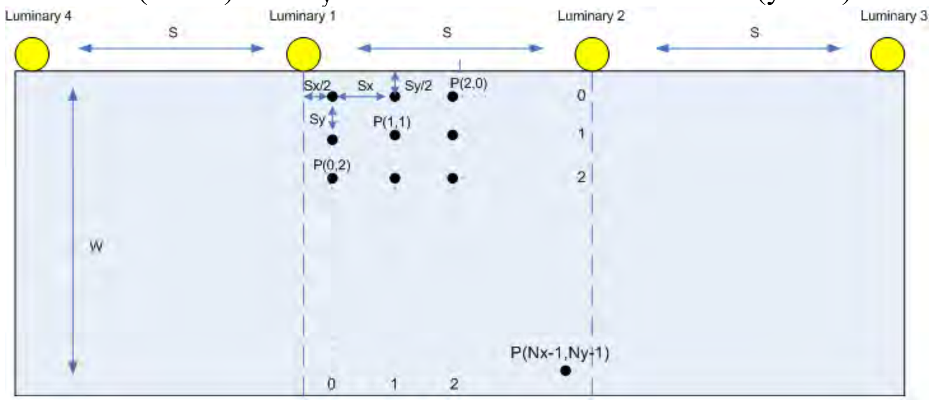

Fig.2 Creation of the calculation grid.

In order to keep the grid centralized on the space between two luminaries, the first point must be located at $S_x/2$ from the x axis and $S_y/2$ from the y axis. S_x and S_y are set by the user from the beginning and N_x and N_y are calculated dividing space between luminaries (S) by S_x and road wideness (W) by S_y.

After finding the rounded values of N_x and N_y, S_x and S_y have to be recalculated.

Each calculation point has two coordinates (x,y) that correspond with its place in relation to the grid. The real distance for each point in relation to the system's origin (Luminary 1) is calculated by Eq. °(1).

$$P(x,y) = P_0\left(\frac{S_X}{2} + x * S_X, \frac{S_Y}{2} + y * S_Y\right) \quad (1)$$

where P_0 is the coordinates of P in relation to the system's origin.

E.g. a point located at P(2,3) with a S of 35m and a W of 9m has an N_x equal to 8 and a N_y equal to 9 (using initial S_x = 5 and S_y = 1), therefore the real values of S_x and Sy are 4.375m (S/N_x) and 1m (W/N_y), respectively, and its coordinates in relation to origin, calculating from Eq. °1, are represented by P_0(10.938m,3.5m). These coordinates are used to calculate the system's main angles.

On this first part, the algorithm creates eight 10x10 matrixes based always on the same grid: one matrix for azimuth angle (ψ) and one matrix for inclination angle (θ) for each luminary in relation to every grid point. Later, the observer matrixes will be created as well, for the observer angle (β). All angles used to execute the main calculations (L and U_o) are presented in Fig. 3.

The γ is the angle between the roadway horizontal plane and the observer's eye, used to find the reduced luminance coefficient in the r-tables [2,4-6].

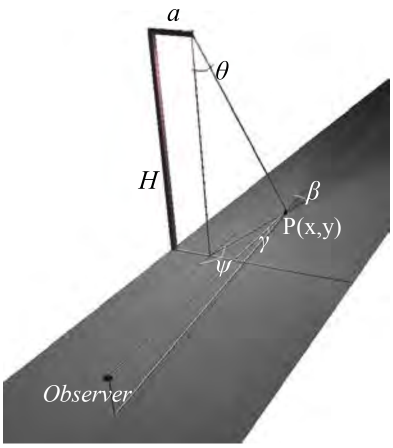

Fig.3 Main angles used to calculate E and L.

The angles represented in Fig. 3 can be calculated using straight trigonometry or algebra and are very important for the calculus, as the luminous intensity tables and r-tables are based on them. For study sake, both methods were used on this work, as the following description.

2.2.1. Azimuth angle (ψ)

The azimuth is the angle between the luminary plane and the calculation point on a horizontal plane (road plane) and is used together with the vertical luminary angle (θ) to find the luminous intensity module in the calculation point direction [2,6].

In this work, ψ was calculated based on the triangle formed by the luminary position and the calculation point position on the road plane, as presented in Fig. 4, where *a* is the boom length, X_0 is the real coordinate (in relation to the origin) of the calculation point on the X axis and Y_0 is the real coordinate of the calculation point on the Y axis.

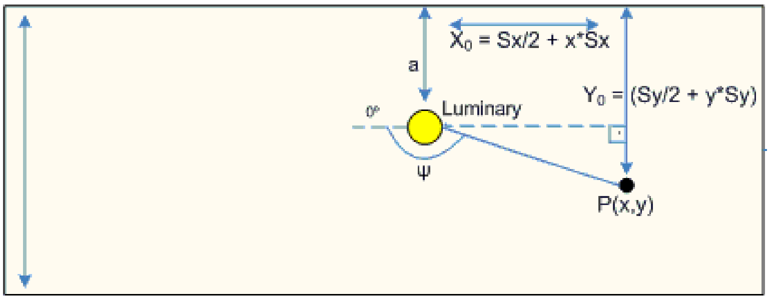

Fig.4 Triangle formed by the luminary position and the calculation point position.

The angle must be calculated in relation to each luminary (four luminaries, as previously stated) in two cases: for $Y_0 < a$ and for $Y_0 \geq a$.

For the first case, ψ can be calculated for the four luminaries using Eq. °(2-5).

$$\Psi_{L1} = 180 + \tan^{-1}\left(\frac{|Y_0 - a|}{X_0}\right) \quad (2)$$

$$\Psi_{L2} = 360 - \tan^{-1}\left(\frac{|Y_0 - a|}{S - X_0}\right) \quad (3)$$

$$\Psi_{L3} = 360 - \tan^{-1}\left(\frac{|Y_0 - a|}{(S - X_0) + S}\right) \quad (4)$$

$$\Psi_{L4} = 180 + \tan^{-1}\left(\frac{|Y_0 - a|}{X_0 + S}\right) \quad (5)$$

In the second case, ψ can be calculated for the four luminaries using Eq. °(6-9).

$$\Psi_{L1} = 180 - \tan^{-1}\left(\frac{|Y_0 - a|}{X_0}\right) \quad (6)$$

$$\Psi_{L2} = \tan^{-1}\left(\frac{|Y_0 - a|}{S - X_0}\right) \quad (7)$$

$$\Psi_{L3} = \tan^{-1}\left(\frac{|Y_0 - a|}{(S - X_0) + S}\right) \quad (8)$$

$$\Psi_{L4} = 180 - \tan^{-1}\left(\frac{|Y_0 - a|}{X_0 + S}\right) \quad (9)$$

The azimuth matrixes are generated using Eq. °(2-9) for each grid point.

2.2.2. Vertical luminary angle (θ)

The vertical luminary angle is the angle between the luminary and the calculation point on the vertical plane, as it is shown in Fig. 3, forming another rectangle whose base is the hypotenuse of the triangle presented in Fig. 4. The angle can be calculated using Eq. °(10).

$$\theta = \tan^{-1}\left(\frac{\sqrt{X_0^{\,2} + (Y_0 - a)^2}}{H}\right) \quad (10)$$

where H is the pole height.

2.2.3. Observer angle (β)

The observer has two angles, as it can be seen in Fig. 3: the angle in relation of the road plane (γ) and the angle in relation to the luminary-point vector (β).

The first is fixed in 1° to 1.5° interval [1-6] and the second is calculated using algebra, assuming two vectors $\vec{AP}$ *and* $\vec{LP}$, as presented in Fig. 5:

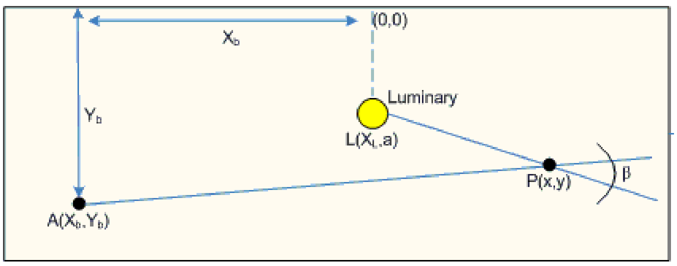

Fig.5 Angle β formed by vector $\vec{AP}$ *and* $\vec{LP}$.

Both vectors are defined by two points and the angle between them is β, which is calculated by the arccosine of the vectors scalar product over the multiplication of their modules [7], as represented in Eq. °(11).

$$\beta = \cos^{-1}\left(\frac{\vec{AP}\cdot\vec{LP}}{\left|\vec{AP}\right| * \left|\vec{LP}\right|}\right) \tag{11}$$

After this part, all angle matrixes are ready and stored in the microcontroller's memory and the parameters calculation can now start.

2.3. *Illuminance calculation (E)*

The illuminance is calculated using the traditional cosine equation published in several studies [2,6,8,9] represented by Eq. °(12).

$$E = \frac{I_r(\psi,\theta) * \frac{\varphi}{1000} * \cos^3\theta}{H^2} \tag{12}$$

where $I_r(\psi,\theta)$ is the relative luminous intensity taken from the luminary *I table* and φ is the luminary luminous flux.

2.4. *Luminance calculation (L)*

For the luminance calculation, the *r_tables* where used to find the approximate result. The equation used is represented in Eq. °(13) [2,6].

$$L = \frac{\frac{r(\beta,\theta)}{10000} * I_r(\psi,\theta) * \frac{\varphi}{1000}}{H^2} \tag{13}$$

where $r(\beta,\theta)$ is the reduced luminance coefficient taken from the *r_table*.

2.5. *Optimization function*

The calculation functions were designed to calculate E, L and U_o starting from six variables: *a*, W, luminary type, pavement type (R1, R2, R3 or R4), S and H. The first four variables are defined by the user, leaving only two variables to be calculated through optimization: H and S. With S been the most important as it is directly connected to energy consuming.

The optimization algorithm start placing the luminaries 50m (S) away from each other and 30m (H) high and begin to decrease S and H, calculating L (E was not used in the optimization function) and U_o every iteration, subtracting the result from the standard value (loaded into the memory) until it reaches zero, when the optimum values of S and H, together with other secondary results, are displayed on a LCD or sent through USB to a computer.

The optimization function was implemented in two ways: proportional and difference-based.

2.5.1. Proportional form

In the proportional form, both S and H are decremented in one unit each iteration making the process very simple but taking a long time to converge, as the decrement doesn't depend on the difference from the parameter being calculated (L and U_o).

Process is done using two loops: an outer loop for S decrementing and an inner loop for H decrementing. Then, for each meter taken from S, all H range is tested.

2.5.2. Difference-based form

This form was called this way for the variable decrease is based on the difference between the last parameter (k-1) calculated and the standard's limit, following Eq. °(14) and Eq. °(15). Therefore, the farther the parameter is from the standard, the bigger the decrease will be, resulting on a faster algorithm conversion.

$$H_k = H_{k-1} - [K_1 * (L_{k-1} - L_{st})] \tag{14}$$

$$S_k = S_{k-1} - [K_2 * (L_{k-1} - L_{st})] \tag{15}$$

3. Results

All algorithm results were compared with simulations on Dialux software which was taken as reliable CAD lighting software, used in several international projects.

The graphic of the algorithm conversion are presented in Fig. 6 and Fig. 7, using a = 1m, W = 8m, n = 2 lanes, SRC 612 Philips sodium-vapor luminary with P_a = 443W and road pavement R3.

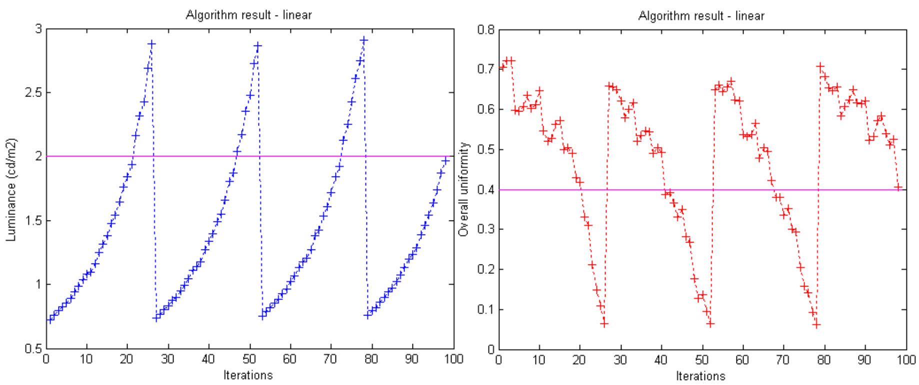

Fig.6 Algorithm graphic conversion for proportional optimization.

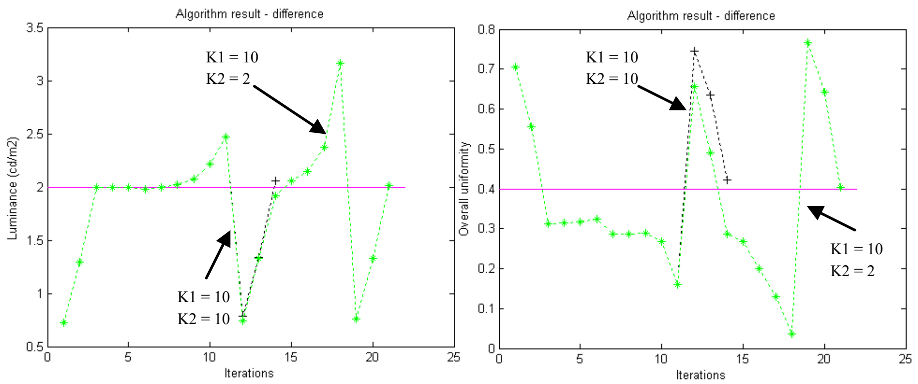

Fig.7 Algorithm graphic conversion for difference-based optimization.

On Fig. 6, the graph shows that the algorithm takes about 96 iterations to convert to the desired pattern, using proportional optimization and on Fig. 7 it takes about 22 iterations using difference-based optimization with K1 = 10 and K2 = 2 (green) and 12 iterations with K1 = 10 and K2 = 10 (black). The continuous lines indicate the EN 13201-1 standard recommendation ($L = 2$ cd/m^2 and $U_o = 0.4$) for ME1 class.

The final results, comparing with Dialux, are presented on Table 1.

Table 1. Final algorithm results.

Parameters	Proportional optimization	Difference-based optimization K1 = 2, K2 = 10	Difference-based optimization K1 = 10, K2 = 10	Dialux (validation)
L (cd/m^2)	1.969	2.009	2.058	2.0
U_o	0.406	0.404	0.422	0.4
S (m)	47	46.72	45.28	47
H (m)	11	10.9	11.25	11
P_r (W/km)	9.4k	9.5k	9.8k	9.4k

4. Conclusions

The final results confirmed that the optimization algorithm is able to calculate a distance between luminaries which meets the standard limit with minimum power consuming and a pole height to guarantee the uniformity, being sufficiently light to be run on a simple hardware (formed by the microcontroller ARM7TDMI ADUC7026, some keys to enter data and a LCD) with no need for an external memory or any other device, becoming an easy-to-use tool to new or existing roadway lighting designs, even though the algorithm secondary function, simulation, was not presented in this work due to space restrictions.

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Experimental Evaluation of a Gas Engine Driven Heat Pump Incorporated with Heat Recovery Subsystems for Water Heating Applications

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Abstract: Engine waste heat recovery represents one of the main advantages of a gas engine heat pump (GEHP) as compared to conventional heat pump system. Engine waste heat can be recovered to heat the supply water (at high ambient air temperature) or to evaporate the refrigerant in the refrigerant circuit (at low air ambient temperature). At the middle range of ambient air temperature (10:15°C), the two possibilities are valid but the GEHP performance is different. The present work is aimed at comparing the performance characteristics of the gas engine heat pump with waste heat recovery subsystems for supplying the hot water demands. In order to achieve this objective, a test facility was developed and then experiments were performed over a wide range of condenser water inlet temperature (34°C to 48°C) and at ambient temperature of 13°C. Performance of the gas engine heat pump was characterized by the supply water outlet temperature, heating capacity, gas engine energy consumption and primary energy ratio. The results showed that a water outlet temperature up to 70°C is obtained when the recovered engine heat is transferred to the supply water circuit. On the contrary, a higher condenser heating capacity (13%) and higher gas engine energy consumption (12.8%) are obtained when the recovered engine heat is transferred to the refrigerant circuit. Furthermore, primary energy ratio of the gas engine heat pump is increased by 17.5% when recovered engine heat is transferred to the supply water circuit. Also, GEHP incorporated with heat recovery subsystems can be used for utilizing the waste heat to provide efficient supply of hot water.

Keywords: *Gas engine heat pump, Heating mode, Water heating, Primary energy ratio, Engine waste heat recovery.*

1. Introduction

In Europe, more than 50% of the total final energy consumption depends on fossil fuel [1]. However, environmental pollution problems increase with consumption of fossil fuels. In order to solve these problems, a development for alternative energy sources and improvement of energy utilization efficiency are required. Heat pumps (HPs) play an important role in solving energy and environment problems as they can improve the overall energy utilization efficiency and can work with environmentally friendly refrigerants [2-4].

Heat pumps can be divided into many categories according to energy sources, namely electric driven heat pumps (EHPs), ground-source heat pumps (GSHPs), solar-assisted heat pumps and gas engine driven heat pumps (GEHPs). A GEHP usually consists of a reversible vapor compression heat pump with an open compressor driven by an engine. In recent years, the GEHP has been paid more attention due to its advantage of reducing the energy consumption, especially in the heating process. Another two advantages of the GEHP are (1) the ability to recover the waste heat released by the engine cylinder jacket and exhaust gas and (2) the easy modulation of compressor speed by adjusting the gas supply. Therefore, the GEHP has a better performance than that of the electric driven heat pump (EHP), especially in the heating mode [5].

Performance characteristics of the GEHP during heating mode were evaluated by many investigators using theoretical modeling [5-7] and experimental approach [8]. Regarding to theoretical modeling of the GEHP, Zhang et al. [5] analyzed the effect of both ambient temperature and engine speed on the heating performance of air to water GEHP based on steady state model. Their results proved that the engine speed had a remarkable effect on both the engine and the heat pump, but ambient air temperature had a little influence on the engine performance. Yang et al. [6] reported an intelligent control simulation model for the GEHP system in heating mode to study the dynamic characteristics of the system. The results showed that the model was very effective in analyzing the effects of the control system. The steady state accuracy of the intelligent control scheme was higher than that of the fuzzy controller. Sanaye and Chahartaghi [7] predicted the performance of the GEHP under cooling and heating operating modes and then compared the simulation and experimental results for various amounts of suction and discharge pressures, fuel consumption and coefficient of performance. They noted that error percentages of suction and discharge pressures, fuel consumption and coefficient of performance are 3.4%, 4%, 6.7% and 7.2% for cooling mode, respectively, and 3.7%, 5.4%, 8.1% and 7.8% for heating mode, respectively.

Regarding to the experimental studies of the GEHP, Lazzarin and Noro [8] evaluated the performance of 'S. Nicola' plant in Vicenza during three years of operation. Plant heating loads are supplied using the GEHP and two condensing boilers. Recovered engine heat is used in water heating. The economic analysis was taken into account while the energy efficiencies were not taken into considerations.

The above review revealed that various investigations on modeling of the GEHPs are available in the literature while there is a lack of experimental data on the GEHPs working with R22 alternatives such as R410A. Thus, the present work is carried out with the aim of evaluating the performance characteristics of the GEHP used in water heating incorporated with different heat recovery sub-systems. In order to achieve this aim, a test facility of the GEHP is constructed and equipped with the necessary instrumentation. This paper is organized as follows. The experimental apparatus to predict the performance of characteristics of the GEHP is described in Section 2 while the data reduction manipulation is given in Section 3. This is followed by the experimental results and discussion in Section 4. Finally, conclusions based on the present work results are reported in Section 6.

2. Experimental apparatus

Fig. 1 shows a schematic diagram of the experimental apparatus, which includes three circuits; namely primary working fluid circuit, engine coolant circuit and secondary working fluid circuit. R410A is used as a primary working fluid while both air and water are used as secondary heat transfer fluids at the heat source (evaporator) and the heat sink (condenser). In the engine coolant circuit, both ethylene-water mixture (65% by volume) and propylene-water mixture (45% by volume) are used as cooling mediums. Pre-calibrated PT100 sensors are used to measure operating temperatures while digital pressure gauges are used to determine the operating pressures at four locations in the refrigerant circuit of the heat pump. The mass flow rate of refrigerant is measured using KROHNE Optimass 7000-T10 while engine coolant and water flow rates are measured using Ultego-II flow sensors. The measurement locations are shown in Fig. 1. All the measuring instruments have been installed and connected to 64 channels in the data acquisition cards (FP-1000). The control system has been established using PRIVA software which provides several possibilities for indoor unit selection and consequently system operation. All the measured data are recorded using DIAdem software and analyzed using an EES program [9] to evaluate the system performance. Performance characteristics of the system in both cooling, heating and combined modes were published by Elgendy et al. [10-12].

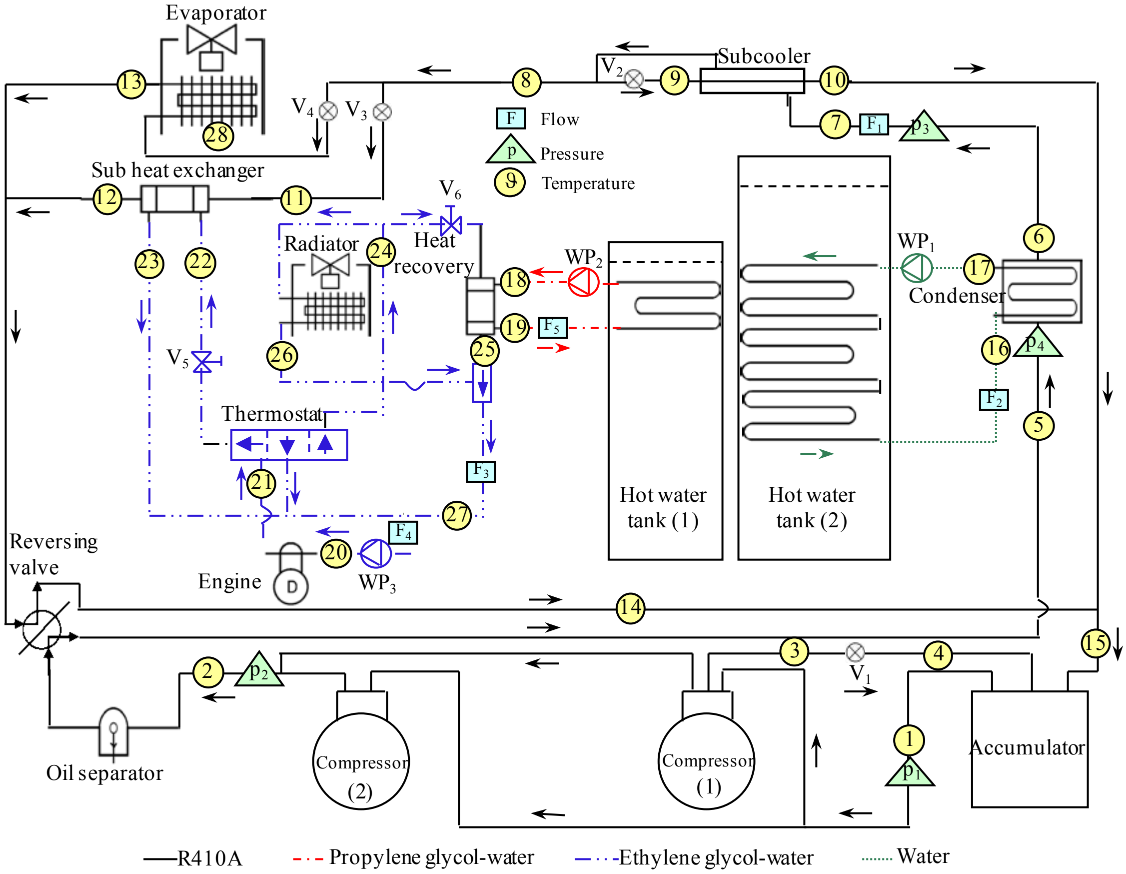

Fig. 1. Schematic diagram of the experimental apparatus with measuring point locations.

2.1. Primary working fluid circuit

The primary working fluid circuit is a vapor compression heat pump. It comprises an expansion device, an evaporator, an open compressor and a condenser followed by a sub-cooler. The expansion device is an electronic expansion valve whereas the compressor is a scroll open type with swept volume of 104cm^3/rev. The type of condenser is a plate heat exchanger with a heat transfer area of 4.6m^2. Two pressure-stats, one on the suction side and the other on the discharged side, are used to protect the compressor from under and over operating pressures. If the pressure exceeds its limits, the compressor would be automatically disconnected. In order to reduce the heat transfer to and from the surroundings, the primary fluid circuit is thermally insulated.

As the refrigerant flows to the compressors (state point 1), the compressors raise the pressure of the refrigerant and deliver superheated vapor (state point 2) to the condenser (state point 5) through an oil separator and a reversing valve. The condensation heat of refrigerant vapor is released to the water flowing through the condenser. Thus, R410A vapor gets condensed (state point 6) and its mass flow rate is measured using flow-meter F_1 before it flows to the sub-cooler. The liquid refrigerant in the sub-cooler is sub-cooled (state point 8) by transfer its heat to the throttled refrigerant flowing through valve V_2. Then, the refrigerant is throttled using expansion devices V_3 and V_4 and evaporated inside either the evaporator or the sub heat exchanger using the heat transferred from either ambient air or the recovered heat from the engine, respectively. Superheated refrigerant coming out of sub-cooler (state point 10), sub heat exchanger (state point 12) and outdoor unit (state point 13) are mixed (state point 15) before entering the accumulator and then returning back to the compressors (state point 1).

2.2. Secondary fluid circuit

The experimental apparatus has two secondary heat transfer fluid circuits; namely hot water circuit and outdoor air circuit. The hot water circuit contains a hot water tank of $1m^3$ capacity, a hot water pump, a condenser and control valves. The water pump (single phase, variable speed) is used to suck and pump the hot water through the condenser and hot water pipeline. The hot water flow rate is adjusted via pump speed. The hot water circuit is thermally insulated to minimize heat loss. The outdoor air circuit consists of an air filter, a fan and an evaporator. The hot water coming out of the condenser (state point 17) is pumped to a storage tank (1) using variable speed water pump WP_1. Storage tank (1) is used for hot water coming from the engine heat recovery while storage tank (2) is used for the hot water coming out of the condenser. The volume flow rates of hot waters are measured using ultrasonic flow meters F_2 and F_5, respectively.

2.3. Engine coolant circuit

The engine coolant circuit includes a gas engine, a coolant tank, a coolant pump, valves and coolant pipeline. Coolant discharged from the coolant pump (state point 20) is heated by the heat released from the engine block and exhaust gas (state point 21). The heated coolant returns to the coolant pump by making a shortcut via a thermostat valve when the coolant temperature is low (lower than 53°C) at engine start-up. When the coolant temperature is high (higher than 53°C) the coolant flows into sub heat exchanger while it flows through all of sub heat exchanger, radiator and heat recovery heat exchangers when the coolant temperature is very high (higher than 67°C). The outlet coolant from both heat recovery heat exchanger (state point 25) and radiator (state point 26) is mixed (state point 27) and its volume flow rate is measured using ultrasonic flow meter (F_3) before returning back to the coolant pump. Heat gained in the heat recovery heat exchanger is supplied to the water in the tank (1) using propylene-water mixture as a working medium (state points 18 and 19). According to engine heat recovered utilization (from the engine block and exhaust gas), the system can be worked in two sub modes:

Mode-I: in which the recovered engine heat is transferred to the secondary water circuit in order to reach higher hot water supply (using the heat recovery heat exchanger). So, valves V_3 and V_5 are closed while V_6 is open.
Mode-II: in which the recovered engine heat is transferred to the primary refrigerant circuit to evaporate the working fluid, especially at low ambient air temperature (using the sub heat exchanger). Hence, valves V_3 and V_5 are open while V_6 is closed.

3. Data reduction

Using the measured data of operating pressures and temperatures of R410A, ethylene glycol-water mixture, propylene glycol-water mixture and water, the specific enthalpy values at the inlet and outlet of each component ($h_1 \rightarrow h_{27}$) are estimated. Then, energy and mass balances are carried out for the main components of the gas engine heat pump to compute their loads in addition to the overall system performance. Condenser heat load ($\dot{Q}_{con}$) can be written based on either primary working fluid (Eq. 1.a) or secondary working fluid (Eq. 1.b) as follows;

$$\dot{Q}_{con} = \dot{M}_{ref,p}(h_5 - h_6) \tag{1.a}$$

$$\dot{Q}_{con} = \dot{V}_{con,w} \rho_w (h_{17} - h_{16}) \tag{1.b}$$

Applying energy balance around sub-cooler, the secondary refrigerant mass flow rate ($\dot{M}_{ref,s}$) flowing through sub-cooler can be calculated as follows;

$$\dot{M}_{ref,s} = \frac{\dot{Q}_{sub}}{(h_{10} - h_9)} \tag{2.a}$$

where,

$$\dot{Q}_{sub} = \dot{M}_{ref,p} (h_7 - h_8) \tag{2.b}$$

$\dot{M}_{ref,p}$ is the primary refrigerant mass flow rate, which is measured using flow meter F_1. Gas engine heat recovery ($\dot{Q}_{HR}$) can be calculated using Eq. (3);

$$\dot{Q}_{HR} = \dot{V}_{hw} \rho_w (h_{19} - h_{18}). \tag{3}$$

Ultrasonic flow meters F_2 and F_5 are used to measure condenser water ($\dot{V}_{con,w}$) and hot water ($\dot{V}_{hw}$) volume flow rates through the condenser and heat recovery heat exchanger, respectively. Primary energy ratio (PER), gas engine heat consumption ($\dot{Q}_{gas}$) and total heating capacity ($\dot{Q}_{tot}$) are the main parameters to be considered in the performance evaluation of the GEHP [13]. PER and $\dot{Q}_{gas}$ can be expressed as follows;

$$PER = \frac{\dot{Q}_{tot}}{\dot{Q}_{gas}}, \tag{4}$$

$$\dot{Q}_{tot} = \dot{Q}_{con} + \dot{Q}_{HR}, \tag{5}$$

$$\dot{Q}_{gas} = \dot{V}_{gas} LHV, \tag{6}$$

where LHV is the gas lower heating value and $\dot{V}_{gas}$ is the measured gas volume flow rate using diaphragm gas meter.

4. Results and discussions

Fig. 2 shows comparison of performance characteristics of the GEHP for the prescribed mode-I and mode-II and at ambient temperature of 13°C. In mode-I, recovered engine heat is transferred to the water supply while recovered engine heat is transferred to the refrigerant in mode-II. The system hot water outlet temperature was adjusted between 35°C and 70°C to

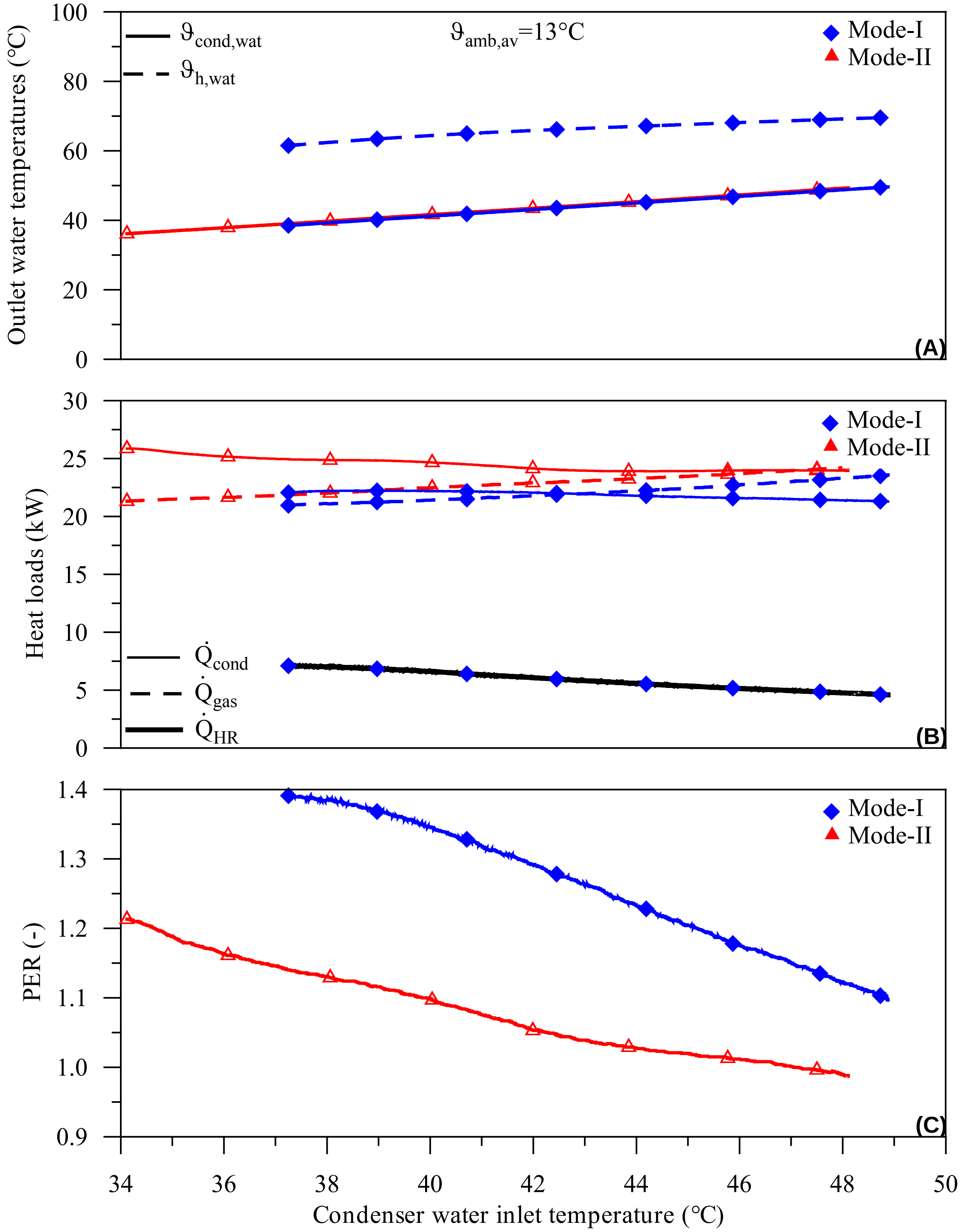

Fig. 2. Effect of condenser water inlet temperature on the performance characteristics of the GEHP for Mode-I and Mode-II. (A) outlet water temperatures, (B) heat loads and (C) PER.

provide heating requirements for several applications like shaving, residential dish washing and laundry [14].

4.1. Effect of condenser water inlet temperature

Measured condenser and heat recovery water outlet temperatures against the condenser water inlet temperature are presented in Fig. 2.A, which indicates that condenser and heat recovery water outlet temperatures increase when condenser water inlet temperature increases. Variations of actual heat loads with condenser water inlet temperature are shown in Fig. 2.B. It is evident from this figure that total heating capacity and gas engine heat recovery decrease while gas engine energy consumption $\dot{Q}_{gas}$ increases as condenser water inlet temperature increases. It is observed that both of the condenser and heat recovery water temperature differences decrease causing the decrease of total heating capacity. In general, as the condenser water inlet temperature changes from 37°C to 48°C, total heating capacity decreases by 8.3% and 4.7% while gas engine energy consumption increases by 14.1% and 11.9% for mode-I and mode-II, respectively. The effect of condenser water inlet temperature on PER can be predicted from Fig. 2.C. A higher condenser water inlet temperature yields a lower PER. This trend is mainly due to both decrease in total heating capacity and increase in the gas engine energy consumption as shown in Fig. 2.C. Clearly, primary energy ratio of the GEHP decreases by 27.2% and 17.3% as the condenser water inlet temperature varies from 37°C to 48°C for mode-I and mode-II, respectively.

4.2. Comparison between mode-I and mode-II

Comparison of the measured condenser and heat recovery water outlet temperatures for mode-I and mode-II are presented in Fig. 2.A. In the two modes, the condenser water outlet temperature lies between 35°C and 50°C. For mode-I, a higher hot water temperature (up to 70°C) can be achieved as a result of recovered engine heat transfer. Variations of actual heat loads for the modes are shown in Fig. 2.B. It is evident from this figure that condenser heating capacity and gas engine energy consumption are high when recovered engine heat is transferred to refrigerant. In general, both condenser heating capacity and gas engine energy consumption increase by 13% and 12.4% as an average values, respectively. So, it is better to transfer recovered engine heat to the refrigerant when one needs a large amount of heat at lower range of temperature (35°C:50°C) while it is better to transfer engine heat to water when a higher water temperature (up to 70°C) is required. The effect of the condenser water inlet temperature on the PER for the two modes can be predicted from Fig. 2.C. A higher PER can be reached when the recovered engine heat is transferred to the water. This can be attributed mainly to the higher gas engine heat recovery. Clearly, primary energy ratio of the GEHP increases by 17.5% as an average value over the entire range of the condenser water inlet temperature (from 37.2°C to 48°C).

5. Conclusion

In the present work, performance characteristics of R410A gas engine heat pump have been experimentally compared under two different modes of heat recovery utilization. In mode-I, recovered engine heat is transferred to the water supply while recovered engine heat is transferred to the refrigerant in mode-II. Based on t he reported results, the following conclusions are drawn:

- Hot water outlet temperatures between 35°C and 50°C are obtained during the considered modes.
- Water outlet temperatures up to 70°C can be reached in a separate tank when recovered engine heat is transferred to water.

- As the condenser water inlet temperature varies from 37°C to 48°C, total heating capacity decreases by 8.3% and 4.7% while gas engine energy consumption increases by 14.1% and 11.9% for mode-I and mode-II, respectively.
- Primary energy ratio of the GEHP increases by 17.5%, when recovered engine heat is transferred to water.

Acknowledgment

The Authors are grateful for the installation of the testing plant and the financial support provided by Wärmetechnik Quedlinburg (WTQ) GmbH. The financial support of the Egyptian government for the Ph.D. of Mr. Elgendy is gratefully acknowledged.

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Building performance based on measured data

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Abstract: With increasing liability for builders, the need for evaluation methods that focuses on the building's performance and thus excludes the impact from residents' behavior increases. This is not only of interest for new buildings but also when retrofitting existing buildings in order to reduce energy end-use.

The investigation in this paper is based on extensive measurements on two fairly representative type of buildings, a single family building in Ekerö, Stockholm built 2000 and two apartment buildings in Umeå (1964) in order to extract key energy performance parameters such as the building's heat loss coefficient, heat transfer via the ground and heat gained from the sun and used electricity.

With access to pre-processed daily data from a 2-month periods, located close to the winter solstice, a robust estimate of the heat loss coefficient was obtained based on a regression analysis. For the single family building the variation was within 1% and for the two heavier apartment buildings an average variation of 2%, with a maximum of 4%, between different analyzed periods close to the winter solstice.

The gained heating from the used electricity in terms of a gain factor could not be unambiguously extracted and therefore could only a range for the heat transfer via ground be estimated. The estimated range for the transfer via ground for the two apartment buildings were in very good agreement with those calculated according to EN ISO 13 370 and corresponded to almost 10% of the heating demand at the design temperature. For the single family building with an insulated slab and parts of the walls below ground level, the calculations gave slightly higher transfer than what was obtained from the regression analysis. For the estimated gained solar radiation no comparison has been possible to make, but the estimated gain exhibited an expected correlation with the global solar radiation data that was available for the two apartment buildings.

Keywords: *Regression analysis, Heat loss coefficient, Heat transfer via ground, Gained heat*

Nomenclature

C	*thermal mass*	$J/^{\circ}C$
F	*heat loss coefficient*	$W/^{\circ}C$
G_L	*heat transfer via ground*	W
P	*power*	W
T	*temperture*	$^{\circ}C$
α	*gain factor*	(-)
	Indices	
d	*dynamic heat storage*	
el	*electricity*	
g	*ground*	
h	*heating system*	
i	*indoor*	
o	*outdoor*	
p	*heat from persons*	
s	*sun*	
t	*total purchased energy*	
v	*ventilation*	
w	*water*	

1. Introduction

Energy performance assessment [1] is normally done by energy consumption calculations, estimations based on energy bills, extensive measurements [2-4] or a combination of these methods. Assessments that are based on extensive measurements are often done by identifying the parameters of the used model The used models may basically be divided in two groups, dynamic or static, and where the overall heat loss coefficient is a commonly used performance parameter.

With increased demands, that new or renovated building meet promised performance, the demands on validation but also on the used energy consumption calculations in the design stage increases. Today, in Sweden, a buildings energy performance usually is expressed in terms of energy use per square meter heated area. The problem with this performance measure is that only a part of the supplied energy is considered, i.e energy directly used for space heating and domestic hot water preparation together with electricity used for the buildings technical systems and common areas. Contributions related to user behaviors such as household electricity, indoor temperature and personal heating are not included together with the contribution from solar radiation.

The objective behind this work is to investigate the possibility to, based on extensive measurements, extract the thermal performance parameters that describes the building itself and where the contributions from the users and the sun are filtered out. This has great significance for a buyer or seller/manufacturer from liability point of view, since the behavior of the building itself is the only thing a seller/manufacturer can guarantee.

2. Methodology

Measurements have been carried out during a year (March 2009-March 2010) in two types of buildings, a single family building outside, Stockholm (built 2000) and two apartment buildings in northern Sweden, Umeå. The apartment buildings (#1 and #2), were built 1962 with 12 and 9 apartments, respectively. Common for all studied objects, are an exhaust ventilation system with a fan operating at a constant speed and no heat recovery and that they are connected to district heating.

Extensive measurements of indoor and outdoor temperatures, used district heating for domestic hot water and heating as well as the total electricity use (households and electricity for the technical systems). In addition, the global solar irradiation has been measured in the near vicinity of the two apartment buildings located in Umeå.

To analyze the energy use, we have used average daily values together with a simplified power balance of a building. In the results presented here, the indoor temperature was taken to be the exhaust air temperature. The main simplification lies in the fact that the effects of wind are not considered together with any impact from humidity and that the heat loss coefficient between indoor and external temperature has been taken to be constant. The latter assumption is based on a constant operation of the exhaust fan in each building. Based on these simplifications the power balance of a building could be described by

$$P_h + \alpha P_{el} + P_p + P_s + P_w = F(T_i - T_o) + G_L + P_d \quad (1)$$

with $P_d = C\frac{T_d}{dt}$ and where T_d is the temperature of the thermal mass.

The contributions to heating from the sun, P_s, gained heat or heat loss due to domestic hot and cold water usage P_w, contribution from body heat, P_p, together with the dynamic heat storage, P_d, is very difficult to measure. These parameters of Eq. 1 have been treated in the following way.

P_s: Experimental data from periods around the winter solstice has been used, in order to minimize contribution from solar radiation when determining the heat loss coefficient, F

P_w: Assumed that the heat transfer from the domestic hot water circulation equals the heating of domestic cold water.
P_p: Based on data from a survey, the contribution to heating was assessed from the number family members and their presence at home.
P_d: Two different approaches A and B for pre-processing measured data have been used to minimize this contribution.

A) Averaging over a time period longer than the estimated time constant of each building.
B) Averaging over two days, that has an estimated equal change of T_d in magnitude but in opposite direction. For an ideal building that has a constant indoor room temperature and is not exposed to solar radiation, the dynamic heat storage could be eliminated by taking the average over two days for which the change in outdoor temperature are equal but opposite, for instance +5 and -5 °C. Based on this approach, an estimate of the change in the temperature of the buildings thermal mass, ΔT_d, was taken to be represented by the change in $\frac{Ti+To}{2} + \omega T_i$ between two consecutive days. The weight factor, ω, between the two terms should be used in relation to the thermal mass the two terms represent.

The advantage with B) is that the number of data is only reduced by approximately half, whereas an averaging over a time period longer than the time constant of a heavy building may reduce available data to a degree that a regression analysis becomes hazardous.

Thermal performance measures, such as the heat loss factor, ground transfer and contribution from solar radiation and gained heating from electricity has been estimated by a linear regression analysis but also the sensitivity of these parameters to the choice of indoor temperature, length of analyzed period, variation in ambient temperature etc. For a full description, see [5].

3. Results

A basic approach in this work is to use the period of the year when the contribution from the solar radiation is smallest, in order to simplify Eq. (1). In Figure 1 below, the measured global solar radiation is shown. The measurements are made at Umeå University which is in the close vicinity of the two apartment buildings, less than one kilometer.

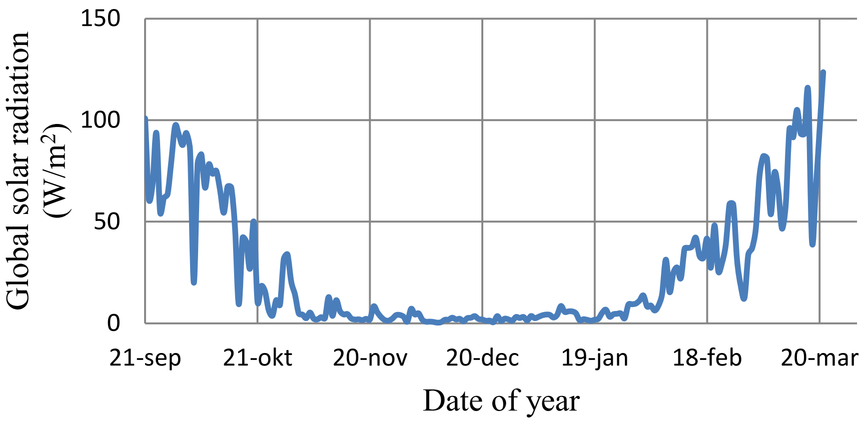

Fig.1. Global solar radiation, measured at Umeå University

When analyzing data from periods around the winter solstice (December 21: st), the contribution P_s is negligible according to Figure 1. Together with P_w = 0 and using pre-processed data to minimize the dynamic heat storage, Eq. (1) simplifies to

$$P_h + \alpha P_{el} + P_p = F(T_i - T_o) + G_L \tag{2}$$

With access to measured data of P_h and P_{el} together with P_p based on a survey, Eq. (2) becomes

$$P_t = F(T_i - T_o) + (1 - \alpha)P_{el} + G_L \tag{3}$$

Where $P_t = P_{el} + P_h + P_p$.

The total electricity use, P_{el}, is a parameter of Eq. (3) and in Figure 2 below, data from the period 1 November to February 6 is presented versus $(T_i - T_o)$. The data have been pre-processed according to B).

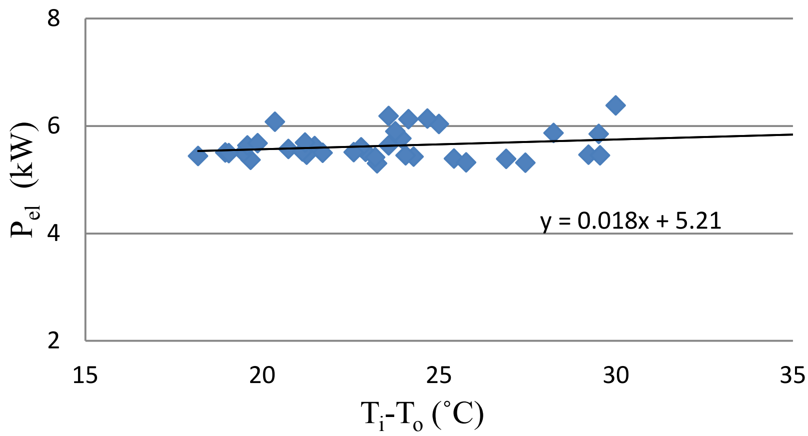

Fig.2. P_{el} versus (T_i-T_o) for building #1 together with a linear regression

As seen from Figure 2 the measured total use of electricity is fairly constant and may, with a fairly good accuracy be represented by a linear function of $(T_i - T_o)$. The pre-processing of data (according to B) reduces strongly the daily variation of P_{el} and yields similar results as pre-processing by averaging daily data over a period longer than the time constant. This behavior is found for both apartment buildings as well as the single family building.

If P_{el} may be described as

$$P_{el} = P_{el,0} + k(T_i - T_o) \tag{4}$$

a linear regression according to

$$P_t = F_t(T_i - T_o) + P_{t,0} \tag{5}$$

would, based on Eq. (3) yield the following relation between F and F_t according to

$$F = F_t - (1 - \alpha)k \tag{6}$$

based on the assumption that the heat transfer via ground is constant during the analyzed period and that gain factor, α, also is fairly constant. Since k in Eq. (4) is small (Figure 2), the impact on the value of F_t, determined by a linear regression according to Eq. 5 is very small. This means that α may be treated as constant, but also that $F \cong F_t$ since k is small and α is expected to be closer to unity than zero.

The following alternatives for pre-processing data according to A) and B) were investigated.

A*n*: Average over *n* consecutive days, where n is between four days (A4) for the single family building and six days (A6) for the apartment buildings.

B1: Apartment buildings: Since the estimated thermal mass is fairly equal for the climate shell and the internal walls, ω was taken to be equal to 1 and thus was ΔT_d taken as the change of $(T_i + T_o)/2 + T_i$ between two consecutive days.

B2: Single family building. Since the internal walls were light, ω was taken to zero, and thus ΔT_d was calculated as the change of $(T_i + T_o)/2$ between two consecutive days.

A linear regression according to Eq. (5) (Building #1 for the period 1 November to February 6) are presented in Figure 3. Data has been pre-processed according to B6.

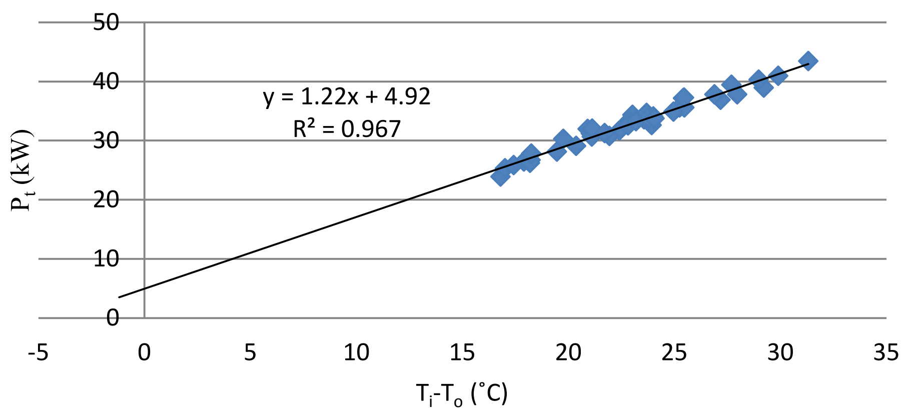

Fig. 3. P_t versus $(T_i$-$T_o)$ for building #1. The data are from the period, 1 November to 6 February 6, and the data has been preprocessed according to B6.

The results in Figure 3 support the assumption of a constant heat loss coefficient. In table 1, the results based on a regression analysis (Eq. 5) for all investigated buildings are compiled for time periods of two month around the winter solstice using different pre-processing techniques.

For the two apartment buildings, as seen in table 1, the variation in the estimate of F_t is reduced when using pre-processing of data according to B1 than compared to A6, with an average variation of 2%, and a maximum of 4%, between different analyzed periods close to the winter solstice. For the single family building the variation is within 1% for both methods of pre-processing data.

Besides F_t, the regression analysis also gives the intercept, see Figure 3, which could correspond to the heat transfer via ground during that period. But P_t includes the total electricity use, P_{el}, and the contribution to heating is only αP_{el}, where 0≤ α ≤1. This means that the for the case shown in fig. 4, the intercept $P_{t,0}$ = 4.9 kW should be reduced with (1-α)·$P_{el,0}$ to obtain an estimate of the heat loss via ground, G_L.

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Table 1. Compilation of the results based on a two month period, with different schemes for preprocessing experimental data. The relative deviation from the average value is given within brackets. For the apartment buildings the results are also given for the longest period when the measured global radiation was less than 20 W/m^2.

		F_t [kW/°C]			
		Building #1		**Building #2**	
Pre-processing		A6	B1	A6	B1
2-month	21/11-21/1	1.34 (6%)	1.23 (1%)	1.04 (4%)	1.01 (1%)
	1/11-31/12	1.22 (-3%)	1.24 (2%)	1.01 (1%)	1.02 (2%)
	1/12-31/1	1.22 (-3%)	1.19 (-3%)	0.95 (-5%)	0.96 (-4%)
$\overline{F}_t$ 2-month		*1.26*	*1.22*	*1.00*	*1.00*
	1/11-6/2	*1.26*	*1.22*	*1.00*	*0.98*

		Single family building	
Pre-processing		A4	B2
2-month	21/11-21/1	0.150 (1%)	0.148 (-1%)
	1/11-31/12	0.146 (-1%)	0.150 (1%)
	1/12-31/1	0.149 (0%)	0.149 (0%)
$\overline{F}_t$ 2-month		*0.148*	*0.149*

The value of *α*, is difficult to determine from available data. Method by using multivariate regression (PLS) [6,7] have been examined, but due to the fact that P_{el} behave very "nice" and is correlated to $(T_i - T_o)$, the uncertainty in the determination of *α* becomes very large and no clear estimates could be obtained. Of the actual electricity use in building #1, hous ehold electricity constitutes about 70% and the remaining 30% for lighting outdoors and for common areas and for the exhaust fan that is situated under the roof and thus out-side the climate shell. An approximate estimates of α, yield a value between 0.6 and 0.8. Based on this, the heat transfer via ground is estimated to be in the range of 2.9 and 3.9 kW. With access to measurements of the basement temperature of building #1, t he design of the building and the fact that the building is situated on a former sea bottom, calculation of the heat transfer via ground was performed according to EN-ISO-13370, se Figure 5.

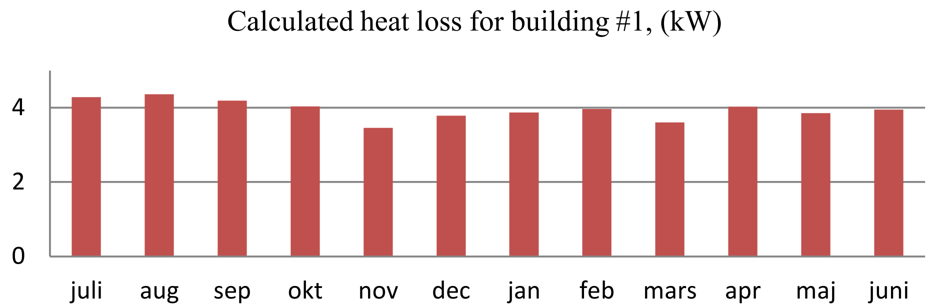

Fig.4. Calculated monthly heat loss via ground according to EN-ISO-13370, clay soil.

Figure 4 shows that the calculated heat transfer via ground both on an annual basis and for the periods analyzed are relatively constant and in good agreement with the estimated transfer of 2.9-3.9 kW for the time period closed to the winter solstice.

If the heat transfer via ground are constant over the year, the utilized solar radiation for heating, P_s, may be estimated, based on a constant heat loss coefficient, F. The results for building #1, are displayed in Figure 6 for the entire measured period assuming a constant level of the heat transfer via ground. The data presented in Figure 5 consists of daily data from 1 January to 31 March of 2010 and 1 April to 31 December 2009 and hence the step in the graph.

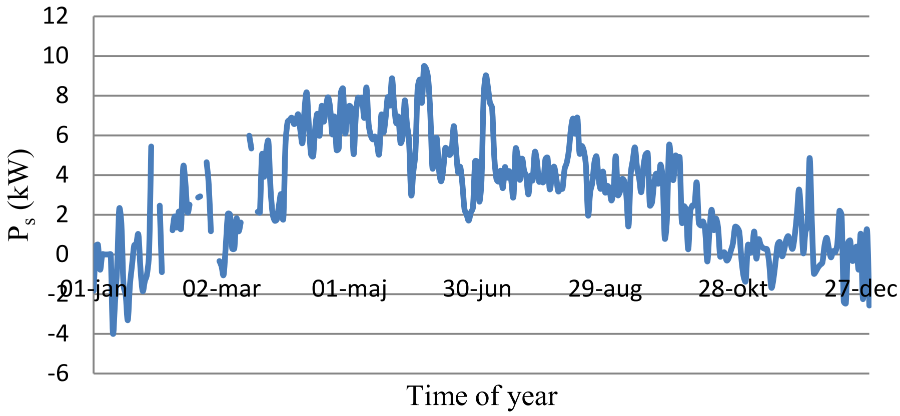

Fig. 5. Estimated gained heat from solar radiation, building #1.

At the beginning and end of the year, P_s fluctuates around zero. The main reason behind this is the use of daily data, and the variation thus reflects dynamic heat storage. If data were pre-processing according to B6, these fluctuations would be reduced, but at the same time, data could not be present in this way since time loses its meaning. The fact that P_s is lower than expected around the summer solstice is probably explained by the Swedish tradition to have open doors and windows during our short but cherished summer.

Since the theoretical calculations of the monthly heat transfer via ground, for the single family building indicated a fairly large variation over the year, a similar analysis is not possible. But based on an estimate of $0.6 \leq \alpha \leq 0.8$], an estimated range for the heat transfer via ground, during the 2-month period of 0.22 t o 0.39 kW was obtained, to be compared with the calculated 0.5 kW for this split level building. Since the heat transfer via ground has a strong variation over the year, could only the difference between gained solar radiation and heat transfer via ground be estimated, (P_s - L_G), if α is known and constant. With α = 0.7, the results shown in Figure 6 was obtained. For the single family building, only incomplete data was available for the summer period and are thus missing in Figure 6.

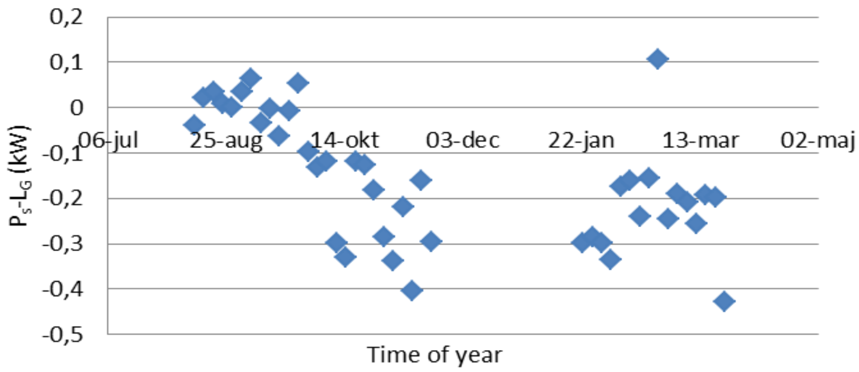

Fig. 6. Estimated $P_{sol} – L_G$ over the period where measured data was available.

Figure 6, indicates that the contribution to heating from solar radiation exceeds the heat transfer via ground until the beginning of October and this situation is reversed in the end of March.

4. Discussion

In this work we have used experimental data from time periods close to the winter solstice and data has been pre-processed to reduce dynamic heat storage effects. Based on this and with access to extensive measurements, the heat loss factor has been determined with a high precision for the investigated buildings. Unfortunately, a fundamental problem remains; no correct answer is available for the heat loss coefficient as reference.

However, based on the high precision and the fact that the obtained estimate of the heat transfer via ground are in good agreement with calculations based on ISO-EN-13370 indicates that the used approach gives consistent results. In addition, the estimated gained solar radiation, of Figure 4, increases in a basically linear way when plotted versus the global solar radiation. This means that the obtained results could be used as feedback to energy calculations.

The buildings investigated in this study have a simple HVAC-system and the next step is therefor to extend this work to more energy efficient buildings with complex systems and also to focus on methods to obtain an estimate of the gain factor α for the electricity use. This could be achieved by a close survey of where and for what the electricity has been used or using multivariate methods or artificial neural networks [8,9].

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Sustainable use of electrical energy at the University of Sonora, Mexico

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Abstract: The University of Sonora as a sustainable higher education institution has been committed for almost two decades to continuously increase its involvement with society by helping in their transition to more sustainable lifestyle and recently by implementing and maintaining a Sustainability Management System (SMS) on Campus which it is actually certified under the ISO 14001:2004 international standard. One of the sustainability programs within the SMS is the Sustainable Management of Electrical Energy (SMEE) that comprises not only energy efficiency initiatives but also energy conservation initiatives. This paper is aimed at describing the experience of the University of Sonora in fostering changes on attitudes and behaviors that result in energy conservation. Before the implementation of the SMEE was common to find lack of interest among students, professor, and employees for energy conservation behaviors such as shutting down air conditioners or turning off lights when they were not necessary given as a result a repeatedly energy wastage and consequently, the generation of CO2 emissions that increase climate change. Findings presented in this paper indicate that changes on attitudes and behaviors can generate good practices for conserving energy and reduce the environmental burden of universities. Sustainability indicators have proven the efficacy and efficient of the SMEE; at the financial dimension, the SMEE has reached savings of over 5, 840 USD in three years; from the environmental dimension, the SMEE has avoided the emissions of 33,287 kg of CO2, but the most important indicator come from the social dimension where wasting behaviors have been modified by increasing community awareness. Positive trends on the SMEE indicators suggest the increasing of awareness of the impact of energy wastage among the university community who act in consequence of this in favor of the environment. Additionally, an awareness survey was conducted to 650 members of the university community such as faculty, students, administrative staff and service personnel to reveal which energy conservation initiatives would be willing to follow, such as: turn off the lights at the term class, turn off the air conditioned when the classroom is not in use, close doors and windows to avoid that the air-conditioning air leakage, etc. Findings show that most of participants are becoming aware of the impact of the energy wastage and they are willing to participate in the SMEE in order to reduce those environmental impacts. Findings also show that willingness of the university community for participating or supporting more than one energy conservation initiatives on campus; the behavior of turn off lights and air conditioners when finishing the class is the preferred option.

Keywords: *Energy conservation, Sustainable management system, Climate change*

1. Introduction

The dependence of petroleum and coal has had terrible consequences for the planet, such as global warming, pollution, and the dependency of some countries over other countries [1]. On global scale, climate change has raised lots of concerns; international initiatives such as the UN Framework Convention on Climate Change have raised alertness about the role of energy in human's impacts reflecting on the environment and the same manner effecting for sustainable development [2]. There is no doubt that human activities alter the climate mainly where CO2 is emitted to the atmosphere producing the greenhouse effect [3]. Clearly, this situation has forced individuals and organizations to put into practice efforts to reduce energy consumption and in particular energy wastage. According to EPA, opportunities for energy conservation are increasingly available in almost every application in any setting such as homes, schools, offices, and industrial environments [4].

The University of Sonora in its intent to become a more sustainable higher education institution has been committed for almost two decades to energy conservation by implementing and maintaining a Sustainability Management System (SMS) on Campus [5].

After more than 5 years of its implementation, the SMS succeed, in July 2008, an ISO 14001:2004 external audit and as a consequence it got the ISO certification; two years later, the SMS was challenged again by two follow-up audits that were conducted and approved with success. So far, this accomplishment has not been mirrored by any other public university in Latin-America.

The goal of the SMS is the protection of natural resources and the prevention, reduction and/or elimination of environmental and occupational risks generated by the members of the university community when using resources in order to carry out its substantive functions of teaching, research, outreach & partnership, and stewardship.

One of the sustainability programs within the SGS is the Sustainable Management of Electrical Energy (SMEE) that comprises not only energy efficiency initiatives but also energy conservation initiatives with the purpose of reducing energy consumption and in particular, energy wastage. For the University of Sonora, energy conservation is related to human behavior; therefore, the SMEE strives to changes negative lifestyles of its community.

Before the implementation of the SMEE was common to find lack of interest to energy conservation initiatives among students, professor, and employees; hence, electrical bills and CO2 emissions were out of control; however, this situation has gradually changed.

Under this context, this paper is going to be aimed at describing the experience of the University of Sonora in fostering changes on attitudes and behaviors that result in energy conservation.

2. Methodology

The Sustainable Management of Electrical Energy (SMEE) Program has several steps that work integrated to reach the strategic objective of changing of attitudes and behaviors and energy efficiency initiatives. These steps can be summarized as follows:

2.1. SMS Scope

The scope of the SMS is the engineering college; this means that energy conservation efforts are focused on facilities within this college. The engineering college is located at block five of the campus which includes eleven typical buildings of a higher education institution such as classrooms, laboratories, and administrative offices.

2.2 Inventory of electrical equipment and accessories

Commonly, energy is used in lighting, computers and peripherals; science equipment and office devices. The inventory of electrical equipment and accessories is conducted annually and involves not only the accounting but also the physical shapes of equipment and installations within the scope of the Sustainability Management System (SMS). The minimum information required by equipment and / or accessory is their power consumption on watt, or its equivalent, as well as their physical condition at the time of conducting the inventory.

2.3 Monitoring procedure.

The monitoring procedure is intended to verify if the electricity is being used efficiently and rationally by the university community. This procedure is done each day, but reporting is on a weekly basis; this consists on certain number of visits made by the reviewers assigned to specific areas in buildings to record if there is a waste of energy. Each wasteful behavior is considering a failure and, if it is possible, interventions on situ must be conducted to timely eliminate and / or reduce energy wastage.

2.4 Indicators

Sustainable indicators are calculated based on weekly records. There are several factors to consider for measuring performance. Wastages are expressed in financial, environmental, and power metrics. Indicators from 2008 to 2010 are shown in tables 2 to table 4.

2.5 Dissemination of information

Increasing energy conservation awareness among the university member is imperative in order to reduce energy wastage behaviors. A key requirement of the SMS is the divulgation of indicators on a quarterly basis. This is done throughout flyers, brochures, and emails.

2.3 *Sustainability Management System (SMS) Survey*

A survey was conducted to faculty members, students, administrative staff and service personnel to indicate which energy conservation initiatives would be willing to follow, such as: turn off the lights at the term class, turn off the air conditioned when the classroom is not in use, close doors and windows to avoid that the air-conditioning air leakage, etc. The surveys were applied to 650 members of the university community. The selection of individuals was selected by a simple random sampling method. The sampling Eq. (1) is following showed:

$$n = \frac{Z^2 \; p \, q \; N}{N\,E^2 + Z^2\,pq} \qquad (1)$$

Where n is the sampling size, Z is confidence level, p is positive variation, q is negative variation and N is population size.

3. Results

3.1 Awareness Survey

The results of the SMS survey are presented in Table 1. In general, most of participants are becoming aware of the impact of the energy wastage and they are willing to participate in the SMEE in order to reduce those environmental impacts. Findings also show that willingness of the university community for participating or supporting more than one energy conservation initiatives; the behavior of turn off lights and air conditioners when finishing the class is the preferred option.

Table 1 Awareness survey

Item	Yes	No
Support the SMS	75	25
Energy Wastage Awareness	70	30
Willingness to participate in the SMEE	90	10
Participation on more than one initiative	95	5
Turn off the lights/ classrooms/room	38	62
Turn off the AC	35	65
Closing door or window/ AC	18	82
Turn off the PC Monitor	9	91

3.2 Calculations of electrical energy metrics

Table 2 shows the monitoring records for 2008, there were recorded 1759 energy wastage events, denominated failures; however; it was possible to intervene an avoid the impacts associated with in 882 out of those 1759. Thank to these interventions, there were avoided the wastage of 10,188 kw; and consequently, the emissions of 9271 kg of CO2. In monetary terms, savings were 1,626 USD.

Table 2. 2008 Sustainability Indicators

Indicator	Units	Amount
Failures	events	1759
Interventions	events	882
Avoided Energy Wastage	kw	10,188
Avoided CO2 emissions	kg	9271
*Savings	USD	1,626

* Exchange rate: US$ 1.00 = MX$ 12.53 at December 14, 2010.
Source: Banco Nacional de México, S.A.

Records for the entire 2009 are shown in Table 3. During this year, there were 446 interventions that avoided the wastage of 11,579 kw and the emissions of 1265.63 kg of CO2. This represented a saving of 1,848 dollars for the institution.

Table 3. 2009 Sustainability Indicators

Indicator	Units	Amount
Failures	events	2,322
Interventions	events	756
Avoided Energy Wastage	kw	11,579
Avoided CO2 emissions	kg	10,536
*Savings	USD	1,848

* Exchange rate: US$ 1.00 = MX$ 12.53 at December 14, 2010.
Source: Banco Nacional de México, S.A.

Table 4 shows records for 2010; the energy wastage avoided was 14,812 kw that represents 13,479 kg of CO2. Figure 1 illustrates the 2008-2010 trend of each indicator; it is possible observe on it the improvements per year of each indicator which suggest that SMEE is fulfilling its goal.

Table 4. 2010 Sustainability Indicators

Indicator	Units	Amount
Failures	events	3,467
Interventions	events	936
Avoided Energy Wastage	kw	14,812
Avoided CO2 emissions	kg	13,479
*Savings	USD	2,364

* Exchange rate: US$ 1.00 = MX$ 12.53 at December 14, 2010.
Source: Banco Nacional de México, S.A.

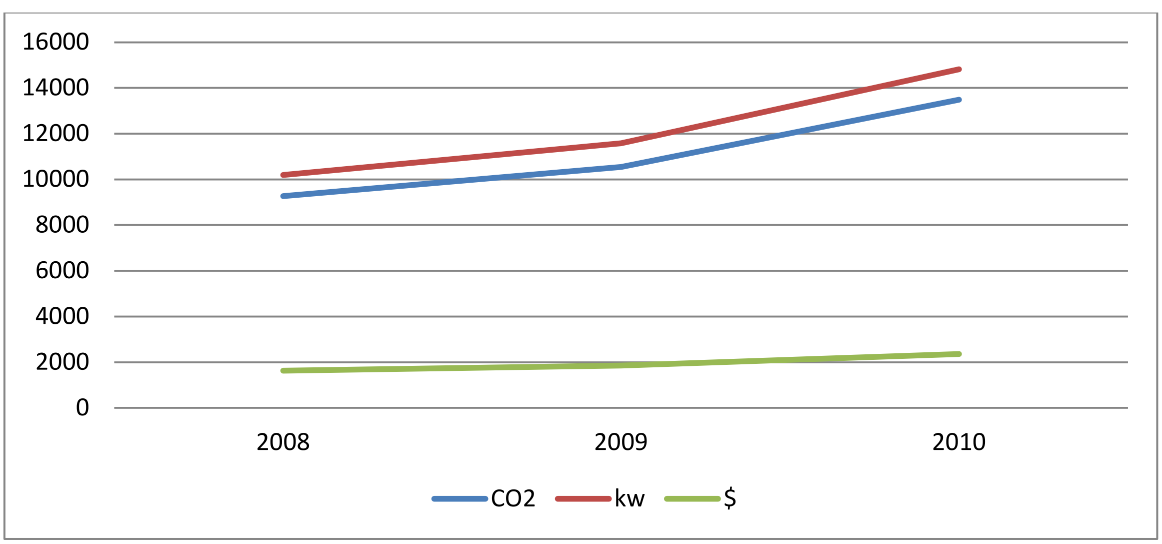

Fig 1. Sustainability Indicators Trend

4. Conclusion

The University of Sonora, through initiatives like the Sustainable Management of Electrical Energy (SMEE) Program, shows that it is possible for universities to reach important economic, social and environmental outcomes.

Findings presented in this paper indicate that changes on attitudes and behaviors can generate good practices for conserving energy and reduce the environmental burden of universities.

Sustainability indicators have proven the efficacy and efficient of the SMEE; at the financial dimension, the SMEE has reached savings of over 5, 840 USD in three years; from the environmental dimension, the SMEE has avoided the emissions of 33,287 kg of CO2, but the most important indicator come from the social dimension where wasting behaviors have been modified by increasing community awareness. Positive trends on the SMEE indicators suggest the increasing of awareness of the impact of energy wastage among the university community who act in consequence of this in favor of the environment.

Result from the 2010 survey indicated the willingness of the community to support and fully commitment to the SMS and in particular with the SMEE.

Become a more sustainable university is a hard task that cannot achieve without the participation of the community, mainly students; they need to get a better understanding of human health exposures and environmental impacts generated because energy wastage.

Turning off lights when the classrooms are not being used or by closing doors when the air conditioned equipment is in use, it can be very helpful for sustainability on campus; yet, before the operation of the SMEE, these events were very common in university lifestyle. Although today those practices still are present, they are not the common denominator. It is clear that the path to sustainability is full of obstacles; yet, there is no other way.

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Energy and Environmental Aspects of Data Centers

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Abstract: Data centers have become an essential operational component of nearly every sector of the economy, and as a result growing consumers of energy and emitters of greenhouse gases (GHGs). Developing strategies for optimizing power usage and reducing the associated life cycle GHG emissions are critical priorities for meeting climate policy objectives. We investigate data center power management through virtualization, a technique that consolidates data center workloads onto fewer computing resources within a data center and deploys computing resources only as needed. Based on an experimentally validated dynamic resource provisioning framework applied to a small scale computing cluster at Drexel University that employed lookahead control, a control scheme using virtualization demonstrated a 25% reduction in power consumption over a 24-hour period. Using the power savings results from the virtualization experiments, and extrapolating those savings to a medium-sized data center that hosts 500 servers, we estimate the avoided life cycle GHG emissions for implementing a virtualization strategy in hourly time-steps for marginal and average electricity units over a 24-hour day during the month of August, when electricity loads are typically highest for the year. Results from this work show virtualization could avoid the emission of approximately 0.8 to 1.2 metric tons CO_2e/day.

Keywords: *Energy, Power management, Buildings, Information technology, Life cycle assessment*

1. Introduction

Data centers have become an essential operational component of nearly every sector of the economy, and are additionally growing consumers of energy, and as a result, a burgeoning source of greenhouse gas (GHG) emissions. In 2008, data centers worldwide emitted 170 million tons of CO_2, an output on parallel with the total GHG inventory of countries such as Argentina and the Netherlands. Moreover, data center GHG emissions are expected to grow four-fold by 2020 and surpass those of the airline industry [1]. Therefore, developing strategies for optimizing power usage and reducing the associated life cycle GHG emissions are critical priorities for meeting climate policy objectives.

This paper investigates use of new techniques for server power management and validates them using a small-scale computing testbed. The validation experiments are integrated with environmental life cycle models that evaluate the consequential reduction in life cycle GHG emissions of computing equipment and data centers as a whole as a result of the power management strategy in combination with expected input sources of electricity and regional electricity mixes. We accomplish this by coupling the data center power optimization strategy with a life cycle model of electricity supply that examines the average electricity mix and marginal units of power supply over a 24-hour period. The power management strategy we examine is known as virtualization, a technique that consolidates multiple online services onto fewer computing resources within a data center and deploys computing resources only as needed.

1.1. Background

Energy management in data centers involves three main components of computer hardware, building, electricity infrastructure: power load distribution of the data operations; cooling systems employed to control ambient conditions in the buildings that house the computers (the HVAC systems); and the electric power supply system (the electricity grid) and sources that make up each composite unit of electricity (measured in kWh) delivered to the data center, consisting of hydro-electric, nuclear, coal, natural gas, oil, and renewable sources (e.g., wind power, biomass, geothermal, etc). In addition to the in-use consumption of energy and emission of GHGs, the three components of a data center (building, hardware, electric utility infrastructure) carry "upstream" energy and GHG emissions owing to the processes and resource inputs and capital equipment used to produce (mine, manufacture, transport, and construct) a data center.

A typical data center serves a variety of companies and users, and the computing resources needed to support such a wide range of online services leaves server rooms in a state of "sprawl" with under-utilized resources. Moreover, each new service to be supported often results in the acquisition of new hardware, leading to server utilization levels, by some estimates, at less than 20%. With energy costs rising and society's need to reduce energy consumption, it is imprudent to continue server sprawl at its current pace.

Virtualization provides a promising approach to consolidating multiple online services onto fewer computing resources within a data center. This technology allows a single server to be shared among multiple performance-isolated platforms known as virtual machines (VMs), where each virtual machine can, in turn, host multiple enterprise applications. Virtualization also enables on-demand or utility computing, a dynamic resource provisioning model in which computing resources such as the central processing unit (CPU) and memory are made available to applications only as needed and not allocated statically based on the peak workload. By dynamically provisioning virtual machines, consolidating the workload, and turning servers on and off as needed, data center operators can maintain service-level agreements (SLAs) with clients while achieving higher server utilization and energy efficiency.

In this research paper, we apply an experimentally validated dynamic resource provisioning framework for integrated power and performance management in virtualized computing environments developed by Kusic and Kandasamy [2,3,4]. Prior research by the authors demonstrated the novelty of the application of advanced control, optimization, and mathematical programming concepts to provide the necessary theoretical basis for this framework. The authors posed the power/performance management problem as one of sequential optimization under uncertainty and solve this problem using limited lookahead control (LLC), an adaptation of the well-known model-predictive control approach [2]. The framework solves an online optimization problem that maximizes the performance objective over a given prediction horizon, and then periodically rolls this horizon forward. The LLC approach allows for multiple objectives (such as power and performance) to be represented as optimization problems under explicit operating constraints and solved for every control step. It is also applicable to computing systems with complex non-linear behavior where tuning options must be chosen from a finite set at any given time (such as the number of physical machines and/or VMs to power up/down). Experimental results obtained using a small-scale cluster show significant promise that LLC can systematically address performance/power problems within the highly dynamic operating environment of a data center. Table 1 summarizes results from prior research that demonstrated that the server cluster, which hosted six heterogeneous servers that host multiple online services, when managed using LLC saved, on average, 26% in power consumption costs over a 24-hour period, when compared to the uncontrolled case when no servers are ever switched off.

Table 1 Control performance, measured as average energy savings and SLA violations, for different workloads[a]

Workload	Total Energy Savings (%)	% SLA Violations (Silver)	% SLA Violations (Gold)
Workload 1	18	3.2	2.3
Workload 2	17	1.2	0.5
Workload 3	17	1.4	0.4
Workload 4	45	1.1	0.2
Workload 5	32	3.5	1.8

[a] Notes: The cluster hosts two services, termed "Gold" and "Silver" enabled by the Trade6 and DVDStore applications. The services generate revenue as per a non-linear pricing scheme that relates the achieved response time-300 ms for each Gold request and 200 ms for each Silver request-to a dollar value. Response times below the threshold result in a reward paid to the service provider, while response times violating the SLA result in the provider paying a penalty to the client.

2. Methodology

We apply life cycle assessment (LCA) methods following ISO 2006 [5] procedures to examine the potential for reducing life cycle greenhouse gas (GHG) emissions when employing power management via virtualization. We examine avoided electricity consumption and GHG emissions based on hourly marginal units of electricity in the Pennsylvania-New Jersey-Maryland (PJM) power mix, and in this way use a consequential LCA approach to the problem [6]. The system boundary investigated consists of the data center work load management on 500 central processing units (CPU), overhead building HVAC needs, and the power grid mix that comprises power supply to the data center (Figure 1). A complete LCA model of the system performance outlined in Figure 1 would normally account for the "upstream" energy and associated GHG emissions of the building, computer hardware, and electric utility infrastructure) in addition to their contributions during operation. However, in this paper we limit our scope to operation related energy and environmental performance to isolate the performance of the virtualization strategy independent of system attributes, but we evaluate the changes in life cycle performance induced on the system by the virtualization strategy.

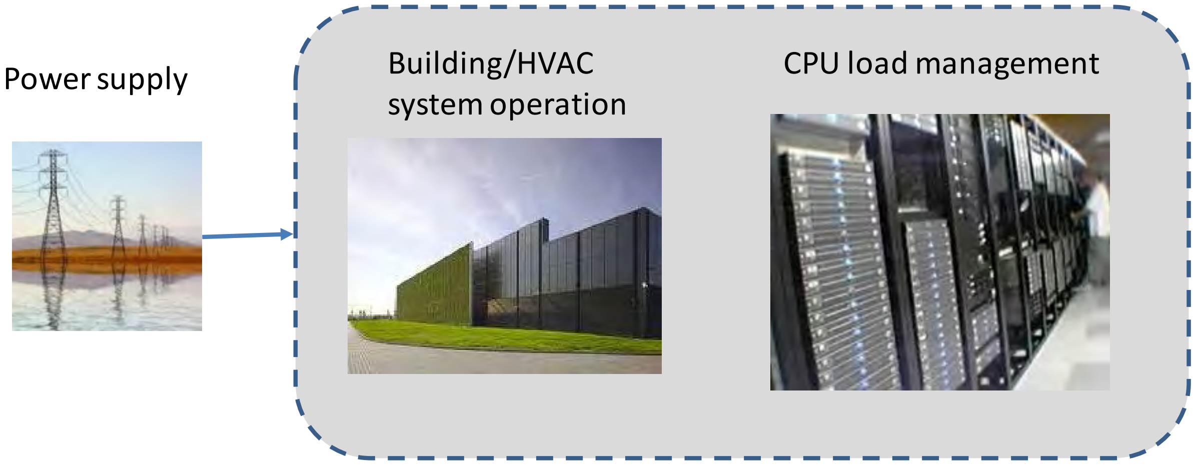

Figure 1: Systems boundary comprising data center and power supply

2.1. Power Management by Virtualization

As noted above, experiments conducted on a cluster of Dell PowerEdge servers indicate that the controller achieves a 25% to 46% reduction in power consumption costs for six different workloads over a 24-hour period when compared to an uncontrolled system while achieving the desired QoS goals.

Figure 2 shows the LLC scheme where we obtain the control actions governing system operation by optimizing the forecast system behavior for the performance metric over a limited prediction horizon [3]. The controller obtains the sequence of control actions that results in the best system behavior over this horizon and applies the first action within this sequence as input during the current time instant. It then discards the rest and repeats this process at each time step. Thus, in a predictive-control design, the controller optimizes the performance metric at each sampling-time instance, taking into account future variations in the environment inputs and their effects on system behavior.

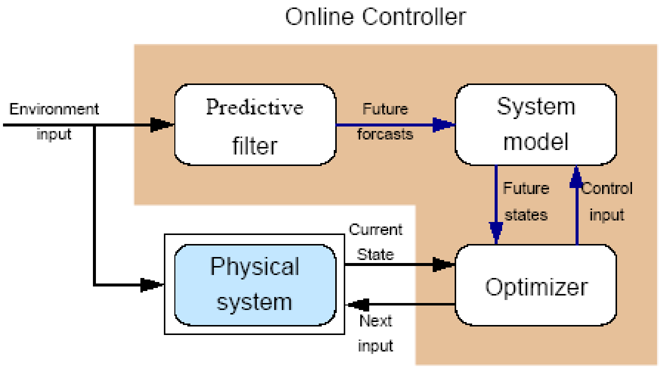

Fig. 2: Structure of the limited lookahead controller

The computer testbed cluster, when managed using LLC saves, on average, 26% in power consumption costs over a 24-hour period, when compared to the uncontrolled case when no servers are ever switched off. Also, when the incoming workload is noisy, the risk-aware controller provides superior performance compared to a risk-neutral one by reducing both SLA violations and host switching activity.

2.2. Life Cycle Inventory Analysis

We constructed a life cycle assessment (LCA) model focused on the consequential GHG emissions avoided through implementation of the virtualization experiments scaled to a small-medium sized data center hosting 500 CPUs. We applied tests from workload simulations that achieved a 41% energy savings relative to the uncontrolled case noted in section 2.2 and assume that power savings scale linearly from the testbed cluster experiments to the 500-CPU data center. For the LCA model that we construct here, we consider the reduced demand for power to the data center resulting from consolidating workloads onto fewer machines. Therefore with respect to unit processes considered in the LCA model, we take into account only the power supply needed for the CPUs in the data center, and do not take into account optimizing the HVAC system shown in Fig. 1. However, we note that a control scheme that seeks to minimize overall energy consumption can include inputs from the building cooling systems and environmental ambient conditions.

3. Results

A systematic analysis of energy savings allowed through optimization of power management in a data center requires consideration of the electricity supplying the data center and the upstream fuel/resource extraction and transport of energy sources to individual power plants (e.g., coal, nuclear, natural gas, and fuel oil). Typically LCA models employ life cycle inventory (LCI) data that describe electricity grid mixes averaged over time. Over a year, the national U.S. electricity grid tends to average out to approximately 51% coal, 21% nuclear, 16% natural gas, 7% hydro-electric, 3% petroleum, and 3% other, including renewable sources [7]. However, around the different regions of the U.S., regional averages are known and can be used to estimate net life cycle emissions related to power consumption.

LCA attempts to quantify the resource intensity and damages associated directly with the flow of resources and wastes associated with products, processes, and activities, or more generally, "systems". Analysts have tried for some time to track inputs and outputs across different economic sectors in order to capture actual energy and materials consumed for those systems. The structure of electric power distribution within a regional grid does not make it possible to trace individual electrons from source to sink, which is why analysts use average electricity mixes. In the case of data centers, a better approach for understanding power consumption by source, is to track electricity consumption by time of day, as this would show how the data center consumes electricity during peak and off-peak times, and thus the implications for using coal, the highest carbon emitting power sources, versus natural gas, the more efficient of the carbon-emitting sources.

Another debate in LCA literature regarding the trace of electricity usage is the question of whether to count the marginal or the average unit of electricity output. Some argue that each additional unit of demand placed into an electricity grid should correspond to the marginal unit consumed. For example, if a new data center is constructed and it sources its power from the Northeast electricity grid, the marginal unit approach would assume that electricity consumed came from the last kWh of output, the marginal source, since the overall mix at any given time is already meeting existing demand. Analyzing the problem this way, we would expect that a new data center built into a region and relying on electricity supply, would therefore use the marginal unit at each time step during the day. Put another way, any savings in energy from the data center would save GHGs from the marginal unit of output. For the majority of the peak hours, of the day, this could reduce coal-sourced power. At mid-peak hours this may reduce lower-GHG emitting natural gas sources, and in off-peak hours it may save coal-GHG emissions. Approaching the problem this way, we took data from a typical power supply curve on a peak August month, approximated the electricity mix based on peak load distribution curves (Figure 3), and then approximated the mix and GHG savings or avoided coal power based on a data center optimization strategy.

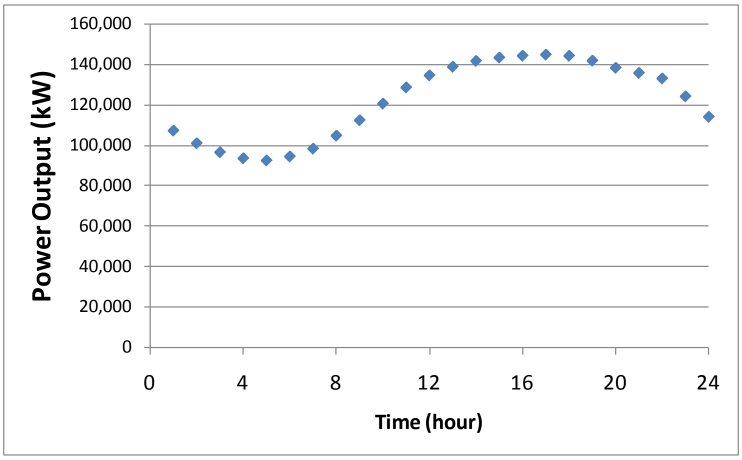

Figure 3: Peak load distribution in August 2006 (source: PJM)

The energy savings over the 24 hour day allow up to 61% power savings during late hours and early afternoon, when marginal sources shift between coal and natural gas. Figure 4 shows the energy savings over the 24-hour period resulting from optimizing workloads in the data center (see References [3] and [4] for further detail on the workload trace and optimization scheme applied). The largest energy savings occur during hours 3 to 15 of the day, corresponding largely with peak power demand times. Accordingly, there could be significant savings in net life cycle GHG emissions from fossil energy sources.

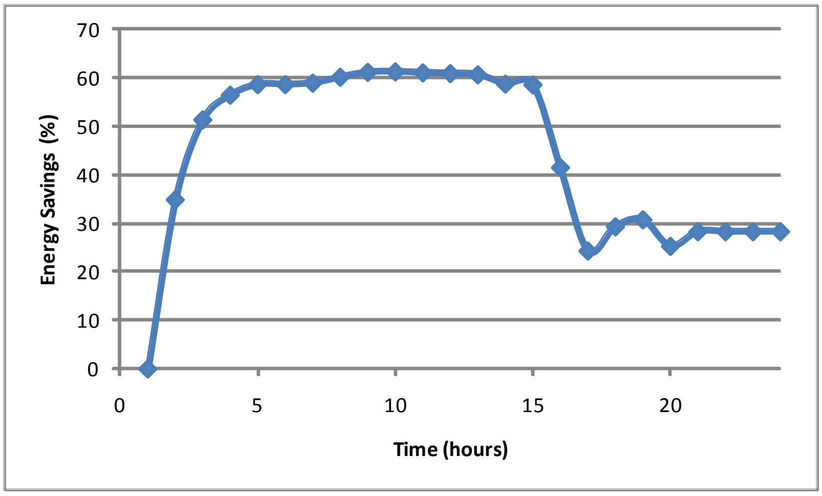

Figure 4: Energy Savings over a 24-hour period estimated in 2-minute intervals

We combined the hour-by-hour energy savings estimates with the life cycle electricity supply measured in average and marginal units based on the PJM electricity grid. Figure 5 shows the avoided GHG emissions from deploying the virtualization strategy. We see that counting the marginal unit of electricity results in a larger estimate of avoided GHG emissions. This is especially evident between hours 4 through 11, and is the result of an expected reduction in GHG emissions from coal-based electricity, the marginal unit used during that time interval.

When we sum up the avoided GHG emissions over the day by integrating over the two curves shown in Figure 5, we find that a medium sized data center can avoid 0.8 metric tons CO_2e day^{-1} and 1.2 metric tons CO_2e day^{-1} when counting the average and marginal units of electricity avoided, respectively.

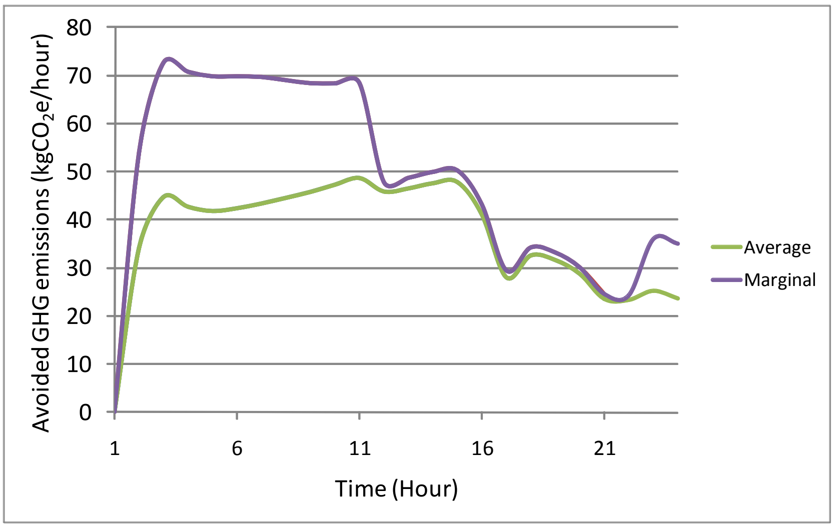

Figure 5: Estimated avoided greenhouse gas emissions resulting from Energy Savings over a 24-hour period estimated in 2-minute intervals

4. Discussion

This research demonstrates the usefulness of LCA models to estimate the full set of resources saved and environmental damages avoided by power management in data centers. We focused on energy savings enabled through power management. During runtime, the data center is typically managed to reduce resource consumption from the computing, power and cooling infrastructures, and SLAs are used to define the operational requirements of the infrastructure based on the desired performance. The life cycle approach builds in the upstream resources that supply the data center, and time-of-day analysis further delineates specific resources consumed coupled with typical demand patterns of internet resources.

The model tested herein describes performance of one data center located in a particular climate zone during summer peak power demand times, with electricity supply from that zone. This may not be the case in practice since data centers are located throughout the world and different data centers may be deployed as coupled systems when needed in order to optimize performance constraints other than energy/environmental. Knowing this, there may be opportunities to migrate workloads to data centers around the globe to take advantage of latitudes and climates that have the ability to employ passive cooling, and thereby reduce further the need for energy demand on data center HVAC. Design and control of the data centers may also create synergies with renewable power such as wind that tend to go online at night or potentially other day-time renewable energy sources such as photovoltaic for electricity supply. Through scenario analysis that uses LCA, novel building and locating strategies can be identified to further reduce the energy and carbon intensity of this sector. Understanding the interaction between data center location and real time power consumption is critical to optimizing computer cluster usage, since demand during peak hours tends to source marginal sources of power (coal), which tend to be the highest CO_2 emitting sources, rather than low-emission alternative sources of energy. These aspects will be investigated in relation to data center design, resource planning, and operation in future work.

There is much opportunity to improve data center performance as part of building design for specific climate zones and in selecting power aware computing hardware. Addressing building design, cooling strategies may include locating the data center on the ground floor or in underground spaces. Certain design approaches for passive cooling of the data center include use of underfloor air distribution systems with natural convection to create zoned ecosystems around equipment, localized air-handling units to redirect warm air from equipment rooms to other building zones, and outside air for cooling. Much additional energy savings can be achieved through coupling building/architectural design components into the power management and control strategy. Temperature sensors, embedded in the physical infrastructure, can be used to guide resource-provisioning decisions that consider the data center as a whole rather than at the level of an individual cluster(s). Workload can be dynamically managed taking into account the impact of provisioning decisions on the overall operating cost of the data center (for example, cooling costs). Automated migration of a virtualized workload from one set of servers located in a hot zone to a cooler zone in the data center (or one that costs less to cool) has potential to significantly reduce cooling costs and overall energy and GHG emissions.

Building on the preliminary results discussed here, our future work will aim to develop a control framework wherein power/performance criteria can be applied to all aspects of data center operation. Such a framework would aim to analyze the three critical components, hardware, building, and electric utility infrastructure (Figure 1) for designing “green” data centers on a life cycle basis, along with operational control and location choice.

Acknowledgements

This research was supported by the Drexel Engineering Cities Initiative (DECI) at Drexel University. Spatari thanks A.E. Huemmler of the University of Pennsylvania for comments and discussion on this manuscript.

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An Intelligent Knowledge Representation of Smart Home Energy Parameters

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Abstract: Homes in today's world tend to include more and more electrically powered devices. Much effort is put on improving these facilities, but their integration towards a smart home often remains unconsidered. While there are some promising approaches to integrate devices with the help of knowledge bases, they are still not fully convincing. In all cases they fail to cover the energy behavior of installed devices which is a severe shortcoming with respect to the increasing energy demand of a home. As most residents are still unaware where the energy is consumed and which actions eventually lead to a lower demand, an energy related knowledge representation is of importance. This paper proposes such an energy knowledge base modeled as ontology. This artifact comprises a comprehensive collection of miscellaneous energy related information and allows home automation systems to make intelligent decisions upon this knowledge. Using the ontology, energy consumption in the home itself can now be optimized by executing intelligent control strategies that incorporate and exploit the additional knowledge in their algorithms. Likewise, also renewable energy suppliers are represented and may be considered by a smart home system in order to reduce the overall ecological footprint of the residents and provide additional services for home control.

Keywords: *Energy Parameters, Smart Homes, Ontologies*

1. Introduction

The deployment of automation technology in the home offers several attractive benefits, among them most prominently increased energy (or even resource) efficiency, improved residential comfort and peace of mind for the home owner. As private households are undoubtedly one of the main energy consumers today, also a positive effect for the environment can be expected if energy consumption is reduced. In the last decade, **smart homes** have emerged as the keyword for such automated dwellings. The vision is a house populated by a multitude of devices (actuators and sensors) that cooperate in an intelligent way to control different domains of the home such as lighting/shading, heating/ventilation/air-conditioning but also home appliances and consumer electronics. While in building automation well established solutions have already existed for a longer time, additional challenges arise for systems that need to be tailored to the needs of private households: In this domain, integration of diverse appliances into a homogeneous system is far from trivial due to different interfaces, usage paradigms and operation modes. Additionally, the intelligence promised by smart homes requires tailored use cases and scenarios to be developed and offered by the future systems. Consider, for example, a smart home system automatically scheduling a dishwasher to start when energy from renewable energy sources becomes available, e.g., when the sun is shining on a photovoltaic installation or once some energy provider offers cheap energy. Such a system could also be the central point to integrate demand side management [1] applications into the house, e.g., by shifting energy intensive operations to a more convenient point in time. These use cases require not only all devices to be interoperable but also demand some understanding of the current state of the affected environment. Information about the building, its embedded devices, its tenants and their

[1] This work was funded by the HdZ+ fund of the Austrian Research Promotion Agency FFG under the project 822170.

behavior as well as of the inside and outside conditions must be available and represented in some way for the smooth and successful operation of the smart home system.

2. Motivation

More and more energy facilities in modern buildings become interlinked in order to allow advanced control over various parts of the house. Up to now, however, only basic services are featured: lights and shutters can be linked via pre-configured scenes, or, for example, a central "OFF" function can be provided. More intelligent functions like ensuring comfort in a residential home while at the same time behaving energy efficiently are not feasible yet. The reasons for this are manifold, but one of the most important issues is the interoperability of devices. This integration is often not guaranteed due to the heterogeneity of underlying technologies. An orchestration of their services can often just be achieved through interconnection using gateways which are difficult to configure and may still limit inter-device services [2]. Once integrated, all devices may be controlled and operated through a central home control system. However, this does not automatically imply that also all data of the devices becomes available throughout the integrated system. Based on these current shortcomings of smart homes, two main challenges can be identified: the need for an integrated system where all devices can equally participate, and some storage facility that provides pervasive access to all kinds of data originating from devices, the smart home or other sources. Thus, an abstract view on the underlying technologies is desirable to facilitate the integration of different building automation devices and also home applications. Further, often it is not known to a resident how much energy certain devices in the household consume. Many devices also waste energy when they are currently not in use e.g., during their stand-by times. To reduce these idle times it would help a smart home to know about the occupancy of rooms and during which times facilities in the home are mainly used. Especially in the case of consumer electronics like TVs it makes sense to unlink them from the power grid during times when the residential home is not occupied and just turn them back into stand-by mode when usage is expected. For household appliances like dishwashers or washing machines it would be beneficial to know how to schedule tasks with respect to the energy supply side. This way, peak loads on the power grid can be reduced and at the same time the environmentally friendliest energy provider can be chosen. The definition of energy tariffs and providers in the knowledge base of the smart home therefore allows yet unconsidered improvements with respect to energy consumption. The representation of such facts needs to be sophisticated and open to changes, because it is not only likely that new and probably unknown devices are added to the smart home, but also information about energy providers and their tariff schemes are changing frequently. These difficulties are addressed by the realization of a knowledge base for smart homes that is proposed in the following chapter.

3. Methodology: An Ontology for Smart Homes

The intelligent information representation in smart homes is necessary, not least because of the vast amount of influences to be considered for an energy efficient operation of the building. To model the data dependencies in an expressive way, the representation as OWL ontology is proposed. OWL is a recommendation of the World Wide Web Consortium (W3C) [3] and its Semantic Web Initiative. The Web Ontology Language bases its form and representation on a formal logic called Description Logic (DL) [4]. With this formal grounding, relationships and concepts existent in DL as well as the possible logical implications can be used in OWL for modeling the represented domain in a sophisticated manner. This way, more complex structures can be expressed than in alternative possibilities like relational database systems. Opposed to classical database schemes, the well-defined logics of DL further allow reasoning over explicitly modeled facts in the knowledge base. This way, the inference of new information out of existing data becomes possible, and queries can be already stated in the knowledge base itself (cf. Sect. 4.2). Also the consistency of the knowledge representation can be assured automatically by the reasoning mechanism, when considering for example the addition of new concepts and relationships. In the case of smart homes, all knowledge can therefore be well organized and brought into an intelligent structure that subsequently can be accessed by the smart home system.

3.1. Ontology Overview

The proposed knowledge base consists of several modules which contain different kinds of parameters important for an energy efficient operation of smart homes (Fig.1).

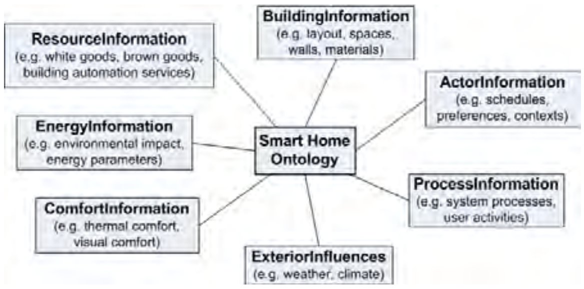

Fig. 1. Smart Home Ontology Main Modules

These different parts are, for example, a building representation including information about architecture and building physics, a user part with preferences as well as an exterior influences module holding for example weather data. In this work, focus is put on the resources and energy parts of the knowledge base: The **resource representation** describes the available facilities and their characteristics. The entire home environment and equipment has to be modeled in the knowledge base for a control system to have a complete view of the operable world, i.e., the building and its devices. The **energy representation** is an important source of information about energy demand and energy supply of the smart home. One of its purposes is to allow a software system to base its operational decisions on the status of the connected facilities in the smart home. Further, a representation of energy providers and energy tariffs enables an ecological and economical use of different energy forms such as electricity or district heating, with respect to renewability and energy costs. The next section describes these two parts in detail and explains the benefits of expressing facility and energy parameters as a linked knowledge store.

3.2. Facilities and Home Automation Systems

In home and building automation (HBA), the interaction of numerous kinds of devices is desirable. In most cases integration is not directly possible because of the heterogeneity of different home automation network standards. With DomoML [5] and DogOnt [6], there already exist two approaches that propose the use of ontologies in this context. DomoML is one of the first proposals structurally modeling household appliances with the help of ontologies. While DogOnt reuses certain ideas of this taxonomy, it tries to overcome limitations of DomoML. As ontology reuse [7] is highly recommended in ontology design, the DogOnt ontology was chosen as a starting point for the resource module of the proposed knowledge base. While not perfectly suitable for reuse, the DogOnt implementation provides an extensive and sophisticated representation of building facilities, functions and possible modes of operation. The authors of DogOnt put the focus of their knowledge base on the intelligent integration of home facilities and automation components and aim at building automation service interoperability [6]. However, energy related issues like energy supply or demand of mapped home automation systems and home appliances have not been considered. Also, building information has only been rudimentarily treated. These facts make the DogOnt ontology a good candidate for integration into the proposed smart home ontology. Referring to Fig.1, the DogOnt ontology can represent the resource part, while interfacing with the more detailed building information branch as described in [8] and the newly developed energy representation module presented in Chapter 4. However, the ontology of the DogOnt project contains several severe design flaws, especially with respect to ontology normalization. Among others, important ontology normalization steps like avoiding asserted polyhierarchies and instead using hierarchical tree structures have been ignored by the creators of DogOnt. Nevertheless, as stated in [9], a normalized ontological representation significantly raises the reusability and is therefore considered as key requirement for large ontologies. As a consequence, the DogOnt representation is first adapted into a semi-normalized form by reformulation of comparatively weak parts of the ontology while making a tradeoff between fully normalized form and practicability. The key design focus of this reformulation is to keep the original hierarchy as far as possible, but, for example, to only allow polyhierarchies to be automatically asserted by a DL reasoner (e.g., Pellet [10]). This normalized version of DogOnt is subsequently integrated into the proposed knowledge base.

4. Results: Energy Information Representation

In order to describe information from the energy domain for a smart home system, some important concepts need to be modeled. These so-called top-level concepts contain the following necessary classifications:

- *Energy providers*: This concept comprises all external energy suppliers providing some form of energy for the residential home.
- *Energy tariffs*: The tariffs that are charged by an energy provider to supply a certain energy type.
- *Energy types*: The different energy types that are available and are either supplied by energy providers, or used as source of energy to produce some secondary energy.
- *Energy facilities*: All energy consuming or energy producing applications that are installed in a smart home.
- *Energy properties*: This concept contains information needed to model energy demand and supply as well as energy costs.

Energy representation, as module of the proposed smart home knowledge base (cf. Fig.1), therefore keeps a wide variety of different parameters useful for the energy efficient operation of a home. To provide the system with a general notion of energy, a classification of **energy types** is needed. This classification has to be tailored to the needs of a smart home with respect to modeled energy types. Therefore, a distinction between final energy, energy sources and useful energy was taken (Fig. 2). This distinction reflects the varied usage of energy types viewed from the providing side as well as from the consuming side.

The concept EnergySource is used to classify different energy providers as explained in Section 4.1 and follows the general definition of sources of energy. Two distinctions are made: The first distinction is into primary and secondary sources of energy. Electricity, for example, is a secondary energy source because it has to be gained through some primary energy source. The second distinction into renewable and non-renewable sources is especially important for resource-efficient energy consumption in a smart home. These two concepts are finally super-concepts of the actual energy sources. Some design decisions are made in order to classify sources of energy: For example, nuclear power is assigned to the non-renewable branch as concept Nuclear, because also nuclear waste is taken into account as some type of environmental pollution.

The other two main concepts are FinalEnergy, and UsefulEnergy which both represent energy that is available for consumption in the smart home. A distinction between these two concepts is realized such that final energy contains energy types that can still be transformed to other energy forms inside the smart home while useful energy types are inconvertible. For example, gas as final energy can be used directly by a gas oven or, with the help of a gas heater, can be transformed to heat, which can subsequently be seen as useful energy.

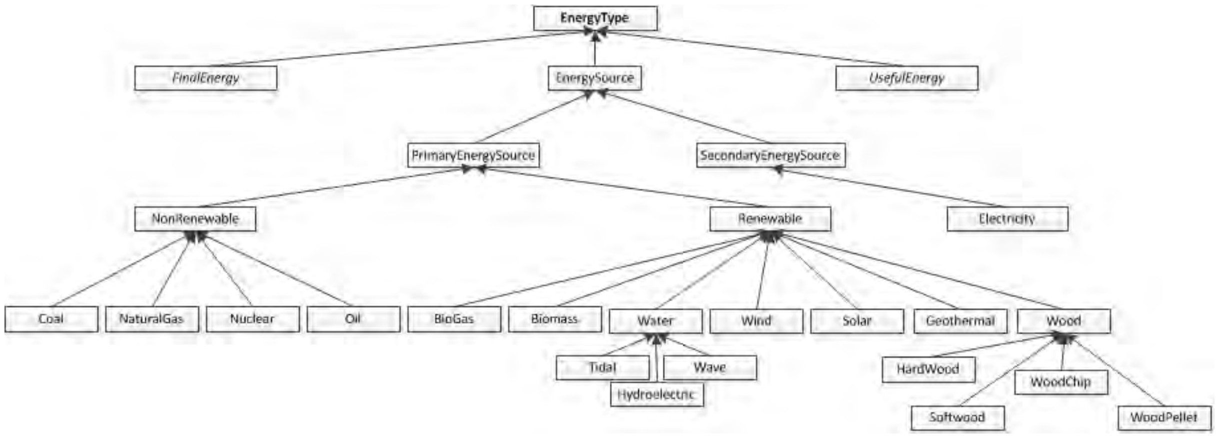

Fig. 2. Types of Energy

These two classifications of energy types do not have subclasses like the energy source branch, but merely contain concrete values which correspond to different forms of energy. This modeling technique is chosen, because for the appliance it does not make a difference if a green or non-green provider supplies the energy, however for the ecological footprint of the smart home user it does (cf. Sect. 4.2). The concrete members of the concept FinalEnergy are for example *Coal*, *ElectricEnergy*, *Gas* and *Wood*, while the concept UsefulEnergy has the members *Heat*, *Cold*, *Light* and *Water*. These groups can always be enlarged or narrowed, according to which end energies should be covered by the smart home system. As can be seen, some energy types occur twice in the knowledge base: once as energy sources and secondly as members of one of these two concepts (cf. Fig.2). The reason for this is that basically two viewpoints are being represented in the energy ontology: The **demand side** and the **supply side**. These two sides need to have a different idea of energy, because there exist energy sources that can be used by an energy provider to generate secondary energy but can also be directly used for consumption in the smart home as final energy. Also for the UsefulEnergy concept such a special case can be found: the specific resource *Water* on one hand acts as a source of energy to generate hydroelectricity, on the other hand it can be directly seen as useful energy in the smart home with different water providers and tariffs. Therefore, the classification shown in Figure 2 is considered as the one with least redundancies and most practical use. The benefits of the realization of final energy and useful energy types as individual values instead of concepts are further discussed in Section 4.2.

On one side it is important to model the demand and supply facilities which are available in the smart home itself. Certainly, it is a better choice to use energy produced by home facilities from solar radiation and geothermal heat than having to rely on the supply of energy from energy providers. On the other side it is also necessary to keep knowledge about different energy providers and their conditions in case energy demand exceeds homemade supply. Therefore, energy information representation is divided in two main axes which contain facilities in the smart home itself, i.e., the demand side and energy producing facilities, and the supply side like energy providers and tariffs, respectively. The following two sections go into detail and describe the certain constructs that have to be modeled for these two main parts. Although a description of the whole energy knowledge representation would go beyond the scope of this paper, important constructs and design paradigms are discussed in order to demonstrate the representation of energy demand and supply in the proposed knowledge base.

4.1. Energy Providers and Supply Side

With the ongoing liberalization of energy markets, knowledge about different energy providers and their tariffs are a valuable addition to the smart home ontology. It is assumed that like in the electric energy market also other markets will be liberalized in the future and therefore a variety of energy suppliers is classified in the proposed knowledge base (Fig.3).

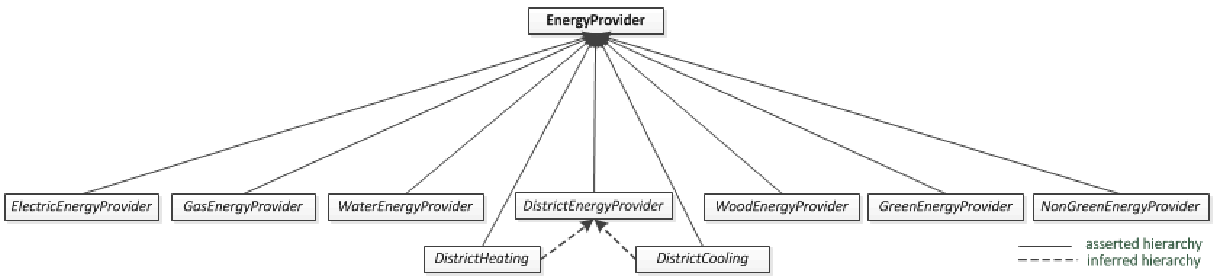

Fig. 3. Classification of Energy Providers

This conceptualization of energy providers comprises different energy forms as well as the distinction between green and non-green suppliers. Reasoning on this hierarchy with a DL-reasoner, makes inferred hierarchies possible as shown in Figure 3 for district energy providers. Furthermore, reasoning can classify newly added individual energy providers and associate them with the respective subclass. This quality of an ontological representation can aid the characterization of green and non-green energy providers with respect to the way they supply energy. For example, some electricity provider which provides electric energy only through hydropower will become a member of the classes ElectricEnergyProvider and GreenEnergyProvider. In case this energy provider adds some non-green way to provide energy (e.g., nuclear power), the classification will be automatically corrected by the reasoning mechanism and the company will further be listed as NonGreenEnergyProvider. In addition to the way how suppliers generate energy, it is needful to know the different kinds of **energy tariffs**. Of course not every company has the same rates for energy supply and also different tariff switching times can exist which have to be considered in the knowledge base too. Therefore, a general notion of time is required which is achieved by integrating the OWL-Time ontology for time representation [11]. With the reuse of this time ontology, characterization of tariffs according to their active times becomes possible. Together, energy provider and energy tariff form the main concepts of the supply side. They can further be used by a smart home control system to choose the environmentally friendliest and monetarily optimal energy supply at a specific point in time.

4.2. Energy Facilities and Demand Side

Energy facilities with respect to the smart home are all appliances which either consume or produce energy. For the facilities represented in the ontology, the actual energy consumption as well as the maximum energy consumption per defined state of operation is stored. Further, it is important for an autonomous system to know if a certain facility needs permanent power supply. With this information, an intelligent system can for example unlink appliances from the power grid when they are not immediately needed.

The connection between energy demand side and energy supply side is made via an ontology design pattern called **class-individual mirror** described in [12]. For this design pattern, the final energy types already explained at the beginning of this chapter act as pivotal elements. The example in Fig. 4 shows the application of the pattern for these two parts of the ontology.

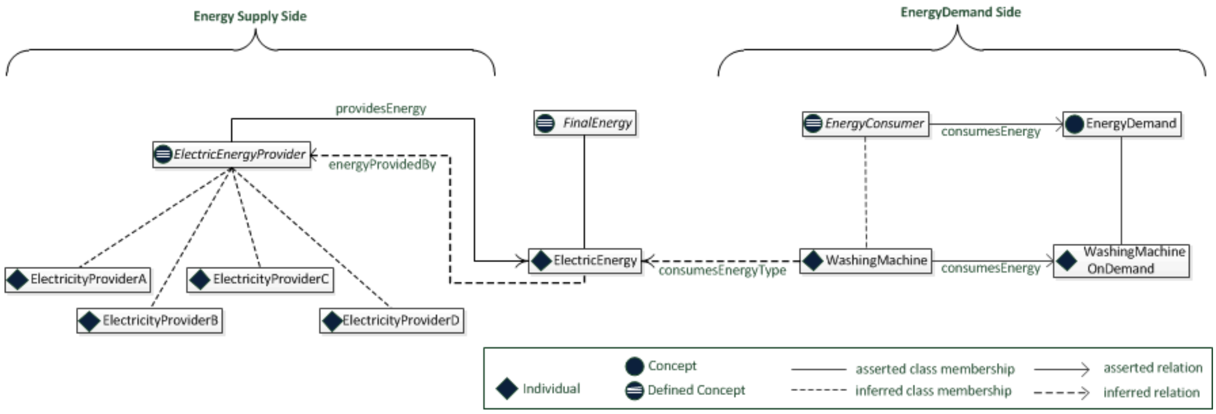

Fig. 4. Connection between Energy Providers and Energy Facilities

The benefit of using this pattern is that the pivotal *ElectricEnergy* element holds information from the energy supply side. This can be used for choosing the electricity provider on an appliance level: If the depicted washing machine is scheduled to start at a certain point in time, the home automation system just needs to know which energy type it consumes. The *ElectricEnergy* element already holds information about which energy providers supply the energy by the energyProvidedBy relation that has been inferred by the DL-reasoner. Energy tariffs and other properties of the energy providers like if they are green or non-green suppliers can subsequently be retrieved from the ontology by the properties that have been defined for each electricity company. This way, important queries have already been modeled in the knowledge base, which represents a clear advantage over classical database systems. Among other things, this leads to a higher independency between the data representation and the software system.

5. Conclusion and Outlook

This paper proposed a central knowledge base which is mandatory to enforce novel energy efficiency control strategies in smart homes. It was shown that ontologies are a well suited technology to use as smart home knowledge representation. The ontology constructs as well as the formal grounding in Description Logics allow the depiction of more detailed and interconnected information than known from classical information representation systems. Additionally, because of the foundation in logics, reasoning on stored facts becomes possible which allows inference of new information and guarantees the knowledge model's consistency. As a proof of concept, the part of energy related data was modeled as OWL ontology. Special focus was given to the domains demand side and supply side, where in particular the interrelations between the parts were discussed extensively.

A practical example of the application of the energy knowledge base is the energy efficient operation of household appliances and consumer electronics. Information about scheduled programs and desired finishing times can, for example, be used by a software system to derive which renewable energy provider offers the optimal tariff for the planned task. Furthermore, time slots for the execution of tasks give the system the ability to wait until off-peak electricity is offered, thus on one hand saving money for the customer, while on the other hand behaving environmentally friendly by consuming excess energy.

Next steps regarding the presented resource and energy ontologies will concern their integration into a software framework as well as the definition of an interface that allows autonomous smart home control systems to easily access the knowledge store. Finally, other important parts of the comprehensive knowledge base for smart homes will be defined, modeled and constantly refined.

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Modeling phase change materials behaviour in building applications: selected comments

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Abstract: In a recent meeting of IEA's Annex 23, several members presented their conclusions on the modeling of phase change materials behavior in the context of building applications. These conclusions were in agreement with those of a vast review, involving the survey of more than 250 journal papers, undertaken earlier by the group of École de technologie supérieure. In brief, it can be stated that, at this point, the confidence in reviewed models is too low to use them to predict the future behavior of a building with confidence. Moreover, it was found that overall thermal behaviors of PCM are poorly known, which by itself creates an intrinsic unknown in any model. Models themselves are most of time suspicious as they are often not tested in a very stringent or exhaustive way. In addition, it also appears that modeling parameters are somewhat too simplified to realistically describe the complete physics needed to predict the real life performance of PCMs added to a building. As a result, steps are now taken to create standard model benchmarks that will improve the confidence of the users. Hopefully, following these efforts, confidence will increase and usage of PCM in buildings should be eased.

Keywords: *Phase change material, PCM characterization, Mathematical model, Model validation*

1. Context

The ever increasing level of greenhouse gas emissions combined with the overall rise in fuel prices (although fluctuations occur) are today's main reasons behind efforts devoted to improve the use of various sources of energy. Economists, scientists, and engineers throughout the world are nowadays in search of: 1) strategies to reduce the demand; 2) methods to ensure the security of the supplies; 3) technologies to increase the energy efficiency of power systems; and 4) new and renewable sources of energy to replace the limited and harmful fossil fuels.

One of the options to improve energy efficiency is to develop energy storage devices and systems in order to reduce the mismatch between supply and demand. In this context, latent heat storage could be considered. Indeed, it is particularly attractive since it provides a high-energy storage density and has the capacity to store energy at a constant temperature – or over a limited range of temperature variation – which is the temperature that corresponds to the phase transition temperature of the material. For instance, it takes 80 times as much energy to melt a given mass of water (ice) than to raise the same amount of water by 1°C. For the interested reader, excellent global reviews that pertain to phase change materials and their various applications were proposed by Zalba et al. [1], Farid et al. [2], Zhang at al. [3], Tyagi and Buddhi [4], Regin et al. [5], Mondal [6], Mehling & Cabeza [7], Sethi & Sharma [8], Verma et al. [9], Sharma et al. [10], Dutil et al. [11] and Cabeza et al. [12].

2. Modeling in building applications

A better management of the fluctuations of the external temperatures, wind, solar load, and heating or cooling needs is possible by the use of phase change materials. In building applications, these materials undergo a phase change close to the desired room temperature, which allow storing a large amount of heat in a relatively small volume compared to liquid water, brick or concrete. This results in direct energy savings as the solar gains can be used when needed, thus reducing the energy consumption for heating in the winter and cooling in the summer. Moreover, in many countries, these materials could also be used to reduce the peak consumption leading to money savings in this particular case.

Nevertheless, high fidelity models are needed to guide the decisions of the architects and/or HVAC engineers in choosing optimum designs. Unfortunately, to formulate, implement, and validate such models is a rather difficult task mainly due to the non-linear nature of the problem. In addition, other technical issues add complexity to this problem. Here, we will discuss two of the most significant problems that should be addressed by the scientific community: phase change material characterization and model validation [11].

2.1. PCM characterization

The first problem faced even before beginning the modeling process is the characterization of the phase change materials (PCMs) themselves. In building applications, composite PCMs are the favored packaging method for inner walls applications. In this form, PCMs can be integrated into a building using the same techniques used for gypsum panel, which would provide a seamless integration. However, this type of material is rather difficult to characterize.

The key problem comes from the interaction with the substrate and the PCM in confined pores. This interaction affects both the melting and freezing temperatures as their respective enthalpy. To our knowledge, this phenomenon was first observed in building application by Hawes et al. [13], when they noted a drift in thermal properties of a PCM laced concrete over time. They attributed this effect to a migration of PCM in smaller pores. Their interpretation was supported by a previous work of Harnik et al. [14] on icing behavior of concrete.

Many physical models have been proposed to explain this behavior [15-25]. The thermodynamic properties of PCM composites are related in complex way to the size of the pores and to the chemical properties of the matrix and of the PCM. Mechanical confinement shifts the phase transition to higher temperatures due to increased pressure. Chemical interaction including dissolution between the compounds can shift up or down the melting/freezing temperature. The stochastic nature of the nucleation process means that supercooling is favored in small volumes. In consequence, melting and freezing phase change occurs at different temperatures. The phase change range is also broadened. This has the practical consequence that it is necessary to measure both melting and freezing curves and this over a wide range of temperature.

Even then, adequate characterization of PCM is a difficult task. For example, we have observed that reported enthalpy of melting and freezing can differ by more than as 15% in composite PCMs (ex: construction material [26-28] and polymer [29-31]). This is obviously unphysical since conservation of energy imposes that both values should be equal if the energy is stored in the PCM. Still, there is a possibility that some energy might be stored mechanically by the deformation of the matrix as a consequence of the PCM dilatation. To our knowledge, this hypothesis has never been tested. While, if proven true, this phenomenon might provide new approaches to fine tune composite PCM thermal behavior.

In practice, the broad width of the composite PCM freezing/melting curve impairs the separation between latent and sensible heat. In addition, in some cases, there is an indication in many published measurements that at least a part of the PCM stays in supercooling state during the whole thermal cycle. In addition, heat capacity value and conductivity are different between liquid and solid phases. All these problems make very difficult to define a meaningful baseline to extract the latent heat curve.

In addition, hysteresis in the cooling/heating curve has been observed [32-36]. This behavior is not fully explained but is likely to be related to a complex interaction between the stochastic nature of the nucleation process (heterogeneous or homogeneous), progressive dissolution, glass transition or metastable crystalline phases. This has for consequence that each DSC curve is dependent on t he history of temperature and its rate of change. Measurement procedures for this effect are still in development.

In general, thermophysical properties measurements are done on a small sample. However, due to the non classical behavior of composite PCM, it is unclear whether these measurements are representative of the macroscopic thermal properties of the material. A more detailed study is under investigation, which consists on the consideration of the heat transfers within the calorimeter cells. The goal is to determine the true value of specific enthalpy regardless of experimental conditions (sample mass, heating and cooling rates) [38]. This method also allows the determination of thermal properties by inverse methods [39]. In addition, potential drift in the thermophysical properties overtime are not always taken into account in the experimental protocol. Through a literature review, we have observed that tests of the stability of PCM composite extend from a few cycles to 5000 t hermal cycles! Since, for building applications, lifetime of components are decades long the latter value is certainly more suitable.

In conclusion, improved thermal characterisation procedures are needed and will be certainly welcomed by modellers.

2.2. Model validation

The validation of modelling algorithms is also troublesome. While not restricted to building applications [11], it is more critical in this case due to the relatively small temperature changes involved in a typical building application. In surveyed papers on modeling, all older models for PCMs behavior had experimental counterparts to validate the modeling of the problem. This was done to adequately validate the appropriateness of the set of equations and that of the subsequent formulation of a numerical method to solve the relevant sets of discretized equations. Many of these early studies also involved analytical solutions used to validate the model for selected problems that admit closed form solutions [11].

However, as time went by, the authors relied more and more on ot her studies, mostly numerical ones, to validate their own numerical results. Many of the recent studies discuss their results qualitatively only, as the comparison with a graph taken from a publication may be somehow hazardous. And, interestingly, among the numerous – more than 250 – references and studies reported in [11], in only one the authors stated that the results were not "in good agreement with those found in the references". In recent studies, the proportion of analyses which rely on commercial codes increases and the discussions that pertain to stability, convergence, grid independence and other related numerical issues decrease.

Statements are almost never made on the agreement or disagreement with previous results. This may be explained partly by the engineering scientific culture, where challenging or trying to duplicate previous works is not a common practice. As an illustration of this observation, we noticed that the work of Heim and Clark [40-41] predicts accumulation of heat on a seasonal basis. This is certainly an extraordinary claim that would open door to new applications. Nevertheless, up to now, nobody has either duplicated or refutated it.

However, engineering sociology merely reflects the practical constraint of doing such cross-validations. Materials, geometries, testing conditions and models are almost always different from one study to another. In such conditions, even for the most dedicated researcher, it is very hard to validate previous work. In our mind, this is a serious issue. Without a common ruler, it is impossible to formulate a meaningful recommendation about a technology.

Finally, we found that there is little comparison between various models and experiments. Every research group seems to have its own numerical model. To our knowledge, all these models were claimed to work well. Nevertheless, recent works [32-37] indicate that the presence of hysteresis creates some problem in the modeling itself since the thermal behavior of the PCM will depend on the history of heat loading. At this moment, solution to this problem is an open question. While this is a very new concern and might not be that important, this raises some doubts on previous results.

2.3. Further steps

To address some of these problems, the IEA annex 23 has prepared two standard cases to test numerical models [29-30]. The first of these tests was a simple unidirectional wall, with inclusion of a classical phase change material within the wall. Three teams developed a model for this case. While two of those models were closely predicting the same results, a third model presented a significant discrepancy with the other two. At this moment, not enough models are available to find the root cause of the observed difference. The main suspect is a small variation in the numerical description of the latent energy curve.

The existence of such divergence with a simple situation is by itself a strong warning about the models reliability. A second benchmark is now proposed. This benchmark is based on a small cubicle using PCM in its walls. In that case, high quality experimental data are used as a reference. To populate a database of benchmark, members of the annex 23 are invited to submit there own experimental data.

These initiatives are certainly a step in the right direction. Their use as a validation tool should be considered by any researchers working into application of PCM in building. Nevertheless, results are too fragmentary at this point to produce general guideline for researchers.

3. Conclusion

While the applications of PCM in building are promising as a tool to reduce energy consumption, there are still many roadblocks on the widespread utilization. To optimize their utilization in buildings, reliable models are needed. At this point, the confidence in models is too low to be use to predict the future behavior of a building. However, thermal behavior of PCM themselves are poorly known, which by itself create a huge unknown in model. Models themselves are suspicious as they are rarely tested in a very stringent way.

In addition, it also appears to us that modeling parameters are somewhat too simplified to realistically describe the real life performance of PCM addition into buildings. For example, seldom complete meteorological information (solar irradiation, external temperature and wind) are used as inputs. However, correlation and anti-correlation between these factors could strongly affect the results. In addition, in most systems modeled, thermal loads are restricted to solar heating. Additional heat from appliances will certainly affect the results. Also most of the time modeling is done on individual rooms or few rooms aligned in a perfect east-west alignment and empty. In real life, most houses are not perfectly oriented, have additional room with little solar heating, are equipped with furniture, and are occupied by people. This will both modify the thermal loading and the effective storage mass of the building. From our analysis of the literature, typical gain in energy efficiency by the utilization of PCM is expected to be roughly about 10-15%. In consequence, the factors not included in models could easily change the overall conclusion about the pertinence of PCM in building application.

The steps taken now by the IEA ECES IA Annex 23 to create standard model benchmark will improve the confidence of the users. Phase change material characterization is still an unresolved issue, but many research teams work on it. Hopefully, following these efforts, confidence will increase and usage of PCM in building will be more straightforward.

Acknowledgements

This work was supported by the t3e industrial research chair and its financial partners. The authors would like to acknowledge their invaluable contributions. The work was partially funded by the European Union (COST Action COST TU0802) and the Spanish Government (project ENE2008-06687-C02-01/CON). The authors would like to thank the Catalan Government for the quality accreditation given to their research group (2009 SGR 534).

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Energy efficiency learning and practice in housing for youths

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Abstract: This paper explores the energy efficiency learning and practices of youths aged 18–25 years. The studied youths are involved in a project, initiated by a municipally owned housing company, to educate residents and change everyday behaviour, making it more sustainable and energy efficient. This project, which forms our case study, covers socio–technical features such as energy systems and the individual metering and billing of heating, electricity, and hot and cold water. How did the youths perceive and use the systems? Have their attitudes and behaviours concerning energy-related practices changed during the project? The results indicate that a combination of technology (e.g. metering and visualized energy use) and social activities (e.g. educational activities and meeting neighbours and housing company staff) changed some practices involving what was perceived as energy wasting behaviour (e.g. using stand-by modes and taking long hot showers), while other practices (e.g. travelling and heating) were harder to change due to socio–technical barriers. The youths displayed knowledge gaps in relation to the energy system and their basic understanding of energy (the difference between heating and electricity).

Keywords: *Everyday life, youths, housing, socio–technical systems*

1. Introduction

A common notion is that children and youths represent our future hope in terms of changing unsustainable behaviour. Sustainability is now integrated into Swedish pre-school and primary school curricula and covered in secondary school and university courses. Environmental awareness might also be important in working life, for example, if an employer is involved in an environmental certification scheme. However, for most people, learning about sustainability and, for example, energy conservation and low-energy lifestyles is not included in their everyday activities. As an adult, education is voluntary, and it can be assumed that few people intentionally seek a deeper understanding of environmental issues. Many are exposed to information from various sources, such as their energy supply company or local municipal energy advisors. However, mere information provision is considered a soft and perhaps weak policy means, and research finds that it has little or no effect on behaviour [1], while learning can reach deeper into people’s values and might even change behaviour [2–4]. One key difference between learning and information provision is that learners receive feedback on their thoughts and actions, as learning often involves communicating with other people (possibly using various information and communication technology tools) [1]. Information provision is one-way and, by definition, is not communication at all. Published research into intervention and energy conservation behaviour is mostly found in the areas of psychology and social psychology [1,5–7], while the present research focuses on another level of behaviour, namely, socio–cultural and socio–technical behaviour; consequently, we chose *learning* and *practice* as our central areas of research [8–13].

The starting point of this research was to explore the learning of youths and young adults in an after-school setting outside conventional formal learning facilities. Specifically, we examine learning about sustainable energy-use behaviour and energy conservation in the homes of 18–25-year-olds. We use a qualitative case study methodology, the overarching aim of which is to understand energy learning among youths and young adults in a project targeting energy conservation attitudes and behaviour. The main objectives are to explore stated energy-use behaviour from the end-user perspective and to assess the success or failure of a project aiming to change behaviour through learning. We would also like to suggest ideas for improving the learning approach that may be useful to stakeholders and policy-makers.

2. Theory and methodology

The analyses presented here will be based on our understanding of social learning; this concept stems from research into the learning in action approach [14] and practice theory [15]. Under certain circumstances, knowledge can be assimilated by an individual and put into action, possibly leading to change [16]. Liedman [17] stresses that knowledge must be *put in a wider context* and be *put to the test*. This is also the basis of Säljö's situated learning approach [14], according to which learning is not a harmonious occurrence but the result of individual struggle and commitment, hence, a *process*. Practice theory takes a similar approach to understanding human action, which is seen as resulting from a combination of structural prerequisites and individual and social processes. Instead of making situations the centre of analysis, Gram-Hanssen [8] emphasizes people's practices and activities when performing everyday tasks. We take this approach here, starting our analysis with *how* the studied youths and young adults *do things*. Practices are complex phenomena and can extend outwards from the home or the places where they usually occur. Gram-Hansen quotes Schatzki when defining practices as our "doings and sayings" [15]. Gram-Hansen has developed Schatzki's theories by introducing physical features and technology, making the approach more socio–technical.

Given the qualitative approach of this research and our aim of understanding a socio–technical phenomenon, case study methodology is suitable. Case study research focuses on real-life phenomena, and the inclusion of various contexts is encouraged when relevant [18]. Qualitative research aims at making detailed descriptions and creating in-depth understanding of phenomena. The boundaries of a case study can either be well defined in advance [19] or gradually be defined during the research [20]. The present research is a small case study based in a well-defined geographical area, the Ringdansen development, but the boundaries of the examined social learning extend beyond the neighbourhood.

The case study focuses on the "Youth Housing" project in the Ringdansen development in the town of Norrköping, Sweden. Since 2008, Linköping University has collaborated with the owner of this development, Hyresbostäder i Norrköping AB (HNAB), a housing company owned by Norrköping municipality. In 2009, HNAB initiated a project to attract a "new group" of tenants to the Ringdansen neighbourhood and enhance its green profile. The concept and organization of the project were not created in collaboration with Linköping University but were HNAB's own initiative and design; the collaboration merely gave Linköping University researchers easy access to the neighbourhood. HNAB has recently been promoting Ringdansen using the Climate-Clever Living programme, and a new logo has been launched. The programme offered a 50% rent discount to people aged 18–25 years, who could earn two-year leases for two- or three-bedroom flats in one of the residential buildings. To earn a lease (20 in total), one had to commit to involvement in a programme including various activities, for example, meetings and practical outdoor actions such as picking up litter in a recreational area near the neighbourhood. The meetings the housing company organized for the youths typically included a presentation on an environmental issue, such as global warming or global food consumption, supported by a movie or guest lecturer, followed by discussion of practical actions for reducing one's environmental impact, as related to the issue presented. The meetings were independent of each other and entailed no homework or reflections between the meetings. It was our initiative to ask permission to evaluate the project after one year.

Various data collection techniques can be used with case study methodology [18]; for our objectives, however, we chose to conduct focus group interviews. Focus group interviews produce primary data on the thoughts and understandings of people talking with each other in the same situation [21,22]. In the focus groups for the present research, we concentrated on issues related to energy and the environment. The analyses of interviews are our own; the results of the analyses were presented to housing company representatives, who gave us feedback on them. Since only 20 households participated in the Youth Housing project, yielding a small number of possible respondents, we invited all members of these households to attend the focus groups. Fifteen household members participated, representing almost 50% of the total, comprising nine women and six men. Four focus groups were organized by two researchers, one responsible for recording the interviews and taking notes and the other for keeping the conversation going and introducing new topics when the current topic seemed to be exhausted. The topics were presented using six pictures depicting the neighbourhood, energy, and the housing company. The youths responded to and understood what the pictures visualized in quite similar ways, even though divergent practices were related to the pictures during discussion; these results will be presented in the next section. The interviews were digitally recorded and transcribed, resulting in 50 pages of text. The relatively small amount of text made it possible to manually organize the primary data into various themes in accordance with the energy and environmental focus of the research project. The analyses were inspired by the hermeneutic research tradition and the hermeneutic circle [23]. There is always a risk of "going native" relative to the object of study and when interpreting the results. However, the researchers did not participate in conceiving or organizing the "Youth Housing" project and had no vested interests in whether or not the results of the project could be considered fulfilled.

3. Results

The results of the focus group interviews can be organized into three themes: stated behaviour in relation to heating, stated behaviour in relation to electricity and stated behaviour in relation to the individual metering and billing system (IMB) of the Ringdansen neighbourhood.

3.1. Stated behavior in relation to heating

Chilliness and technical issues were central when the youths talked about their behaviour in relation to heating. All apartments are equipped with a thermostat for temperature control device which should allow occupants to set indoor temperatures of 18-22° C and each flat pays individually for its use of heath. However, most youths found the indoor temperature too cold, with the thermostat set at its highest level, compared with earlier living experiences and with what they were used to in earlier homes (this was the youths' own impressions and does not reflect measured values). A common observation was that the insulation performance was inadequate due to a design flaw concerning the windows. One interviewee thought that the sealing around the windows was not good enough, and many youths experienced air ingress around windows and draughty flats. All flats are equipped with a ventilation outlet under the windows and many youths created their own solutions to prevent cold air coming into the flats through these outlets, for example, by using towels to block the ventilation outlet to raise the indoor temperature. Another practice was to put on slippers and more clothes if the indoor temperature was perceived as too cold. One interviewee claimed that it was unnecessary always to turn up the thermostat and said "If it is cold indoors, I put on my slippers and a cardigan". That was a common practice for many youths, said that the fear of higher energy bills was their main motivation. For some people, environmental factors such as melting polar icecaps and dying polar bears were important reasons for not using more energy than needed. One youth claimed that these issues could be difficult to understand, but said: "I think that we here (i.e. in the Youth Housing project) can learn from each other".

Many youths struggled to learn how to use the thermostat as a temperature control device and it was described both as a tool for heating control and as a tool that simply did not work.

> Respondent 1: I thought that it (i.e. the thermostat) would be better than it was. I thought that it was pretty cool to have a thermostat indoors, only because I've seen them on TV but later I was …
> Respondent 2: Always in American movies.
> Respondent 1: Yes, everybody has a thermostat as a temperature-control device, and they can lower their thermostat because it is often very warm inside. But we have more like …
> Respondent 2: Raise the thermostat because it is so cold.
> Respondent 1: Yes it is like that here.

Some perceived the thermostat, as a temperature control device, as difficult to understand and as a barrier to controlling the indoor temperature. One youth said that it was strange that you could not simply set the thermostat to the temperature you wanted indoors (the thermostat was not marked with numbers). Some thought that the thermostats should function differently, and others did not like the thermostats at all because they were difficult to understand ("I do not like it at all"). Some youths described the thermostats as a tool for deciding how much heat to use in the flat, saying that it was a useful innovation since everybody had to pay for their own energy use. A common practice among many youths was to lower the thermostat in daytime and then raise it in the evenings. It was also common to turn off the heating system in summer, since it was usually not needed then. Youths with small children said it was a difficult decision to turn off the heat, since the children needed a warmer indoor temperature.

3.2. Stated behaviour in relation to electricity

The difference between heat and electricity was not obvious to all the youths. During discussions about the thermostat, it turned out that many had a knowledge gap regarding how their flats were heated, and one youth did not distinguish between electricity and heating consumption, even though the flats were heated with district heating and not with electricity. The thermostat technology was a barrier to a few who equated the thermostat with both temperature control and electricity, assuming that if the thermostat was turned off, the electricity to the flat would be cut, which was not the case. One also assumed that the level on the thermostat would affect the electricity bill, and was afraid of receiving higher electricity bills if the thermostat was set too high. All youths, however, said it was important to save electricity because this affects the global environment and can reduce the greenhouse effect.

Trying to reduce the amount of electricity used was an ongoing process in many households. A common energy-saving practice that many were using was turning off electrical appliances when not in use and not simply leaving them in stand-by mode. As one youth put it:

> We always unplug all the cords for our electrical appliances, like all lamps, the TV, the microwave, for everything. The cords have to be unplugged.

Interviewees said that it was easy to forget to unplug cords and turn off appliances when unused, although many said that they tried remember. One respondent said that, before the household had moved to the neighbourhood they seldom turned off the TV when they went to bed, now, however, they always turned it off. Another respondent claimed that the computer was always left on before, even though no one was using it. The move to the youth living project had changed that, and nowadays the household always turns off the computer when not in use. Most respondents found that it easy to remember to save electricity when they first moved into the neighbourhood, though many remarked that it was easy to forget about electricity use in everyday life. Similar studies have noted the same phenomenon (24).

> Respondent 7: You forget. It is so easy to forget.
> Respondent 8: I thought about it a lot at the beginning, but I can say that now I am a bit careless about it.

During the focus group interviews, energy were also connected to travelling and small-scale energy production, which some youths wished was installed in the neighbourhood. Many youths used cars for transportation but not all households had access to a car, so many used the bus or bicycle for everyday transportation. The bus was said to be slow, and it was sometimes faster to ride a bicycle instead of taking the bus to the city centre. Many youths had great hopes that the housing company would embark on small-scale energy production, and expected leading-edge energy-production innovations and energy-efficient technology to be implemented in the neighbourhood. The youths described the housing company in mostly positive terms. They appreciated its accessibility and the meetings it organised in the Youth Housing project, though some wanted more concrete action from the housing company.

> Respondent 3: It is the next step. For now they try to engage people. The next step is …
> Respondent 4: Action.

3.3. Stated behaviour in relation to individual metering and visualization

The system for individual metering and billing was appreciated by most youths. The ability to influence the costs by paying for the rent and energy use separately was regarded as an advantage of the Youth Housing project, since it is seldom the case in Sweden. One youth said individual metering and billing was the best thing about the Youth Housing project. Many thought that this system was environmentally friendly, since it makes individuals start thinking about the energy they use, as they have to pay for it themselves. By making it obvious that energy has a cost, the system almost challenges individuals to save energy:

> It is good, especially from an environment perspective, and I think that you should not use more than you need. That is important.

When the bill came every month the system visualized the energy used in numbers and kilowatts, although many were vague as to what a kilowatt really represented or how it was measured. Understanding the energy consumption data on the bill or how the system worked was not considered that important. Feedback systems have been used in earlier studies with varying results, frequent feedback being found most effective [1]. In the present case, the energy bill functioned almost like a feedback system, giving feedback every month on energy used in terms of how much money the youths had to pay. Saving energy was often equated to saving money, since lower electricity use results in a lower electricity bill. Households would even compete against themselves, by trying to get lower electricity bills every month. They would think back over their energy behaviour in the current month versus in earlier months, and try to learn what to do or not to do the next month. The incentive to save money was a frequently citied reason, since many households were low-income or student households.

Trust in system’s features and functions was high among the youths. No one doubted that their bill accurately recorded their energy use, but assumed that the technological system was working as it was supposed to, although it is always possible for technical systems to have flaws. The youths could not really determine by themselves whether the metering system was working as intended, and it was not usual to compare one’s energy used with one’s neighbours’. Social activities initiated by the housing company helped influence resident attitudes and were appreciated. One youth said that before he did not think his use could make a difference. After he moved to the neighbourhood, however, he changed his mind:

> I think that involvement with the other youths in the block affects my consciousness and has made me more aware of the importance of everybody doing something when it comes to energy saving.

4. Discussion

Results indicate that a combination of technology (i.e. metering and visualized energy use) and social activities initiated by the housing company (e.g. educational activities and meeting neighbours and housing company staff) changed some of the practices involved in what were perceived as energy-wasting behaviour (e.g. using stand-by modes and taking long hot showers), though other practices (e.g. transportation and heating) were more difficult to change due to socio–technical barriers. Learning related to the home and various household activities might, according to the theories of situated learning [14] and practices [15], be the right approach to altering unsustainable behaviour, shifting it in the direction of low-energy living. The housing company is on the right track in choosing a learning approach for their Climate-Clever Living project. However, regarding the Youth Housing project, few respondents referred to specific things they had learnt in the first year of the project. Instead, reference was made to the fellowship between young residents of the neighbourhood. Most respondents, however, approved of the housing company's ability to inform them of energy and climate issues. Over the course of the year the project had run, the housing company had earned the youths' trust when it came to environmental matters [25].

Learning as a struggle [14] to become more knowledgeable was not acknowledged to any great extent by either the housing company or its tenants. The struggle mostly involved learning how to use devices, such as a thermostat, in the meetings, not learning and retaining changed behaviour, for which information provision alone has been demonstrated to be insufficient [1]. No pressure was put on the youths to reflect on or analyse their behaviour. Formal learning usually involves homework and studying for tests; in this project, however, learning was supposed to take place in the homes of the tenants and in the interaction with other tenants and the housing company. As a result, changing basic practices at home was never discussed in depth, and some youths went back to their former and less-energy-efficient modes of behaviour – as exemplified when they talked about saving electricity. Instead, the youths emphasized new, more innovative initiatives and a desire for the housing company to take action, rather than emphasizing how to do one's laundry in an energy-efficient way or manage the temperature of one's flat. The more innovative ideas included bicycle pools, second-hand clothing businesses, and solar panel and PV installation. Ongoing reflection on current practices and struggle to change one's behaviour may not be fun, but are necessary in order to change behaviour.

Putting new knowledge in a wider context is also crucial in efforts to create change [17]. It might be difficult to recognize the relationship between individual energy consumption and environmental problems [26] – although this was not a problem here – so context is always important. The contexts made available in the project were either the neighbourhood of Ringdansen or the other extreme, the globe. The neighbourhood might be too narrow a context in which to fully understand a new behaviour, while the globe might be too overwhelmingly large to relate to. Here, learners need help navigating through various contexts and must be shown how a behavioural change might influence contexts at various scales, i.e. the household, building, neighbourhood, precinct, town, region, country, continent, and globe. It was possible for the youths to compare their energy use with their neighbours', but they said they seldom did that. We suggest that the data collected through the IMB system be used to set household behaviour in a wider context and make it possible to compare individual efforts with those of the entire neighbourhood and at other geographical levels.

5. Conclusions

An overall conclusion is that the project was successful in terms of changing some attitudes and energy-related behaviour. However, the youths displayed knowledge gaps in relation to the energy system and their basic understanding of the installed energy systems (e.g. the difference between the heating and electricity systems). Learning as a process must be acknowledged and the difference between providing and obtaining *information*, and learning and assimilating *knowledge* must be recognized when designing change-creation projects and schemes. Learning is an ongoing process that differs between individuals. Consequently, changing behaviour is better approached as a *scheme* than a project.

Learning includes *socio–technical features*. To facilitate learning and change, it is essential to provide infrastructure so that learning can take place in a wide range of places and not be restricted to certain, special places. In this case, HNAB has provided some state-of-the-art technical infrastructure, such as individual metering and billing. However, the infrastructure might also be social networks and include, as in this case, neighbours or even professionals from the housing company. These networks can give rise to more formal support groups than those existing between some youths, either in person or via the Internet. Technology has great potential as a tool for change, but that potential is underused in Ringdansen. We should not be afraid to approach learning about low-energy living in a fun way, making use of residents' creative ideas, like those of the studied youths.

For HNAB and perhaps other housing companies in Sweden, our results suggest that the present model of education for youths might be made more accurate and more flexible. It might be too challenging to target all groups of tenants at the same time, but starting with "easy" groups that are already somewhat interested in environmental issues is definitely the right way to proceed. The next group to target might be senior tenants, for example. According to a survey conducted in Ringdansen, the housing company is perceived as trustworthy by youths and young adults, so HNAB representatives should be the ones presenting data and discussing environmental issues with tenants. However, it is crucial to focus more on facts and data about a range of environmental issues and then provide opportunities to reflect on and discuss the information given. We would like to see *a more comprehensive model* of how the housing company will work on change creation in the future.

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Reducing Households' Energy Use: A Segmentation of Flanders on Adoption Intention of Smart Metering Technology

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Abstract: Research has shown that feedback on energy use can aid households to reduce it significantly. In this context, smart metering technologies, and more specifically technology components interacting with data gathered and provided by a smart meter, allowing to provide the consumer with personalized feedback, consumption visualization, automated control,… could play an important role. After all, by means of this technology, households can be made more aware of their energy use and encouraged to reduce it. This paper applies a user centered approach towards the estimation of the adoption potential for smart metering technologies in Flanders, Belgium. We conducted a representative quantitative survey with 1314 respondents living in Flanders. A segmentation on ownership of, attitude towards and adoption intention of smart metering devices was performed on the data. Traditional approaches of intention surveying often result in an overestimation of the innovation adoption potential. To overcome this problem, the Product Specific Adoption Potential scale (or PSAP-scale) was used and 6 segments were found. These segments were labeled "Current Owners", "Innovators", "Early Adopters", "Early Majority", "Later Adopters" and "Out of Potentials. The verification of the adoption potential of smart metering devices for different pricing scenarios revealed a rather high price sensitivity.

Keywords: *Consumer behaviour, smart metering, adoption potential, willingness to pay*

1. Introduction

Most residential energy users are not aware of their usage pattern. On a global level, the amount paid every month is the only indicator of energy use for the majority of the households. On appliance level, households have little or no knowledge on the amount of energy that their appliances consume, or its share in the total household energy use. Mansouri-Azar et al. [1] proved that a majority of their respondents did not know which of their electric appliances consumed most energy. At the time the research was carried out, lighting, freezer and dishwasher were the most consuming appliances in the UK households. Nonetheless, most of the respondents mentioned the washing machine in their top three.

The positive effect of feedback on energy use has been examined and confirmed in many studies [2-6]. It is generally recognized that households can be motivated to reduce their energy use when receiving correct feedback. Several forms of feedback can be distinguished ranging from more detailed billing over comparative and historic feedback to direct feedback at the time of use. According to Raaij and Verhallen [7] feedback has three functions:

(1) learning: the provided feedback gives the consumer information on the results of certain actions;
(2) habit formation: the feedback helps in forming certain new habits with regard to energy conservation. These habits should remain when the feedback is removed;
(3) internalization of behaviour: feedback helps to create new attitudes and habits that become embedded in a person's behaviour. These habits and attitudes will influence energy-related actions in situations where the feedback will not be present.

Smart meters can play an important role in providing this feedback to consumers and many applications are possible. Smart meters connected to in-home displays, internet applications, smart phone and tablet apps can provide residential consumers with basic insight into their energy use at a given time during the day, but the possibilities go far beyond this. Smart appliances connected to smart meters can stimulate an efficient appliance use supported by time-of-use pricing mechanisms and availability of renewable energy sources. The question however remains to what extent the consumer is interested in adopting these smart metering applications and, from a business perspective, what is their willingness to pay for these applications? These two questions will be addressed in this paper.

2. Methodology

We conducted a quantitative survey with a representative sample of the population of Flanders, Belgium. The questionnaire was designed to make a segmentation based on attitude towards smart metering technologies and distributed through both online and offline channels in June, 2010. A total number of 1314 respondents completed the survey.

Two parameters were taken into account for creating the segmentation: the ownership of smart metering devices (such as power meters) and the interest and purchase intention of smart metering devices.

The first parameter could easily be measured using one question asking for the ownership of these smart metering devices.

The second parameter concerns the interest and purchase intention of devices for smart metering in terms of adopter segments as formulated in diffusion theory [8]. According to this diffusion theory, the adoption of an innovation depends largely on a person's innovativeness determined by the moment upon which a person decides to start using an innovation. The diffusion of an innovation in a social system follows a clockwise pattern. Rogers [8] distinguishes between five adopter segments. The Innovators (2.5% of the population) are the most innovative group of adopters. They will be among the first to adopt an innovation, followed by those categorised as Early Adopters (13.5%), Early Majority (34%), Late Majority (34%) and Laggards (16%). In order to assign the respondents to one of the adopter segments for smart metering devices, the Product Specific Adoption Potential scale (PSAP) [9-11] was used. The scale was developed as a valid alternative to traditional single-intent questions used in traditional market research, which systematically lead to over- or underestimation of the adoption potential of innovations. The model has been validated for several innovations (e.g. [11, 12]). Instead of a single intent question asking for the adoption likelihood of an innovation, three questions are asked. The adoption intention is measured for optimal and suboptimal product offerings. A calibration heuristic based on the answers on all 3 intention questions assigns the respondent to the appropriate adoption segment [9].

First, the respondents received an introductory text about smart metering devices and their possibilities. Smart metering was described as the use of a new type of electricity meter, which offers households the ability of closely monitoring their energy consumption. After reading this text, **the first (traditional) intention question was asked (PSAP question 1):** *"If you would have the opportunity tomorrow to buy a smart metering device, to what extent do you think that you would buy this device"?* The answering scale provided 5 possible answers:

- I would immediately buy this device;
- There is a large probability that I would buy this device;
- I think I would wait, maybe later;
- I don't think I would buy this device;

- I definitely won't buy this device.

Second, the respondents were asked to rate 10 possible use cases of smart metering on a 5-point scale ranging from "not interested at all" to "very interested". The use cases were:

- Receiving personalized tips to save energy based on your energy usage data;
- Insight in your energy use in real time at every moment of the day;
- Receiving graphs and reports with an overview of the total energy use in a certain period;
- Postulate goals to save energy in the future;
- Making an estimation of the future energy use during a certain period;
- Comparing your energy use with other (comparable) households or houses (e.g. in your neighbourhood);
- Receiving feedback when the energy use exceeds that of a previous comparable period;
- Entering in competition with other households to keep the energy use low;
- Graphs and reports with detailed energy use data per appliance;
- Automatic switch-on/–off of appliances, based on time of the day (e.g. day/night).

Furthermore, the respondents were asked to specify an "acceptable price limit" they are willing to pay for a smart metering device that is capable of providing the 10 use cases that we provided in the previous question. No limitations were imposed. The respondents were free to give any price they thought was acceptable.

After these questions, **a second more personalized intention question was asked (PSAP question 2).** This time, an ideal product was composed using those use cases from the aforementioned list of 10 that the respondent was either "interested" or "very interested" in. This ideal product was then presented as a "smart metering offer" at a price that was acceptable for the respondent, according to the price limit (s)he had indicated, and containing all the applications/use cases (s)he was interested in. Hence, every respondent had to give their adoption intention for this ideal product at their ideal price (which was different for every respondent).

Finally, **a third intention question was asked (PSAP question 3)**. This time, the adoption intention for a "suboptimal product" was measured. Again their ideal product was provided, but at a higher price than the limit they indicated (the ideal price was raised with 20%).

Based on a calibration heuristic, checking for the consistency in intention statements over the different answers on the 3 PSAP questions, each of the respondents was assigned to one of the adopter segments: Innovators, Early Adopters, Early Majority, Late Majority and Laggards.
Furthermore, 2 more segments were added to the segmentation: "Current Owners" and "Out of Potentials". Current Owners are those who indicated that they already possess certain smart metering devices. Although they don't possess a smart meter yet, they have already invested in devices with similar possibilities. Out of Potentials are respondents that showed no interest in any of the use cases that were provided. Late Majority and Laggards were merged into one single segment labeled "Later Adopters" due to small socio-demographic and attitudinal differences.

3. Results

3.1. Segmentation on attitude towards smart metering

Figure 1 indicates that a market potential exists for smart metering in Flanders, as the high proportion of Current Owners, Innovators and Early Adopters and Early Majority indicates. Still, there is also a high proportion of Out of Potentials, which indicates that for certain consumers, using smart metering is already out of the question, no matter the cost of the investment.

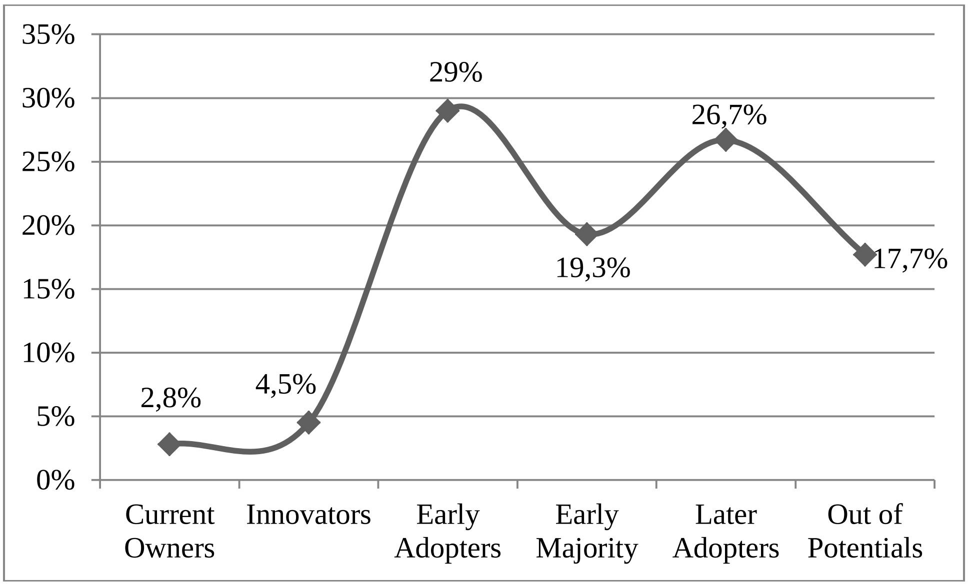

Fig. 1. Segmentation of Flanders on attitude towards smart metering.

Current Owners are the segment that already made some (minor) investments in equipment with smart metering capabilities. These Current Owners were identified by asking for the ownership of appliances that have smart metering capabilities (after being given an introductory text to the possibilities of smart metering). 40 respondents indicated to have such an appliance. When asked for the capabilities of their appliance, … 75% of them appear to have one that displays the energy use per appliance, 20% has a device that displays the total energy use and 5% has a tool that allows monitoring the energy use per circuit. The Current Owners are among the “younger” respondents (average age = 44.3 years). They mainly live in younger households with children.

Innovators are the first segment that did not yet invest in appliances for energy use monitoring. They are very interested in using smart metering devices and exploiting the possibilities. The average age within this segment is 44.8 which makes them on average as old as the Current Owners. The majority of them is married and/or has children. Early Adopters are also interested in using smart metering devices, but to a lesser extent than the Innovators. They are somewhat more reserved. The average age within this segment is 46.3 years. The Early Majority can still be situated within the same age category as the Early Adopters and Innovators (average age: 46.5 years), but they are the less interested group. Their interest in and buying intention of smart metering devices is again lower than that of the previous segments. The difference between the Later Adopters and the previously mentioned segments is larger. Their interest and buying intention of smart metering devices is quite low. The average age in this segment is 50.5 which makes it significantly older than the other segments. Out of potentials are completely uninterested in smart metering devices. They are the oldest segment (with an average age within the segment of 54.6 years). More than a third of them are retired.

3.2. Willigness to pay

Of course, an important factor is the willingness to pay for a smart metering device. The adoption potential forecast for smart metering devices presented in figure 1 is not only based on interest, but also on an assessment of their willingness to pay. However, it is important to keep in mind that this first forecast is based on a scenario without pricing restrictions. The respondents had to indicate which price they are willing to pay for a smart metering device, without any control mechanisms or checks whether the indicated price is also a feasible price for the supply side. Therefore, a next step must be a comparison of the adoption potential for different pricing levels.

The PSAP-scale allows checking the possible influence of pricing. Five scenarios were created in which a cut-off (€50, €100, €150, €200, €300) was made at a given price. Figure 2 presents these five scenarios.

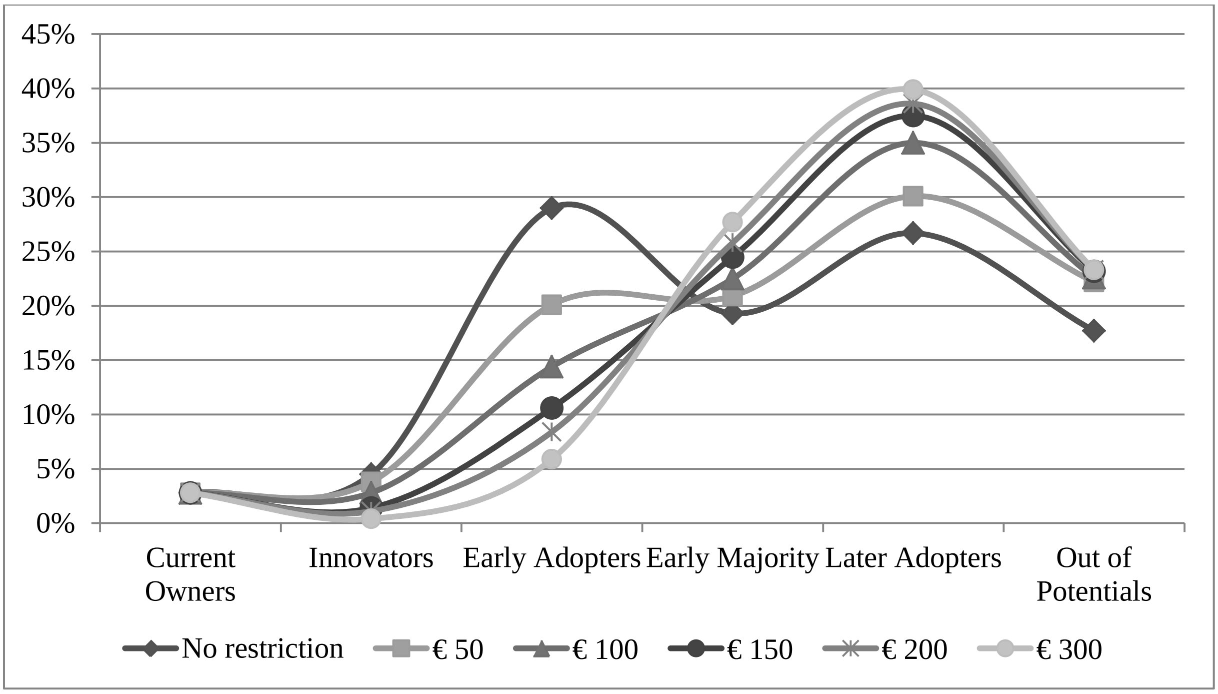

Fig. 2. Adoption potential curves for different pricing scenario.

Evidently, it can be assumed that enthusiasm will decrease as the pricing of the smart metering device increases. The question however is *how much* potential will be lost with each price increase? In the context of delineation of target markets and business cases it will be important to determine a kind of “tipping point” where a certain price increase holds the risk for a too big loss of potential. The “No restriction” scenario provides the original segmentation, in which the respondents could freely indicate how much they are willing to pay for their “ideal” smart metering device. Each of the succeeding scenarios (€50, €100, €150, €200, €300) gives the cut-off that was set. If the price that a respondent was willing to pay is lower than the cut-off that was set, the respondent shifts back one segment in the segmentation. In other words, respondents that combine a high enthusiasm for smart metering with a less realistic willingness to pay (according to the cut-off), slide to the rear of the segmentation. In the scenario in which the smart meter is offered at €100 for example, an initial innovator will not remain an innovator if (s)he indicated his/her willingness to pay to be e.g. €60 or €80.

As can be seen in figure 2, it is clear that the enthusiasm for smart metering is accompanied by a rather high price sensitivity. Where the forecasted size of the innovator segment in Flanders (originally 4.5%) remains almost 4% and 3% in the €50 and €100 scenario, it shrinks to 1% or less if the price threshold of €150 is surpassed. The Early Adopters segment shows a significant drop in size (from 29% to 20%) when a pricing restriction of €50 is imposed. In spite of their high interest in smart metering devices, a considerable proportion of Early Adopters shows a rather low willingness to pay. The drop in size of the segment continues over the following pricing scenarios with a tipping point around €100-€150. After this point, the divergence in the curves remains rather low.

4. Discussion

Providing insights and feedback about energy use is an essential means to create awareness and encourage an efficient energy conservation behaviour. Smart metering can be an excellent means to provide this feedback in real time. However, the question is who's interested in adopting this technology and what is their willingness to pay? In this paper, a segmentation on the adoption potential of smart metering devices was presented. Only a small proportion already own devices with some smart metering capabilities. This segment was called "Current Owners". The rest of the sample was classified in adopter segments. The large proportion of Early Adopters indicates a substantial base of interest in the possibilities of smart metering with regard to energy conservation for households. However, when different pricing scenarios for a smart metering device were applied to the data, a significant drop in the Innovator and Early adopter segments was noticed. In this research, the respondents were asked to indicate the price they are willing to pay for a smart metering device, without any checks whether their indicated price is also a realistic one. The results indicate that households want to invest in energy efficiency, as could be seen from the interest in smart metering devices, but the return must be worth the investment. Therefore, the yearly household electricity use is important to keep in mind. The average consumption of a household in Flanders is about 3500-4000 kWh per year, which corresponds with about €550-€650 per year. If e.g. a saving of 10% can be realized using smart metering devices, this leads to reduction of around €60 on the yearly electricity bill. For households with a significantly higher electricity use, high investments will be more relevant and therefore, their willingness to pay will be higher than that of households with an average electricity use.

Acknowledgement
This article is based on results from the SmartE project which is funded by IWT and various partners: IBBT, IBBT-iLab.o UGent-MICT, UGent-IBCN, KULeuven-CUO, KULeuven-ESAT-Electa, VITO, VUB-SMIT, Telenet, SPE-Luminus, Alcatel-Lucent Bell, Niko, Ferranti and Xemex.

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A simple estimation method to find the proper capacity of a combined heat and power unit

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Abstract: Selecting a proper capacity of the CHP unit is a complicated problem where energy usage pattern of end users and energy price structures must be considered. Thus, advanced computer simulations are used to predict the proper capacity of the unit, however, certain methods require expensive information such as part load performance of the unit and load profiles of end users. This paper suggests a simple method of predicting proper capacity by presenting analytical equations which calculate annual savings with different capacity of the CHP unit. These equations have merit which can be applied to various conditions by covering the energy usage patterns and energy price structures.

Keywords: *Combined heat and power, Capacity*

Nomenclature

c_e	*price of electricity* .... *cents/kWh*	p	*power* .... *kW*
c_f	*price of fuel* .... *cents/kWh*	q	*heat* .... *kW*
c_t	*price of heat* .... *cents/kWh*	T	*time* .... *hr*
hpr	*heat to power ratio* .... *kW/kW*	η	*efficiency* .... *dimensionless*

1. Introduction

Although a combined heat and power (CHP) unit produces both heat and electricity, it cannot control the ratio of output heat to power (heat-to-power ratio). Thus there is a potential discrepancy between the heat/electricity production of a CHP unit and the heat/electricity consumption on the demand side. This issue can be resolved by using a power grid and supplementary water heating system in conjunction with the CHP unit. However, the varying prices of energy consumed by the CHP unit, power grid, and supplementary heating system complicate the proper choice of CHP unit size. This problem is significantly different from selecting a boiler size solely on the basis of the consumption of heat by the end user.

Contrary to expectation, there are only few existing studies on selecting the optimum capacity of a CHP unit. It is certain that appropriate criteria for selecting the proper capacity of a CHP unit cannot be derived from a case study based on parameters that are limited, or classified only into 3 or 4 levels. Procedures such as modeling techniques, mathematical optimization, or simulation programs obtained from other researchers could help to provide relevant standards. However, these methods are actually difficult to adopt, and the use of other people's results requires expensive information, such as long-term accumulated minute-by-minute load profiles. The performance of a CHP unit varies according to the manufacturer, and energy usage patterns vary from one household to the next. Moreover, energy prices related to the use of a CHP system vary in different regions. Thus, although a solution to the problem of selecting the proper capacity of a CHP unit should account for parameters such as system performance, pattern of energy usage, and energy price structure, the required methodology is not easily found in the literature.

This study uses information that is easily obtained (annual average heat load, base/peak power load), and presents a simple and intuitive method for predicting proper CHP unit capacity for

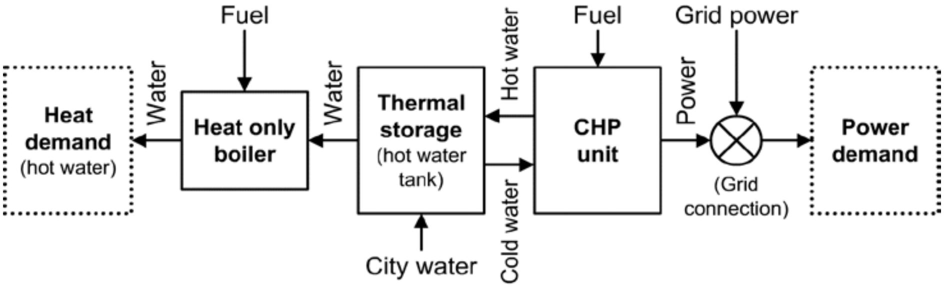


Figure 1. Schematic of the CHP system

end users. The final result is a set of equations for calculating the proper capacity for three classifications (three types of energy usage patterns), and is verified via computer simulation.

2. CHP system

This research is based on a CHP system that includes a CHP unit, thermal storage unit, and HOB (heat only boiler), as shown in Figure 1. The CHP unit operates when there is a heat demand, and the power output of the unit follows the power load on the demand side. This operating strategy is called the "following heat demand and chasing power load" (FHD-CPL) strategy, and is usually preferred where selling electricity back to the grid is impossible, or offers no economic advantage.

3. Problem formulation

In this paper, the objective function for determining the proper capacity is defined as the annual economic savings from using the CHP system. The problem is formulated as follows. The cost of energy consumption per unit time step by a CHP system is denoted by ec_{CHP}, and the cost of energy consumption per unit time step by a separated heat and power (SHP) system is denoted by ec_{SHP}. Equation (1) presents the formulation procedure and its result. When an arbitrary time T is divided into N intervals of length h, the cost saving in the nth interval is calculated as follows:

$$ECR_n = h\left(ec_{CHP,n} - ec_{SHP,n}\right) = h \cdot c_t \cdot q_{TS,n} + h \cdot \delta_n \cdot f_n \tag{1}$$

$$f_n = \left(c_e - c_e \max\left(1 - r_n, 0\right) - \left(c_f / \eta_{e,n}\right) r_n\right) p_{load,n} \tag{2}$$

where r_n is the power share of the CHP unit against the power load, η_e is the electrical efficiency of the unit, and c_t is the equivalent price of the energy. The above equations are also represented in Figure 2.

$$r_n = p_{CHP,n} / p_{load,n}, \quad \eta_{e,n} = p_{CHP,n} / f_{CHP,n}, \quad c_t = c_t^* / \eta_{t,HOB} \tag{3}$$

Also, δ_n is a parameter which value is 0 or 1 depending on the CHP units operation status in nth interval.

$$\delta_n = \begin{cases} 1 & \text{if CHP unit runs at } n \\ 0 & \text{if CHP unit halts at } n \end{cases} \tag{4}$$

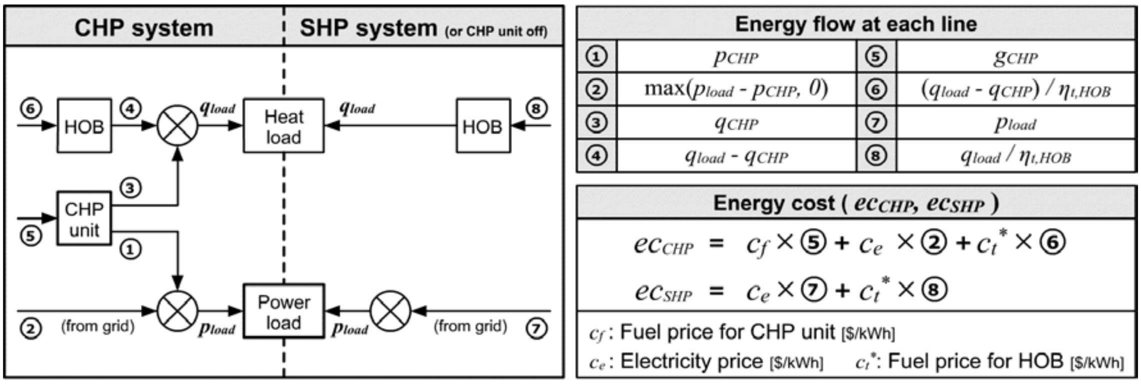


Fig. 2. Problem formulation

The total *ECR* (economic cost reduction) over an arbitrary period *T* is the sum of the ECR_n of the individual intervals.

$$ECR = \sum_{n=1}^{N} ECR_n = h\sum_{n=1}^{N}\left(c_t \cdot q_{TS,n}\right) + h\sum_{n=1}^{N} f_n \tag{5}$$

The first term on the right-hand side of Equation (5) represents the total amount of heat supplied to the end user over period *T*. Since only heat from the CHP unit is supplied to the thermal storage unit, this amount is the same as the total thermal output of the CHP unit over the period.

$$Q_{TS} \equiv h\sum_{n=1}^{N}\left(\delta_n \cdot q_{CHP,n}\right) = h\sum_{n=1}^{N}\left(\delta_n \cdot hpr_n \cdot r_n \cdot p_{load,n}\right) \tag{6}$$

In the above equation, hpr_n denotes the ratio of the electrical output to the thermal output.

$$hpr_n = q_{CHP,n} \big/ p_{CHP,n} \tag{7}$$

Equations (5), (6) and (7) can be rearranged as follows:

$$ECR = h\sum_{n=1}^{N}\left(\delta_n \cdot ecr_n \cdot p_{load,n}\right) \tag{8}$$

$$ecr_n = c_t \cdot hpr_n + c_e \min\left(r_n, 1\right) - \left(c_f \big/ \eta_{e,n}\right) r_n \tag{9}$$

The maximum power load during period *T* is denoted by p_{peak}, and the range from 0 to p_{peak} is divided into a uniform number of classes *M*. The mth class frequency, corresponding to the class mark $p_{load,m}$, can be expressed as a function $\mathrm{n}(p_{load,m})$, and the mathematical relationship between the period *T*, the number of intervals *N*, the number of classes *M*, and the frequency of each class $\mathrm{n}(p_{load,m})$ is given by

$$T = h \cdot N = h\sum_{m=1}^{M} \mathrm{n}(p_{load,m}) \tag{10}$$

$$\sum_{n=1}^{N} p_{load,n} = \sum_{m=1}^{M}\left\{p_{load,m} \cdot \mathrm{n}(p_{load,m})\right\} \tag{11}$$

The following equation for ECR can be obtained by rearranging Equations (8), (10) and (11):

$$ECR = T\sum_{m=1}^{M}\left\{or_m \cdot ecr_m \cdot p_{load,m} \cdot \mathrm{n}\left(p_{load,m}\right)/N\right\} \tag{12}$$

where or_m is the availability factor of the CHP unit in the m[th] class. Over period T, or_m is assumed to have a constant value or, which is unrelated to any of the classes.

$$or_m = \left(\sum \delta_n \middle| p_{load,n} \in p_{load,m}\right)/\mathrm{n}\left(p_{load,m}\right) \approx or \tag{13}$$

For an infinitely large number of intervals N and number of classes M, Equation (12) can be expressed as follows:

$$ECR = T \cdot or \cdot \overline{ecr} \tag{14}$$

$$\overline{ecr} = \int_0^{p_{peak}} \mathrm{ecr}\left(p_{load,m}, p_{CHP,nom}\right) \cdot p_{load,m} \cdot \mathrm{pdf}\left(p_{load}\right) dp_{load} \tag{15}$$

Here PDF(p_{load}) is the probability density function of the continuous random variable p_{load}.

To satisfy Equation (6), the heat and power load over period T should be periodic. Also, the thermal storage unit should compensate for any discrepancies between thermal output and heat load over period T. Thus it is appropriate to define period T to be a day. The annual energy cost savings are then calculated as follows:

$$AECR = \sum_{\mathrm{day}=1}^{365} ECR_{\mathrm{day}} = \sum_{\mathrm{day}=1}^{365}\left\{T_{day} \cdot or_{\mathrm{day}} \cdot \overline{ecr_{day}}\right\} \tag{16}$$

Also, for the demand side (which has a similar annual power load distribution pattern), Equation (16) can be simplified as follows:

$$AECR = T_{year} \cdot \overline{or_{year}} \cdot \overline{ecr_{year}} \tag{17}$$

$$\overline{or_{year}} = \sum_{day=1}^{365} or_{day} \Big/ 365 \tag{18}$$

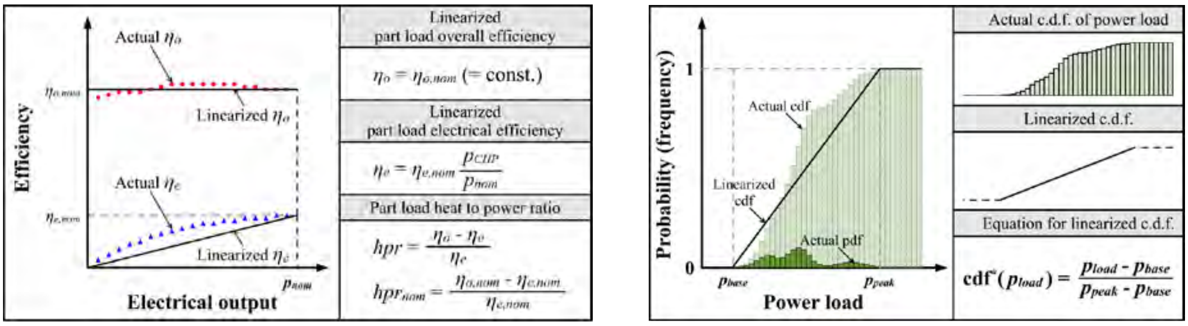
4. Simple estimation via linearization

In this paper, a simple estimation method for predicting the proper capacity of a CHP unit is proposed, based on linearization of the non-linear functions in Equation (17).

4.1. Partial load performance of the CHP unit and CDF of the power load

Equation (9) includes η_e and hpr, which are related to the performance of the CHP unit. In this study, the partial load performance is assumed to be as shown in Figure 3 (a). Applying this to Equation (9), and substituting into Equation (15) yields

$$\overline{ecr} = \left\{\alpha + \beta \cdot \mathrm{cdf}\left(p_{CHP,nom}\right)\right\} p_{CHP,nom} \tag{19}$$



(a) Partial load linearization (b) CDF of power load

Figure 3. Part load performance and cumulative distribution function

Here,

$$\alpha = c_t \cdot hpr_{nom} + c_e - c_f / \eta_{e,nom}, \quad \beta = c_t - c_e, \quad \text{cdf}\left(p_{load}\right) = \int_0^{p_{load}} \text{pdf}\left(p\right) dp \tag{20}$$

The PDF and cumulative distribution function (CDF) of the demand-side power load follow the pattern shown in Figure 3 (b). The CDF in Equations (20) is assumed to be a first-order function, as shown in Figure 3 (b). The assumed CDF for each interval, based on division in terms of the base power load and peak power load of the demand side, is as follows:

$$\text{cdf}^*\left(p\right) = \begin{cases} 0 & \left(p < p_{base}\right) \\ \left(p - p_{base}\right) / \left(p_{peak} - p_{base}\right) & \left(p_{base} \le p < p_{peak}\right) \\ 1 & \left(p \ge p_{peak}\right) \end{cases} \tag{21}$$

4.2. Distribution of the daily average heat load

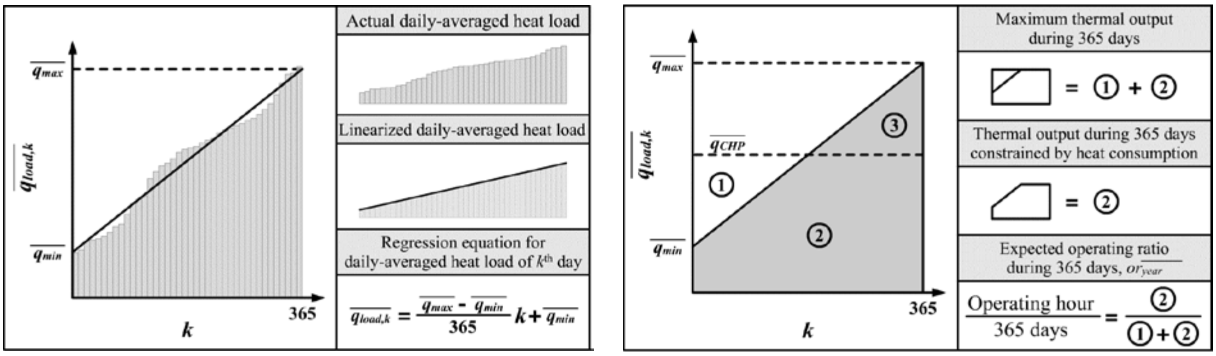
The maximum daily average heat load of the demand side is denoted by $\overline{q_{max}}$, and the minimum daily average heat load of the demand side is denoted by $\overline{q_{min}}$. If the daily average heat load for the k[th] day is assumed to be a first-order function, as shown in Figure 4 (a), or_{year} in Equation (18) can be obtained as shown in Figure 4 (b). Based on the procedure illustrated in Figure 4 (b), or_{year} can be expressed as a function of p_{nom} as follows:

$$\overline{or_{year}} \approx \begin{cases} 1 & \text{for} \quad p_{nom} < \overline{q_{load}} / \left\{hpr + \text{cdf}\left(p_{nom}\right)\right\} \\ \overline{q_{load}} / \left[\left\{hpr + \text{cdf}\left(p_{nom}\right)\right\} \cdot p_{nom}\right] & \text{for} \quad p_{nom} \ge \overline{q_{load}} / \left\{hpr + \text{cdf}\left(p_{nom}\right)\right\} \end{cases} \tag{22}$$

Here,

$$\overline{q_{laod}} = \left(\overline{q_{\max}} + \overline{q_{\min}}\right) / 2 \tag{23}$$

Thus *or* can be calculated solely on the basis of the CDF of the average annual heat (q_{load}) and the power load on the demand side.



(a) Linearization of heat load (b) Calculation of operating ratio

Figure 4. Distribution of daily-averaged heat load

5. Simple estimation method

Equation (17) can be written as follows:

$$AECR = T_{year}\underbrace{\left(\overline{or_{year}} \cdot p_{nom}\right)}_{U}\underbrace{\left(\overline{ecr_{year}}/p_{nom}\right)}_{V} \tag{24}$$

In Figure 5, p_{nom} is divided into intervals according to energy usage patterns (Type 1, Type 2, Type 3), and the forms of U and V in Equation (24) are graphically expressed for each interval. The proper capacity $p_{nom,pr}$ can be obtained by finding the maximum value of this simple polynomial (the order of UV is less than 2 over the entire range). The proper capacities for each type are shown in Table 1, based on the simple estimation method. However, one should be aware that this method does not provide the optimal capacities when α is negative or β is positive. In these circumstances, a CHP system cannot guarantee an economic advantage.

6. Validation

We verified the performance of our technique with a previously validated simulation program. This program was developed in earlier research, and the results (such as the amount of electricity generated and the thermal output) were obtained from a simulation based on the end user's load profiles. The details of this program are not included in the present paper, but can be found in the article "Optimum generation capacities of micro combined heat and

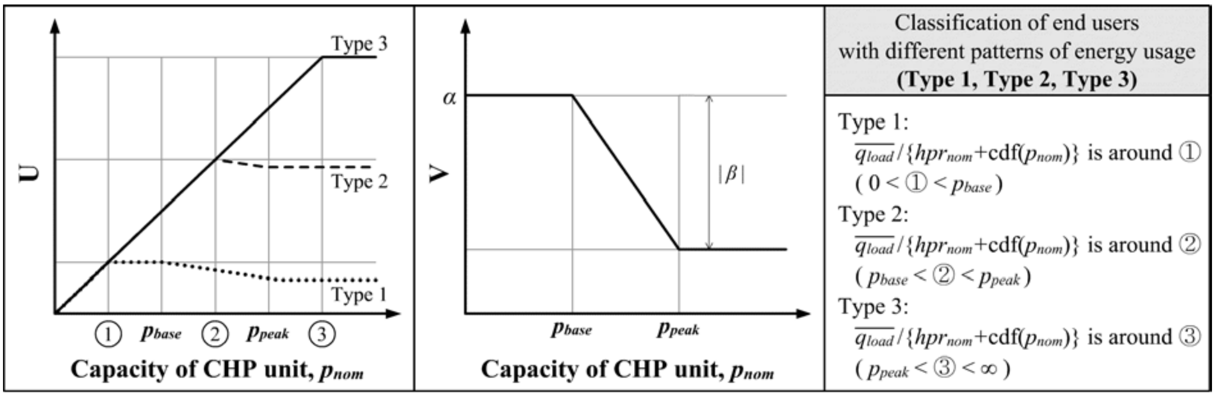


Figure 5. Simple estimation method

Table 1. Proper capacities for each type

Pattern of energy usage	Proper capacity
Type 1	$p_{nom,pr} = \overline{q_{load}} / hpr_{nom}$
Type 2	$\alpha/\beta \geq -p_{base} / (p_{peak} - p_{base}) \rightarrow p_{nom,pr} = p_{base}$ $\alpha/\beta < (p_{base} - 2\overline{q_{load}}/\overline{hpr}) / (p_{peak} - p_{base}) \rightarrow p_{nom,pr} = \overline{q_{load}} / \overline{hpr}$ otherwise $\rightarrow p_{nom,pr} = \{(1-\alpha/\beta)\, p_{base} + (\alpha/\beta)\, p_{base}\}/2$
Type 3	$\alpha/\beta \geq -p_{base} / (p_{peak} - p_{base}) \rightarrow p_{nom,pr} = p_{base}$ $\alpha/\beta < (p_{base} - 2p_{peak}) / (p_{peak} - p_{base}) \rightarrow p_{nom,pr} = \overline{q_{load}} / \overline{hpr}$ otherwise $\rightarrow p_{nom,pr} = \{(1-\alpha/\beta)\, p_{base} + (\alpha/\beta)\, p_{base}\}/2$
Parameters	$\alpha = c_t \cdot hpr_{nom} + c_e - \frac{c_f}{\eta_{e,nom}}, \quad \beta = c_t - c_e, \quad \overline{hpr} = hpr_{nom} + X$ $X = -A + \left\{ A^2 + \frac{\overline{q_{load}} - hpr_{nom} \cdot p_{base}}{p_{peak} - p_{base}} \right\}^{1/2}, \quad A = \frac{1}{2}\left\{ hpr_{nom} + \frac{p_{base}}{p_{peak} - p_{base}} \right\}$

power systems in apartment complexes with varying numbers of apartment units.”[1]

The AECR (annual economic cost reduction) result derived from Equation (24) was compared with that obtained from the simulation (numerical experiment). The partial load performance, demand-side energy usage pattern, and other information used in each method are listed in Table 2. We point out that the predictions obtained by the simple estimation method were based solely on the boldface entries in Table 2.

Table 2. Information used in each method

	Simulation program	Simple estimation
$\eta_{e,nom}$, hpr_{nom}	0.32, 1.78 [1]	**0.32**, **1.78**
$\eta_e(lf) / \eta_{e,nom}$	$1.03 - 0.98 \cdot 0.0315^{lf}$ [1]	*lf*
hpr (*lf*) / hpr_{nom}	$(0.96 + 0.76 \cdot 0.0454^{lf}) / (1.03 - 0.98 \cdot 0.0315^{lf})$ [1]	1
Distribution of p_{load} (PDF and CDF)	(Simulation uses load profiles [1])	Using equation (21) (p_{base} = **10 kW**, p_{peak} = **280 kW**)
Annual-averaged heat load	(Simulation uses load profile [1])	**242 kW**
c_t, c_e, c_f	6 cents/kWh, 12 cents/kWh, 6 cents/kWh (both)	

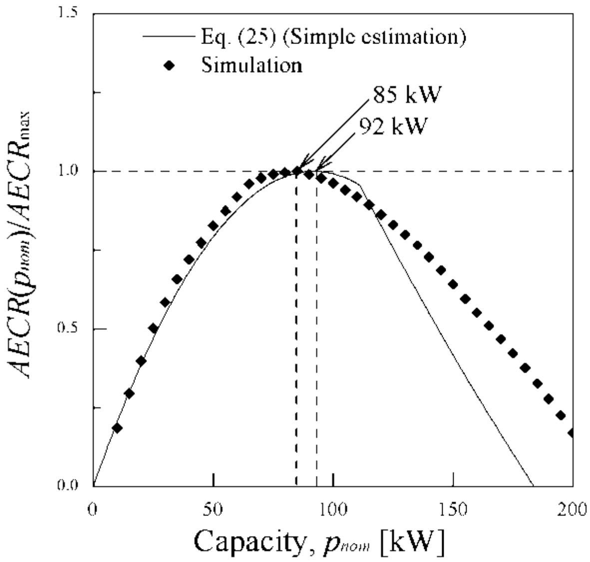


Figure 6. Comparison of the simple estimation method and a previous study

Figure 6 compares the standardized AECRs of each method (*AECRs* of different capacities, $AECR(p_{nom})$ divided by the maximum AECR, $AECR_{\max}$). The AECR calculated via Equation (24) attained a maximum at p_{nom} = 92 kW, while the AECR calculated via the simulation program reached a maximum at p_{nom} = 85 kW. Hence the results were in good agreement. In this manner, we can calculate the maximum (proper capacity) of a CHP unit by using the simple estimation method shown in Table 1.

7. Conclusions

In this paper, a simple estimation method was proposed to predict the proper capacity of a CHP unit. The advantages of this technique are described below.

First, if the relevant information (such as electrical and thermal load profiles and nominal efficiencies of the CHP system) are opened to the public, the technique proposed in this paper provides useful method to estimate the proper capacity of the micro-CHP system without using complicated (and expensive) simulation programs suggested from others.

Second, the method that has been suggested in this paper could handle different kinds of conditions by employing various energy prices and system's performances. For example, it could be applied into different situations in various countries (having different energy price policies and different CHP prime movers such as stirling or turbine engine).

Third, the most important aspect in this paper is that we suggested the simplest model among the others which can be cost-effective and easy to apply.

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Electricity intensities of the OECD and South Africa: A comparison

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Abstract: Improving a country's electricity efficiency is considered one of the important ways to reduce a country's greenhouse gas emissions. This paper's main purpose is to compare the South African total electricity intensity with these of the OECD members, in order to establish a sense of South Africa's relative performance. These results will assist in ascertaining possible scope for improvement, and if such exits, determining in which of the industrial sectors. To calculate the electricity intensities, we defined them as the ratio of electricity consumption to total output and then compare the South African with their OECD counterparts in total and disaggregated levels. For some of the countries the data were not sufficient for analysis over a long time period. Our results indicate that South Africa not only suffers from higher total and sectoral intensity levels but also the gap between them is increasing at an alarming rate. We conclude that for South Africa to improve its industrial competitiveness and achieve its stated commitments to the reduction of greenhouse gas emissions, it will have to improve its efficiency. This is likely to be achieved only through a concerted sector-specific approach.

Keywords: *Electricity, Intensity, South Africa, OECD, Comparative Analysis*

1. Introduction

Improving the electricity efficiency of a country is an important step towards decreasing greenhouse gas emissions originating from fossil fuel based electricity generation and consumption. From a policy-making perspective, the studying of efficiency is significant since it is a measure that combines the electricity consumption with the economic output [1] and the comprehension of the behavior of electricity demand under economic structural changes is imperative [2]. In the past a large number of studies were conducted to identify the dynamics, determinants and characteristics of electricity intensity in developed and developing economies [3, 4, 5, 6], resulting in showing the electricity intensity increases, as a consequence of economic growth and decreases as the economy progresses, shifting to services-based sectors [7]. This trend can be compared to the famous environmental Kuznets-curve [8, 9], but applied to the electricity intensity.

Here we seek to answer the question whether South Africa follows the international trends regarding electricity intensity. We do this by conducting a comparison between South Africa's national and sectoral electricity intensities and the equivalents thereof of the member countries of Organisation for Economic Co-operation and Development (OECD).

The main reason for focusing on the electricity intensity and not on energy in general lies with the fact that the energy sector is too diverse for comparative analysis. For instance, the intensity trends in the use of petrol are dependent on whether the country is an oil-producer or not. On contrary, the OECD members and South African electricity sectors present similar characteristics, especially regarding their generation, which is regulated and controlled by a monopolist. Hence, we argue that energy intensities would not be a comparable indicator between the selected groups of countries.

On a national level, the exercise will indicate whether there is scope for improvement. Furthermore, the analysis on a sectoral level will be beneficial because, firstly, it is imperative to understand the differences in economic and energy characteristics of each sector [10]; and secondly, not all the economies produce the same goods and service in the same proportion [11].

The next section of this paper will introduce the meaning of electricity efficiency and intensity as well as the current situation of electricity efficiency in South Africa. This is followed by the description of the data used and an international electricity intensity comparison on both a national and a disaggregated level. Finally, we conclude with a discussion on the findings.

2. Background

Following the political transition in 1994, the new democratically elected South African government considered energy issues as of great importance for the economic development of the country. In the first White Paper on Energy Policy [12] energy efficiency was mentioned among the cross-cutting issues. More specifically for the industrial and commercial sectors, the government committed itself to the following:

- Promotion of energy efficiency awareness
- Encouragement of the use of energy efficiency practices
- Establishment of energy efficiency standards for commercial buildings
- Monitoring the progress

While progress on these was slow due to pressing socio-economic and development considerations, the South African Department of Minerals and Energy released its first Energy Efficiency Strategy in 2005 [13]. The purpose of the Strategy was to provide a policy framework toward affordable energy for all and diminish the negative consequences of the extensive energy use in the country. Its national target was to improve electricity efficiency by 12% by 2015. The document, however, had limited impact to date and is currently being revised.

Fig. 1 shows the economy-wide electricity intensity and its growth for the period 1994–2006. Total electricity intensity showed a sharp upward trend until 2004. The period 2005-2006 was characterised by a notable decrease in the electricity intensity of 8.4% Firstly, the electricity prices increased by 182% in 2003 and it was highly impossible for the electricity consumers to react and change their behaviour in the short-run. Hence, the drop in electricity intensity (caused by a decrease in electricity consumption) might be considered the lagged impact of the high increase in electricity prices. Also, from a policy perspective, the first Energy Efficiency Strategy in 2005 [13] might also be the cause of a decrease in 2005/06.

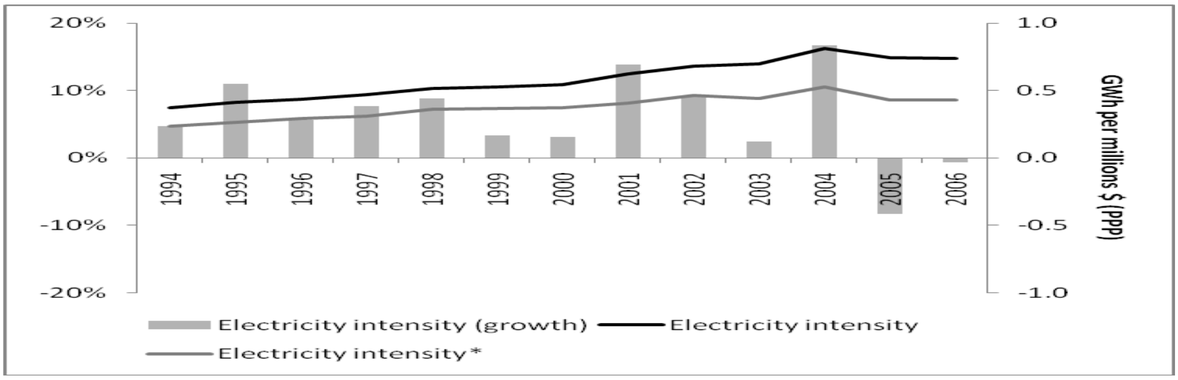


Fig. 1: Electricity intensity and its growth in South Africa: 1994 to 2006
**excluding residential, commercial and non-classified electricity consumption*

Sources: Authors' calculations based on IMF [14] and OECD [15]

However, if the industrial, transport, and agriculture sectors' electricity consumption is included only in the calculation, a lower intensity is observed with the growth not being as steep as before. Large inter-sectoral variations, however, exist[1].

Given this general information, how does South Africa compare, both on a national as well as sectoral level, with the OECD countries? We turn to this next.

3. Methodology and data

Several studies concerned with inter-country comparison of electricity intensities have been conducted [16, 17, 18, and 19]. These studies have, however, encountered certain difficulties, such as the heterogeneous definition of the variables as well as the diverse interpretations of the ratios calculated. We tried to avoid these problems by estimating the electricity intensities for each country using the same definition (i.e. electricity consumption/gross domestic product (GDP)) and the same dataset. We selected the OECD members because this group provides us with a wide spectrum of developed and developing countries with different economic and energy-related characteristics, but with its data and definitions being consolidated under one umbrella organisation. This limits the risk of data inconsistencies.

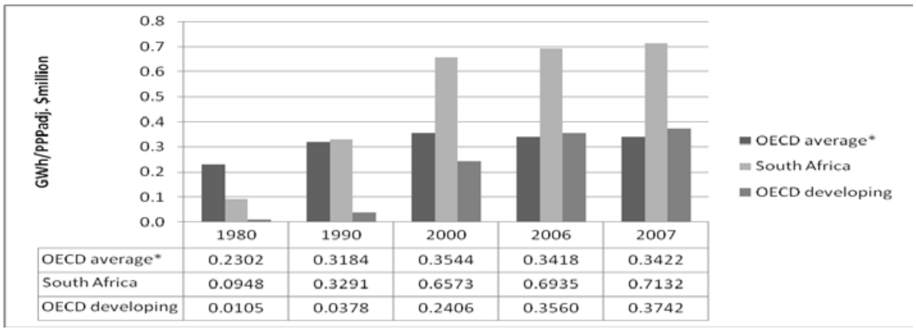
The data for electricity consumption (total and sectoral) were obtained from the OECD's Energy balances for OECD countries [20] and for South Africa from Energy balances for non-OECD countries [15]. The national GDP data (in current prices), the consumer price index (base year 2000) and the Power Purchasing Parity (PPP) adjusted real exchange rate values for all the countries were derived from the World Economic Outlook April 2010 of the International Monetary Fund (IMF). The disaggregated data for output for OECD members were derived from the STAN Database for Structural Analysis of OECD.

4. Results of comparative analysis

In 1980 South Africa's electricity intensity was substantially lower than that of OECD countries (see Fig. 2). This is to be expected to some extent given the high level of welfare enjoyed by a minority of people based on an industrial sector that services only a few with limited focus on exports at that point in time. Given the country's skew income distribution, a skew electricity usage was also presented: the higher income sectors were the most electricity intensive, too.

The country's electricity use rose sharply since the early 1990s with the abolishment of sanctions, the internationalisation of the markets to international trade, and the more stable economic and political situation after its first democratic elections in 1994. Hence, after 1994, the country's exports of electricity have been increased as well as the growth of the economy. These facts led to a strong impact on electricity use and since the 1990s, however, the electricity intensity in South Africa kept rising at an alarming rate (0.329 GWh/ mil $ adj PPP in 1990 to 0.713 GWh/ mil $ adj PPP in 2007) and currently far exceeds that of the OECD countries (0.318 GWh/ mil $ adj PPP in 1990 to 0.3422 GWh/ mil $ adj PPP in 2007) with no sign of any change.

[1] Data available upon request



	1980	1990	2000	2006	2007
OECD average*	0.2302	0.3184	0.3544	0.3418	0.3422
South Africa	0.0948	0.3291	0.6573	0.6935	0.7132
OECD developing	0.0105	0.0378	0.2406	0.3560	0.3742

Fig. 2: Evolution of electricity intensity: Average OECD and South Africa
** It excludes Czech Republic, Slovak Republic and Turkey due to lack of data of 1980 and 1990.*
Source: Authors' calculations based on IMF [24] and OECD [25, 28]

In the same figure, we extracted the developing economies of the OECD group (Hungary, Poland, Mexico and Turkey) and weight their average against South. Its electricity intensity was higher than that of the average of the OECD developing economies, throughout the years. Following this analysis, we disaggregate the OECD average to examine how South Africa compares with the OECD countries individually over the study period. The economy-wide percentage change of electricity intensity for the period 1990 to 2007 as well as the electricity intensity of 2007 for the OECD members and South Africa is presented in Fig. 3.

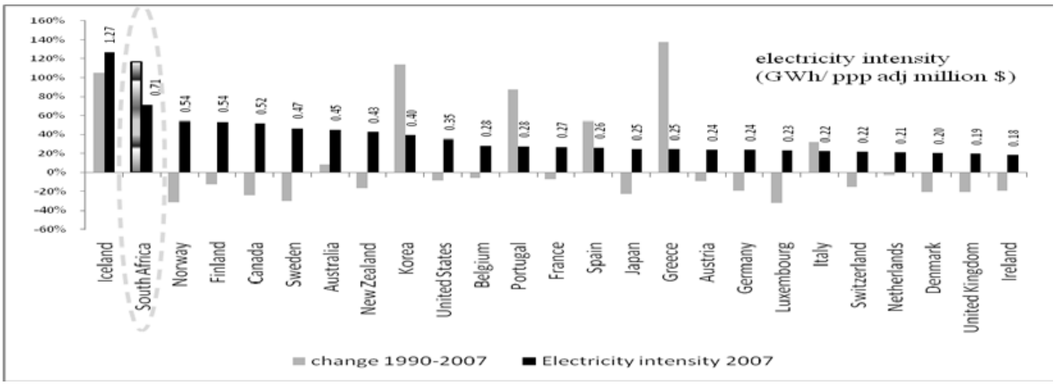


Fig. 3a: Electricity intensity in 2007 and its growth (1990 to 2007) for South Africa and OECD members [2]
Source: Authors' calculations based on IMF [14] and OECD [15, 20].

From Fig. 3a it is clear that South Africa has shown an increase in electricity intensity of 117% over the study period. This is in sharp contrast to the average of the OECD members which was only 10.09%. Only the Mediterranean countries (Spain, Greece, Portugal and Italy) as well as Korea and Iceland experienced an increase in their electricity intensities. Both their output and electricity consumption increased substantially, but the increase in consumption was higher than the growth in output and therefore their intensities experienced such sharp increases.

A further remarkable trend can be observed from Fig. 3a. There is a statistically significant negative, or inverse, relationship between the level of electricity intensity in 1990 and its

[2] It should be noted that Poland, Hungary, Mexico and Turkey were outliers (hence, excluded from the figure) with changes in electricity intensity for the examined period of 382%, 401%, 493% and more than 1,000% (from 0.0006 in 1990 to 0.723 in 2007) respectively. Also, the Czech and Slovak Republics were excluded due to lack of data points for 1990

growth over the study period[3]. This implies and that the higher the electricity intensity of a country in 1990 was, generally speaking, the more negative its growth was from 1990 to 2007. Countries such as Norway, Canada and Sweden, who were the most electricity intensive in 1990, were the ones that managed to decrease their intensity of electricity usage meaningfully, namely by 32%, 24% and 30% respectively. On the contrary, Italy, Portugal and Greece with the lowest intensities in 1990, raised them by 33%, 88% and 138% respectively. South Africa, however, does not fit this trend well. It had an average electricity intensity in 1990 and yet it had the second highest increase (after Greece) of its intensity (117%). The country, therefore, does not follow international trends in this regard.

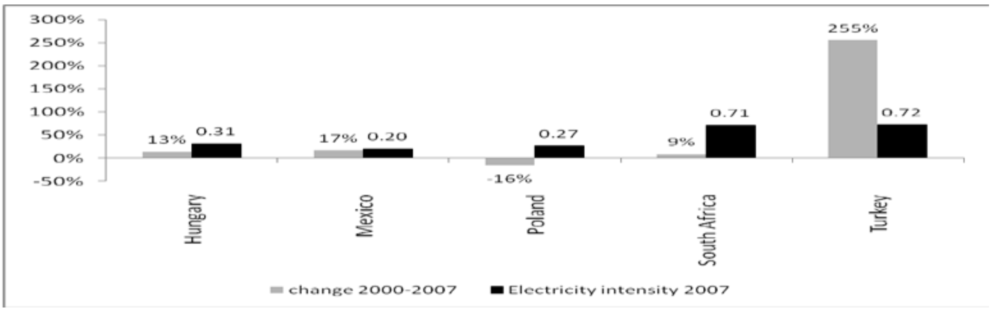


Fig. 3b Electricity intensity in 2007 (in GWh. $million (PPP adj)) and its growth: 2000-2007 for South Africa and OECD developing countries.
Source: Authors' calculations based on IMF [14] and OECD [15, 20].

Figure 3b presents a rather dismal picture for South Africa's electricity intensity in comparison with developing countries of the OECD. Its intensity was more than three times higher than this of Hungary, Mexico and Poland and at the same levels as Turkey. However, its growth for the period 2000 to 2007 was significantly less than this of Turkey (255%) and less than Hungary's and Mexico's (13% and 17%). However Poland managed to reduce its electricity intensity by 16% for the same period.

The results from Fig. 3 clearly indicate that South Africa's electricity intensity was not only higher than the majority of OECD countries in absolute terms (for 2007), but also showed excessive increase for the period 1990 to 2007 compared to the rest of the countries in the studied group. The next question that arises is whether this trend holds for all the economic sectors of South Africa.

To investigate the differences among industrial sectors, Table 1 presents the sectoral electricity intensities for South Africa and OECD average in 2006 and their differences. The majority of the South African sectors are more electricity intensive than the OECD average. Only four out of thirteen were more efficient than OECD and they are 'construction', 'food and tobacco', 'machinery' and 'transport equipment'. The order of magnitude in which they outperformed their OECD counterparts is on average 150.5%. This is in stark contrast to the degree in which the sectors whose intensity levels are worse than their OECD counterparts, namely 980.7% - a 6.5-fold difference.

[3] The results of the chi-square test and the Bartlett chi-square test are statistically significant confirming the existence of such relationship (chi-square= 3.63 (p-value=0.057) and Bartlett chi-square=3.41 (p-value=0.065)

Table 1: Sectoral electricity intensities in 2006 and output share: South Africa and OECD (Intensity: GWh/millions $ adj PPP; output: percentage)

	South Africa		**OECD**		**Differences**	
Sectors	**Intensity**	**Output**	**Intensity**	**Output**	**Intensity**	**Output**
Agriculture and forestry	0.316	6.00%	0.016	4.00%	1875.0%	50.00%
Basic metals*	1.095	7.10%	0.111	5.10%	886.5%	39.22%
Chemical and petrochemical	0.203	16.30%	0.034	15.20%	497.1%	7.24%
Construction	0.002	10.50%	0.087	16.60%	-97.7%	-36.75%
Food and tobacco	0.021	12.00%	0.023	8.30%	-8.7%	44.58%
Machinery	0.005	2.90%	0.028	15.00%	-82.1%	-80.67%
Mining and quarrying	0.634	14.60%	0.026	3.00%	2338.5%	386.67 %
Non-metallic minerals	0.524	1.60%	0.02	2.00%	2520.0%	-20.00%
Paper, pulp and printing	0.207	2.80%	0.021	5.50%	885.7%	-49.09%
Textile and leather	0.067	2.50%	0.01	1.90%	570.0%	31.58%
Transport equipment	0.003	9.80%	0.004	10.50%	-25.0%	-6.67%
Transport sector	0.089	12.50%	0.013	11.20%	584.6%	11.61%
Wood and wood products	0.069	1.40%	0.027	1.50%	155.6%	-6.67%

* Includes 'iron and steel' and 'non-ferrous metals'

'Basic metals' have the highest electricity intensity in both South Africa and the OECD countries. Comparatively speaking, however, South Africa's 'basic metals' sector was significantly more intensive (886%) than the OECD average before adjusting it to its respective size (or contribution to output) and 644% thereafter. The most efficient sector was 'construction', mainly due its high labour intensity and lower use of electricity-demanding technologies. On top of that the South African 'construction' sector was significantly more efficient than the OECD average. Why the 'construction' sector is more efficient compared to the rest can only be speculated about. This is due to a number of inter-linked factors; one of them being the labour intensity of the sector. This is since all the South African sectors are more labour intensive in comparison with the OECD countries, especially "construction", which is 600% higher than its OECD equivalents. The difference of the rest of the South African sectors to the OECD ones is in the range of 100-300%. The weighted difference shows that the South African intensity was 156% lower than the OECD average.

While most electricity intensive South African sectors, i.e. 'basic metals' and 'non-metallic minerals' present high differences with the OECD average (644% and 2517%), 'Mining and quarrying' does not follow suit. The South African electricity intensity was 2305% higher than the OECD average, however, considering that the South African mining sector is a dominant one for the economy (14.6%) while a very small proportion of the OECD production (3%), the difference albeit is still very meaningful.

5. Conclusions

The study of electricity efficiency has recently become an important topic for two main reasons. Firstly, it is highly linked to negative consequences of greenhouse gas emissions and secondly it is a measure that combines electricity use with economic output [1]. Our analysis shows that South Africa's electricity intensity was at a level much higher than that of the OECD countries and the gap between South Africa and OECD is also increasing at an alarming rate. While alarming, it points towards scope for improvement necessary if South Africa is to remain competitive in trade regimes including carbon trading considerations with its OECD counterparts [21, 22].

South Africa has shown an increase in electricity intensity over the study period of 117% – more than doubling its electricity intensity from 0.32 GWh/ millions $ adj PPP to 0.71 GWh/millions $ (PPP). This is in sharp contrast to the average of the OECD members, which was only 10.09%. From our results, nine out of thirteen South African sectors are more intensive than their OECD equivalents, and by a considerable margin. Although 'basic metals', 'mining and quarrying' and 'non-metallic minerals' were the most electricity intensive sectors, these sectors presented the greatest gap with those of OECD being more efficient.

In summary, it became apparent that for South Africa to reduce its electricity intensity it has to either reduce its electricity usage or increase its production while keeping its electricity consumption stable. The lack of appropriate policies and the low and stable prices of electricity in the country for the studied period might be the main reasons for the results. South African producers were not concerned for electricity efficiency given the relatively low price levels of electricity over the period. Progress can be made by a concerted industrial policy to enhance the use and development of electricity efficient appliances. Electricity price reform, such as what has been recently announced, whereby the electricity price level is significantly increased in conjunction with block rate tariffs that charges a higher rate to those that consume more, is also vital. A nation-wide demand-side management program is also essential in the wake of these results in order to improve efficiencies.

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Direct energy use in the livestock-breeding sector of Cyprus

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Abstract: Energy consumption for most sectors in Cyprus is not well monitored and therefore their impact on greenhouse gases emissions has never been estimated. Thus, the aim of this study was to estimate the energy consumption in livestock breeding activities in Cyprus, and estimate the respective emissions of greenhouse gases. The energy consumption considered is related to all direct energy uses on a farm except transport. All data available from national sources have been taken into account and the consumption of energy per animal was estimated to be 401 k Wh/cow, 624 k Wh/sow and 0.618 kWh/chicken. The direct energy consumption in livestock breeding was estimated to be 53 G Wh for 2008. The greenhouse gas emissions from this were estimated to be 15.6 kt CO_2 equivalent of which 91% is CO_2. The contribution of livestock breeding to the total agricultural energy consumption has been found to be 10-15%. Comparing the energy consumption per animal to other countries in a sample for which data was available, the consumption for Cyprus has been found for all animal species to be lower, mainly due to the warmer climatic conditions.

Keywords: *Direct energy consumption, Livestock breeding, Cyprus, Greenhouse gases emissions*

1. Introduction

Sustainability, energy and climate change during the recent years are increasingly gaining political attention. The European Union has already set legally regulated targets on climate and energy in June 2009 [1] and has just recently agreed to the new sustainability and financial strategy of the Union, the EU2020 [2] which also includes climate and energy targets. Currently, there are several legal obligations in the European Union at country level and installation level that require baseline data on sectoral energy consumption to be available. Decision 406/2009/EC [3] is among those obligations that requires Member States of the European Union to reduce greenhouse gases emissions from sectors not included in the European emissions trading system, i.e. waste, agriculture, transport, energy use in household and services and agriculture. Cyprus is facing a large deficiency in statistics for several sectors, among which the energy sector. One source of greenhouse gases emissions for which a target has been set by Decision 406/2009/EC [3] is energy use by livestock breeding.

The uses of energy in a farm can be classified into direct and indirect [4]. Direct energy use is associated with the consumption of energy (fuels and electricity) in a farm. Indirect energy use is the energy consumed for the production and transport of materials used in a farm (e.g. feed and machinery). 70% of total energy use on dairy cattle and pig farms is for indirect uses [5].

Traditionally, animal farming in Cyprus was characterized by small; family ran units, spread throughout the island, but the increasing demand in meat and other products, the production of genetic material and the automation introduced in the production, have caused an increase in animal farming, which have caused certain areas of the island to have high animal density. A typical animal farm in Cyprus, as in the rest of the world, consists of one or more buildings distinguished in three types: animal breeding areas, support buildings and waste treatment and storage areas. In most areas in Cyprus, electricity is supplied by the central network of the solely electricity provider, the Electricity Authority of Cyprus (EAC). Electricity in Cyprus is produced predominately by heavy fuel oil (HFO), with only a small amount produced by diesel [6]. It is expected that by 2014, natural gas will also be available for use. The most commonly used fuel in farms in Cyprus is diesel, which is mainly used for heating of the housing areas. During the last years the consumption of Liquid Petroleum Gas (LPG) for heating is rapidly increasing.

Not much data is readily available on energy consumption for livestock breeding in Cyprus. This paper brings together all the available data for stationary uses of energy for cattle, pig and poultry farming in Cyprus. Based on this data, the total energy consumption is estimated for the total population of the three animal species in Cyprus for 2005-2008. For 2008 the greenhouse gases emissions are also estimated and compared to other sources of emissions. Finally, results for both energy consumption and greenhouse gases emissions are compared to international literature.

2. Methodology

The main stages of the methodology applied are presented in Figure 1: (a) estimation of total energy consumption, (b) estimation of energy consumption according to source of energy and (c) estimation of the greenhouse gases emissions.

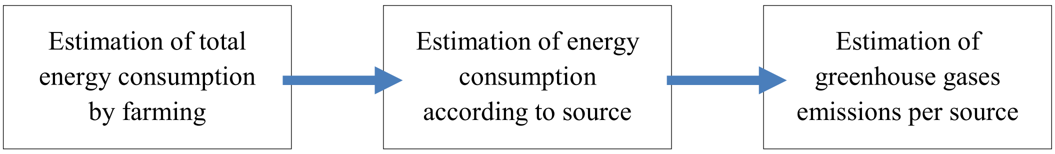

Fig. 1. Methodology implemented for the estimation of greenhouse gases emissions from energy consumption in livestock breeding in Cyprus.

2.1. Estimation of direct energy use from livestock breeding of Cyprus

The main sources of available data in Cyprus is limited to environmental impact assessment reports for animal farms submitted to the Department of Environment according to the Cyprus Law No. 140(I)/2005 on the assessment of environmental impacts from works [7] and annual reports submitted by installations that are above the benchmarks of the Integrated Pollution Prevention (IPPC) Directive [8]. Table 1 summarises the weighted energy consumption per animal in Cyprus as these were reported by the sources presented above; i.e. total amount of energy divided by total number of animals.

Table 1. Annual energy consumption per animal in Cyprus.

	Dairy cattle farms (kWh/cow)	Pig farms (kWh/sow)		Chicken farms (kWh/chicken)	
	178[*]	763[+]	1015[+]	0.741[+]	0.500[+]
	908[*]	1282[+]	244[+]	0.498[+]	0.292[+]
	610[*]	918[+]	1742[*]	0.578[+]	0.344[+]
		892[+]	64[*]	0.592[+]	0.760[*]
		181[+]	328[*]	layer chicken 0.864 [10,11]	
		1087[+]	111[*]	broiler chicken 0.644 [10,11]	
		225[+]	227[*]		
Weighted Average	401	624		0.618	

[+] data submitted by installations that are above the IPPC levels for 2008 [9]

[*] data submitted for new installations according to the Environmental Impact Assessment report prepared [10]

Using the average annual energy consumption per animal in Cyprus of 401 kWh/cow, 624 kWh/sow and 0.618 kWh/chicken and using the animal population for 2005 - 2008, the total energy consumption for animal breeding of cattle, pigs and chicken in Cyprus for the same period was estimated by multiplying the animal population by the per animal consumption (Table 2). The animal population data used was according to the latest published annual animal population census of the Department of Agriculture [12]. The results of Table 2 were also based on the following assumptions:

(a) Layer chicken and broiler chicken have the same, average energy consumption because not sufficient data was available for the population of each type.
(b) Dairy cows and other cattle were assumed to have the same energy consumption per animal because in Cyprus the animals are in the same farms.
(c) Goats and sheep are not taken into account for the estimation of the total energy consumption by livestock breeding in Cyprus because no data is available yet.
(d) No distinction is made into breeding methods and waste management technologies used.
(e) Energy consumption of waste management technologies is also included in the energy consumption of the farm.
(f) Both gestating and farrowing sows have been considered for the population of sows because the difference in energy consumption is small to be taken into consideration.

Table 2. Animal population and total energy consumption from livestock breeding in Cyprus for 2005 - 2008.

	Animal population (x1000)				Annual energy consumption (GWh)			
	2005	2006	2007	2008	2005	2006	2007	2008
Cattle	57.6	56.1	54.9	55.9	23.1	22.5	22.0	22.4
Sows	61.4	64.7	64.3	46.6	38.3	40.4	40.2	29.1
Chicken	3007	2763	2800	2820	1.9	1.7	1.7	1.7
Total					63.3	64.6	63.9	53.3

2.2. Estimation of greenhouse gas emissions from direct energy use in livestock breeding of Cyprus

The distribution of energy consumption according to source (Table 3) was estimated using the average energy breakdown according to the IPPC annual reports for pig and chicken farming [9].

Table 3. Average energy breakdown of energy consumption in Cyprus for chicken and pig farms according to IPPC annual reports [9]

	Electricity	Diesel	LPG
Cattle*	28.5%	44.8%	26.7%
Pigs	28.7%	48.3%	23.0%
Chicken	28.3%	41.3%	30.4%

* cattle farms energy consumption = average of pigs and chicken due to lack of data

Using the emission factors of the greenhouse gases and the fuel densities proposed as default by the IPCC 2006 guidelines [13], the CO_2 emission factors from electricity production based on the weighted average specific emissions of the electricity producing units of Cyprus [6], and the global warming potentials proposed by the 1996 IPCC guidelines [14], the emissions of a specific greenhouse gas by an animal species (GHG_{animal}) were estimated by equation 1 in t CO_2 equiv.

$$GHG_{animal} = (EF_{GHG})_{fuel} \times EC_{fuel} \times GWP_{GHG} \quad (1)$$

where $(EF_{GHG})_{fuel}$= emission factor for a specific gas for a specific energy source (or fuel), t/TJ and GWP_{GHG}= is the global warming potential of a specific gas. The energy consumption of a specific energy source (or fuel), in (EC_{fuel}) was estimated by Eq.2:

$$EC_{fuel} = (\%_{fuel})_{animal} \times EC_{animal} \quad (2)$$

where $(\%_{fuel})_{animal}$ = percent contribution of a specific energy source (or fuel) to the total energy (or fuel) consumption of an animal species, % and EC_{animal} is the total energy (or fuel) consumption of an animal species, TJ. All the data used is presented in Table 4.

Table 4. Parameters used for the estimation of GHG emissions

Parameter in Eq.1	Description	Value
$(EF_{CO2})_{electricity}$	Electricity CO_2 EF*	78.94 t/ TJ [6]
$(EF_{CH4})_{electricity}$	Electricity CH_4 EF	3 kg/ TJ [13]
$(EF_{N2O})_{electricity}$	Electricity N_2O EF	0.6 kg/TJ [13]
$(EF_{CO2})_{diesel}$	Diesel CO_2 EF	74.1 t/ TJ [13]
$(EF_{CH4})_{diesel}$	Diesel CH_4 EF	10 kg/ TJ [13]
$(EF_{N2O})_{diesel}$	Diesel N_2O EF	0.6 kg/TJ [13]
$(EF_{CO2})_{LPG}$	LPG** CO_2 EF	63.1 t/ TJ [13]
$(EF_{CH4})_{LPG}$	LPG CH_4 EF	5 kg/ TJ [13]
$(EF_{N2O})_{LPG}$	LPG N_2O EF	0.1 kg/TJ [13]
GWP_{CO2}	GWP*** of CO_2	1 [14]
GWP_{CH4}	GWP of CH_4	1 t CH_4 = 21 t CO_2 eq. [14]
GWP_{N2O}	GWP of N_2O	1 t N_2O = 296 t CO_2 eq. [14]
	Energy conversion	3600 kJ/kWh [13]
	Diesel Energy content	43 TJ/ Gg [13]
	Diesel Density	0.85 kg/l [13]
	LPG Energy content	47.3 TJ/ Gg [13]
	Butane liquid density	0.57-0.58 kg/l [13]
	Propane liquid density	0.50-0.51 kg/l [13]

* EF = emission factor, ** LPG = liquid petroleum gas, *** GWP = global warming potential

3. Results and Discussion

Data collected from the available studies and reports in Cyprus, have shown that energy consumption per animal varies considerably among farms. The available data has a very large range for all animal species, i.e. 178 - 908 kWh/cow, 64 - 1742 kWh/sow, 0.292 – 0.760 kWh/chicken. Nevertheless, the average of the results are reasonable when compared to other countries and the total contribution of the sector to energy consumption by agriculture.

3.1. Contribution of livestock breeding to agricultural energy uses

Comparing the results obtained for livestock breeding energy consumption (Table 2) to the total energy consumption by agriculture [15], the contribution of direct energy use in livestock breeding to the total energy consumption by agriculture has been found to decrease from 14% in 2005 to 11% in 2008. The energy consumption by livestock breeding has reduced considerably from 63 GWh in 2005 to 53 GWh in 2008, due to a decrease in the animal population, which is probably due to the increase in imports of meat. The total energy consumption of the sector has increased from 439 GWh in 2005 to 504 GWh in 2008, probably due to the change in climate conditions. The years of 2006 to 2008 were years with extensive droughts in Cyprus. This has caused the cultivations to require more artificial irrigation since natural precipitation was very limited. Consequently, the energy demand for the irrigation systems was larger. Additionally, the number of small desalination plants installed for agricultural use in coastal areas where saline intrusion takes place has been increasing during the last few years. This has been again caused by the reduction in precipitation and the need for farmers to use their already exhausted water extracting boreholes.

3.2. Comparison of direct energy consumption in livestock breeding in Cyprus to other countries

Cattle in most farms throughout the world are field-grazing most of the time of the year. When the cows are collected indoors due to weather conditions, the housing areas are closed. Therefore energy for ventilation and lighting is needed. In the case of Cyprus cattle is kept in the open but restricted areas instead of fields. With no lighting and ventilation used, energy per animal is considerably less. The comparison is presented in Fig. 2(a).

(a) (b)

Fig. 2. Annual energy consumption for various countries compared to energy consumption in Cyprus (a) per dairy cow found and (b) per sow for farrow to finish.

Figure 2(b) presents the Nova Scotia [18], U.K. [19] and Sweden [16] consumption per sow compared to Cyprus. Cyprus has the smallest consumption among the four areas. This is due to the reason that in pig farming most of the energy demands is for heating. Therefore, in Cyprus, where heating days are significantly less than Nova Scotia [18], U.K. [19] and Sweden [16], the energy demand is also significantly less compared to the same countries.

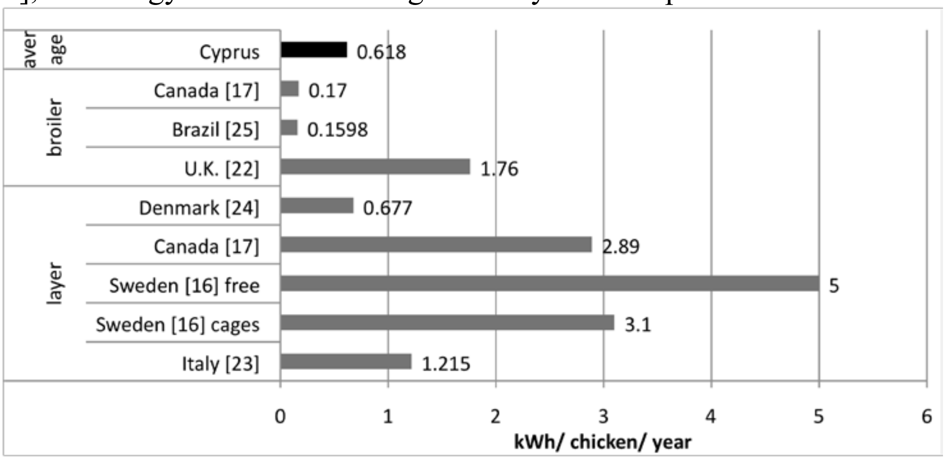

Fig. 3. Annual energy consumption per chicken for various countries compared to energy consumption in Cyprus for layer and broiler chicken.

The energy consumption estimated for chicken farming (Fig. 3) appears not very dissimilar to other countries. Most of the energy consumption is expected to be during summer for ventilation purposes as in Italy [20]. The per-chicken consumption of Denmark [21], Brazil

[22] and Canada [17] is smaller than Cyprus. A probable reason for this is that Denmark has well-developed technologies and therefore higher efficiency in energy consumption than Cyprus. For Brazil and Canada the smaller energy consumption could be due to differences in the methods of breeding.

3.3. Greenhouse gas emissions from energy consumption in livestock breeding

The total GHG emissions from energy consumption in livestock breeding have been estimated to be 15.26 kt CO_2e for 2008 of which 91% is CO_2. For the same year other agricultural greenhouse gas emissions according to the Greenhouse Gas Inventory of the country were 348 kt CO_2e [24]. The emissions according to gas and energy sources are presented in Table 5. The larger emissions are CO_2 emissions from diesel consumption in cattle and pig farming, which correspond to 21% and 29% of the total emissions respectively. Energy related emissions contribute approximately 3% to the total for cattle, 2% for pigs and 1.4% for poultry. Comparing the results to emissions from total agricultural use of energy, energy use in livestock breeding contributes 4% to the total agricultural emissions and 13% to the total agricultural energy emissions. This result is supported by the estimations of "Compassion in world farming" [23] where energy contributes 2% to the total livestock emissions.

Table 5. GHG emissions from direct energy consumption in livestock breeding in Cyprus according to gas and energy source, 2008.

	Cattle	Pigs	Poultry	TOTAL
CO_2 from Electricity, t	1,816	2,375	140	4,331
CO_2 from Diesel, t	2,679	3,752	192	6,624
CO_2 from LPG, t	1,360	1,521	120	3,002
Total CO2, t	5,855	7,649	453	13,956
CH_4 from Electricity, kg	69	90	5	165
CH_4 from Diesel, kg	362	506	26	894
CH_4 from LPG, kg	108	121	10	238
Total CH_4, kg	538	717	41	1,296
N_2O from Electricity, kg	14	18	1	33
N_2O from Diesel, kg	1,608	2,251	115	3,974
N_2O from LPG, kg	136	152	12	300
Total N_2O, kg	1,757	2,421	128	4,307
Total GHG from Electricity, kt CO_2 equiv.	1.82	2.38	0.14	4.34
Total GHG from Diesel, kt CO_2 equiv.	3.16	4.43	0.23	7.82
Total GHG from LPG, kt CO_2 equiv.	1.40	1.57	0.12	3.10
TOTAL GHG, kt CO_2 equiv.	6.39	8.38	0.49	15.26

4. Conclusions

In Cyprus, the annual consumption per animal was estimated to be 401 kWh/cow, 624 kWh/sow and 0.618 kWh/chicken. The estimates were based on available data for Cyprus. According to these figure, the direct energy consumption in livestock breeding of cattle, pigs and poultry is estimated at 53 GWh for 2008, which corresponds to 10-15% of the total agricultural energy consumption. Comparing the energy consumption per animal to other countries in the sample used in the study it was found that energy consumption per animal for Cyprus was, on average, lower. Energy consumption for cows was much lower than the countries for which data was available (Canada, Nova Scotia, U.K., Sweden) mainly because the majority of energy consumption in these countries is for heating which is not needed in Cyprus due to the relatively warm weather conditions. For chicken farming, the results are comparable to Italy, since a large portion of the country has similar climatic conditions to Cyprus (hot and dry).

Using the emission factor of each greenhouse gas according to fuel type proposed by the IPCC 2006 guidelines [13] and for electricity as proposed by national specific data by the Electricity Authority of Cyprus [6], the greenhouse gas emissions for each animal species and energy source were estimated. Comparing these to emissions from total agricultural use of energy, the results show that the emissions from energy use in livestock breeding contribute approximately 4% to the total agricultural emissions and 13% to the total agricultural energy emissions.

These results can be used by relevant Cyprus authorities for the assessment of the impact of measures for the reduction of energy consumption and greenhouse gases emissions.

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Active demand response strategies to improve energy efficiency in the meat industry

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Abstract: This paper is focused on the evaluation and assessment of different energy efficiency strategies applied to electrical appliances related to cool production and ventilation in industrial facilities which manufacture different types of meat products. Two strategies have been analyzed. Firstly, speed variation of fans in drying chambers, which implies modification of the on-off sequences in a way that the fans work for a longer time at a lower speed. A reduction of 1.65% in the total consumption of electricity is achieved. Lastly, use of flexibility in drying rooms based on the interruption of the electricity supply for the cooling production. Using this strategy saves of 5% in the total cost of electricity are achieved. Such results are very promising and demonstrate the effectiveness of these techniques, opening the gate to an innovative point of view about the management of this type of infrastructures to get significant energetic, economic and environmental savings with reduced and acceptable impact in the production process.

Keywords: *Full Food Industry, Power Demand, Energy Conservation, Electric Variables Control, Load Modeling*

1. Introduction

The meat industry is one of the most energy consumption intensive industrial sectors [1] and it is an industrial segment with one of the highest potentials for demand response (DR) implementation [2, 3]. It is the largest segment in U.S. agriculture [4], where poultry and pig meat segment represents the 16% in total World production [5]. The share for the European Union is similar, with the 18% in total World production. In the case of Spain, where techniques exposed in this paper have been tested, the elaboration of different pig meat products, as cured ham or deli products, is worldwide known. Spain produces the 3% of total pig meat in the world.

Regarding the type of energy sources used by such type of consumers, heating processes generally use fossil fuels, as natural gas or diesel, while electricity is mainly used for cooling. Refrigeration constitutes between 45% and 90% of the total final electricity consumption in working days [6], so that efficiency and saving actions must be focused on this energy source.

Different works have been presented in the past [7, 8] in order to evaluate customer demand response in different sectors (mainly for commercial and industrial segments). Nevertheless, they were not commonly applied to the meat industry processes since they are directly related to the final quality of the product, so customers were not willing to change any element or parameter of those processes.

In spite of that fact, these rigid industrial practices are being questioned because of the gradual increase in prices of energy, the higher concern in environmental issues as well as the evolution in technology solutions, so new actions, like the ones proposed in this paper, oriented to improve the energy consumption, start to be taken into account.

This paper presents such type of efficiency and saving actions as the effect of reducing the rotation speed of fans in drying chambers or the use of flexibility that customers may have under a novel approach focused on the identification of packages of energy [8] that could be reduced or eliminated for a period of time without impacting in production processes.

2. The drying process in a cured ham factory

The process of drying in a cured ham factory takes place in especially designed chambers and requires an accurate control of temperature, relative humidity and speed of air [9]. Historically, the process of drying was carried out in specific zones with Continental Mediterranean climate. The process started in December, where temperature and humidity are low, and it used to be completed in summer. Currently, artificial drying chambers reproduce such conditions permanently, so that a continuous production could be achieved.

2.1. The whole process: stages

The traditional Spanish dry-cured ham production is initiated with a salting process and storing of fresh ham at a low temperature before drying in order to stabilize the meat [10]. The temperature of the drying air is gradually increased during the drying process in order to accelerate the reduction of water in meat and the development of the typical aged flavor. According to available bibliography [9, 11] and after studying in detail the process of drying in different factories devoted to the production of Spanish cured ham, four drying stages can be identified for a typical plant, as shown in Fig. 1.

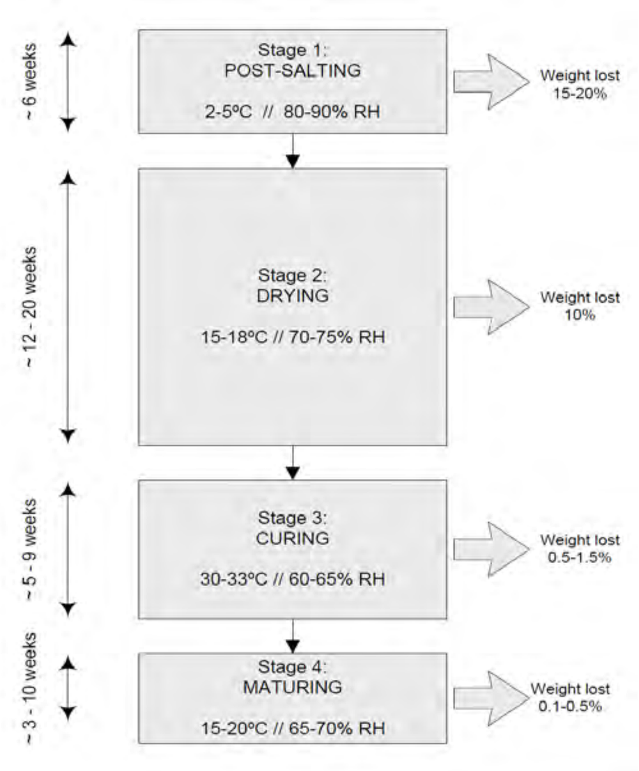

Fig.1. Drying processes in a typical cured ham factory.

- Post-salting stage. Temperature inside the chamber is set between 2 and 5ºC while humidity remains controlled between 80% and 90%. The average duration of this stage is about six weeks, depending on the type of product. The amount of water contained in the

meat is deeply reduced during this stage, reaching values between 15% and 20% in the total weigh of the product.
- Drying stage. The meat loses about 10% of weigh during this phase of the process. Temperature is maintained in 15-18ºC range and humidity take values of 70-75%. It usually takes between 3 and 5 months.
- Curing stage. Temperature is higher (30-33ºC) and humidity decreases up to 65% in this stage, with a typical duration of 5 to 9 weeks. Ham loses between 0,5 and 1,5% of weight in this phase.
- Maturing stage. The ham is introduced then in a maturing chamber until the experts consider that the product is finished. Therefore, the duration of this stage strongly depends on the particular situation of each product, as well as the type of final product to be obtained. Accordingly this stage could take from 20 to 70 days, depending on the type of final product and the amount of water it has already lost. Humidity is maintained below 70% and temperature reaches values of 15-20ºC.

A piece of ham loses during the whole drying process about 35% of the initial weigh that it had at the beginning of the process.

2.2. Psychrometric analysis of a drying chamber

Drying chambers are equipped with different air drying units, which are distributed on the ceiling of each room. Each device consists on a heat exchanger and a fan which forces the air to go through the unit. At the entrance of the unit, there is a first group of pipes containing cold water to cool the moist air and produce the condensation. At the exit, there is another group of pipes containing in that case hot water, which allow the dry air to recover the initial temperature.

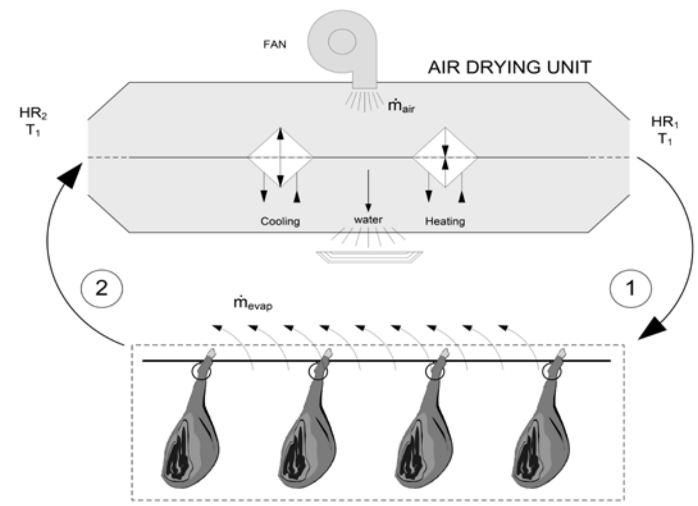

Fig.2. Meat drying process scheme.

The processes involved in a drying chamber facility, regarding the air parameters and flow, are schematically shown in Fig. 2. Dry air starts contacting with the surface of meat inside the drying chamber in point 1. Dry air absorbs the humidity from the surface of meat from point 1 to point 2 so that the humidity ratio ω grows adiabatically [11] from ω_1 to ω_2, as shown in Fig. 3, that depicts the psychrometric chart during the process.

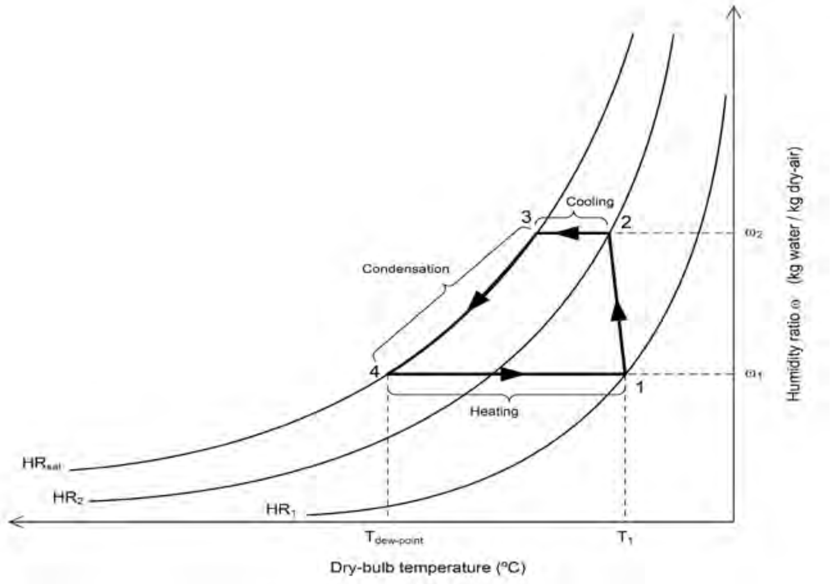

Fig.3. Psychrometric chart for a drying room.

When moist air gets in the air drying unit, the temperature decreases from point 2 to point 3, where the dew-point is reached. Moisture condensation occurs when moist air is cooled to a temperature below its initial dew-point [12]. From point 3 to point 4 temperature decreases while the air drives the water out since the humidity ratio is lower, as the capacity of the air to keep the water is reduced. Dry air is heated again from point 4 to point 1 in order to maintain the temperature inside the drying room, so initial conditions for the air are achieved to start the drying process again.

3. Proposed saving strategies

Two different strategies have been evaluated and assessed in order to achieve significant reductions in the electricity bill in factories devoted to the elaboration of meat products. In particular, speed variation of fans and flexibility strategies have been tested in different factories that produce Spanish cured ham, as it is exposed below.

3.1. Strategy 1: Speed variation of fans in drying chambers

Fans forcing the air to go through the drying units, located on the ceiling of the drying chambers, work intermittently according to the drying plan established by experts for the proper development of the process. The first action proposed is based on the modification of the on-off sequences in a way that the fans work for a longer time at a lower speed, so that the total amount of water extracted from the drying chamber remains constant.

The computation of boundary limits on possible savings with different operation conditions can be done according to the fan performance equations, and it can be summarized according to the following simple relationships linking fan capacity, speed and power:

- The airflow volume is directly proportional to the fan speed.
- The power required by fans is proportional to the cube of the fan speed [13]

In case the speed of fans were to be reduced, the duration of the ventilation cycle needs to be increased in order not to reduce the total amount of air required to remove all the water transferred by the ham, so the speed reduction would be achieved if fans were working at reduced regime for a longer time.

3.1.1. Obtained results

Results presented in this section have been obtained in a real factory which produces cured ham in Spain.
Four different drying chambers were studied in detail according to the design conditions of the considered factory. Table 1 shows the set point parameters for each one of these chambers:

Table 1. Set point parameters for the different drying chambers in a cured-ham factory.

Drying chamber / stage	Set point temp.	Set point humidity	Duration	Reduction of water
	ºC	*%*	*weeks*	*%*
Post-salting	*3.0*	*82.0*	*6.4*	*12.0*
Drying (I)	*8.0*	*77.0*	*7.1*	*9.0*
Drying (II)	*18.0*	*74.0*	*7.1*	*3.0*
Curing	*30.0*	*70.0*	*3.6*	*3.0*

A psychrometric analysis of each chamber, based on a methodology proposed by authors in [14], was performed in order to get the different values for points from 1 to 4, as described in section 1.2. Table 2 includes the humidity ratio, dry-bulb and humid-bulb temperatures, specific enthalpy and relative humidity for each drying chamber at a pressure of 760 mmHg.

Table 2. Set Characteristic points in the psychrometric chart for the different chambers.

Chamber	Point	Humidity Ratio ω	Dry-bulb temperature	Humid-bulb temperature	Enthalpy	Relative humidity
		kg-w/kg-da	*ºC*	*ºC*	*kJ/kg-da*	*%*
Post-salting	*1*	*0.00376*	*3.00*	*1.66*	*12.29*	*80*
	2	*0.00389*	*2.65*	*1.66*	*12.68*	*84*
	3	*0.00389*	*0.51*	*0.51*	*10.62*	*100*
	4	*0.00376*	*0.09*	*0.09*	*9.85*	*100*
Drying (I)	*1*	*0.00520*	*8.00*	*6.22*	*20.72*	*78*
	2	*0.00542*	*7.45*	*6.22*	*21.3*	*84*
	3	*0.00542*	*5.18*	*5.18*	*19.12*	*100*
	4	*0.00520*	*4.56*	*4.56*	*17.94*	*100*
Drying (II)	*1*	*0.00970*	*18.00*	*15.28*	*41.69*	*75*
	2	*0.01018*	*16.85*	*15.28*	*42.95*	*84*
	3	*0.01018*	*14.40*	*14.40*	*40.68*	*100*
	4	*0.00970*	*13.61*	*13.61*	*38.65*	*100*
Curing	*1*	*0.02019*	*30.00*	*26.23*	*79.58*	*75*
	2	*0.02140*	*27.20*	*26.23*	*82.85*	*93*
	3	*0.02140*	*26.08*	*26.08*	*82.13*	*100*
	4	*0.02019*	*25.23*	*25.23*	*78.06*	*100*

The next step was to calculate the value of reduced speed at which fans need to be adjusted. The rated power of motors is 1 HP at 1500 rpm. The initial time during that fans are switched on is equal to 50% of the stage for post-salting and drying (I), 40% for drying (II) and 35% for curing. The evaluation has been performed by considering that fans will be switched on for the 80% of the duration of each drying stage. Table 3 shows below the variations that affect to speed, power a duration of the different drying stages after implementing the speed reduction of fans.

Table 3. Ratios of speed, power and time after applying the proposed actions.

Drying chamber / stage	**Reduced speed** *rpm*	**Speed ratio**	**Δ power** *%*	**Δ time** *%*
Post-salting stage	*938.0*	*1.6*	*-37.5*	*60.0*
Drying stage (I)	*750.0*	*2.0*	*-80.8*	*100.0*
Drying stage (II)	*656.0*	*2.3*	*-92.5*	*128.6*
Curing stage (I)	*563.0*	*2.7*	*-91.8*	*166.7*

The application of these actions would allow the customer to save 172458 kWh every year, which supposes the 1.65% in the total consumption of electricity. Such savings imply reductions of 13642 € in the annual electricity bill, as well as 67.2 tCO2 are avoided to be emitted into the atmosphere a year.

As shown in this section, significant energy savings can be obtained. However, it is important to take into account that too high reductions of speed, as obtained for the curing stage, could result in the stratification of the air in the chamber and the inappropriate development of the drying process. For that reason, additional ventilation or a lower reduction of power must be assessed in order to apply this type of actions.

3.2. Strategy 2: Use of flexibility in drying rooms

This strategy is based on the interruption of the electricity supply for the cooling production so that the thermal inertia of the system could be used to keep both temperature and humidity inside under limits. Temperature and consequently the humidity ratio for point 4 increases when the cool production is interrupted. Therefore, the duration of this action will depend on the ability of the product not to be affected by that action. Interruptions of about 1 hour do not have negative effects on this type of products. Similarly, the cooling activity will be more intensive during the subsequent minutes after the interruption (payback period), so point 4 will decrease until the set-point is achieved again.

3.2.1. Obtained results

After a period of pre-evaluation which proved the effectiveness of proposed actions [1], the implementation of an intensive campaign of interruptions was carried out in order to reduce the monthly electricity bill. During the whole month of February 2010, two interruptions a day of two ours each interruption were performed in working days. Fig. 4 shows different daily load profiles when interruptions were performed, as well as an average profile and the standard deviation, represented below.

Interruptions were carried out on peak periods, which are established in the contract from 10:00 AM to 1:00 PM and from 6:00 PM to 9:00 PM in January, February and December. As daily interruptions of 6 hours were considered unacceptable, only the last two hours of each peak period were used for flexibility purposes. Consequently, the reconnection of cooling devices took place on shoulder period where prices are lower. As can be checked in fig. 4 the energy saved during each interruption is much higher than the one consumed during the recovery period.

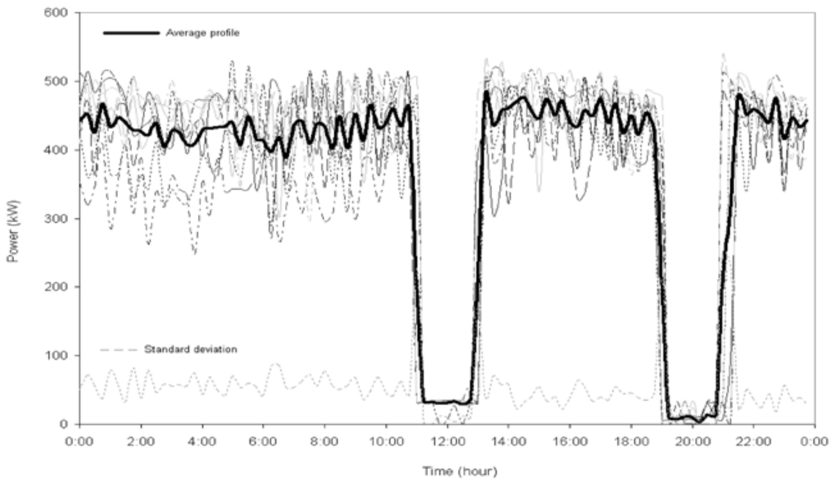

Fig.4. Daily electricity profiles during the campaign of interruptions in February 2010.

The application of such actions allowed the customer to save 1555 kWh every working day in February, equivalent to savings of 207.3 € and 1.52 tCO2 a day. The customer saved 4147 € during February, equivalent to a reduction of 6.21% in the monthly electricity bill. This percentage would be reduced to about 5% if these results are extrapolated for the whole year because the periods defined in the contract are different in other seasons and the difference between peak and shoulder prices is not as high in warmer months as in winter.

4. Conclusions

The use of electricity for intensive cooling processed in the meat industry has been analyzed in this paper, as well as different actions aimed to the improvement of energy efficiency in this sector have been proposed.
This paper provides empirical evidence about the importance that the use of flexibility in such a promising sector as the meat industry could represent in order to reduce the consumption of primary energy and emissions into the atmosphere, at the same time that attractive reductions in the electricity bill are achieved by customers.
Two strategies have been analyzed. Firstly, speed variation of fans in drying chambers, which implies modification of the on-off sequences in a way that the fans work for a longer time at a lower speed. Using this strategy, a reduction of 1.65% in the total consumption of electricity is achieved. Secondly, use of flexibility in drying rooms based on the interruption of the electricity supply for the cooling production obtaining saves of 5% in the total cost of electricity.

Such results are very promising and demonstrate the effectiveness of these techniques, highlighting that a different management of this type of infrastructures can be performed to get significant energetic, economic and environmental savings with reduced and acceptable impact in the production process.

Acknowledgment

The authors gratefully acknowledge the contributions of Campofrío Food Group, S.A.
This work was supported by the Spanish Government (Ministerio Ciencia e Innovación, MICINN) under Research Project ENE2007-67771-C02-01&02/CON

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The importance of end-use technologies for long-term energy use in Sweden

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Abstract: Energy consumption has stagnated in Sweden since the 1970s. It is not known how this was accomplished, but increasing efficiency in consumption has played an important role. In order to understand this a Change-of-stock approach is presented. Basically this approach says that stocks of energy converting artefacts on the consumption side comprise mature technologies with advantages of a path dependent character. These advantages create obstacles for radical technological changes and pushes in favour of incremental changes within dominating technologies. For the sake of testing the relevance of this approach five cases are highlighted. Data over stocks and replacement rates are estimated in three cases. Both factual and counterfactual estimations are presented. What is tested is the fruitfulness of the Change-of-stock approach as a tool for analysis of long-term changes in energy efficiency.

Results from the cases show considerable gains of efficiency in fuel consumption in private cars, and heating efficiency in multi-dwelling houses. Thus incremental changes are important, but are partially offset by changes in characteristics of the artefacts. Radical changes, as the factual change from air to rail, and a counterfactual double switch from gasoline to electric cars and from electric heating to district heating, and probable gains from the phase-out of incandescent lamps, show even bigger gains. Both incremental and radical changes are subject of counteracting tendencies, of a broader nature than that associated with rebound effects, such as more cars per inhabitant and fewer people in each dwelling.

The approach seem to promise a way to analyse energy efficiency that captures both promoting and counteracting factors, and at both the micro and macro level.

Keywords*: Stock, Replacement, Characteristic, Energy efficiency.*

1. Introduction

In several countries energy consumption has been decoupled from economic growth since the 1970s, one of which is Sweden [11]. Since the 1970s total energy consumption has stagnated despite a growth trend in GDP, and since the mid 1980s consumption of electricity has stagnated despite the role of electricity as a factor increasing overall energy efficiency. The oil price shocks initiated a switch of focus from supply to efficiency. Decoupling was a drawn-out affair as there is inertia due to past investments. Path dependence theory explains non-change basically with reference to cost advantages of existing technologies both on production and consumption side (for an introduction to path dependence see [2]). Today it is common to use an analogy to pedagogy, so that "learning curves" represents cost reductions in production of energy converters (in a broad sense) and in the familiarity in use of these converters. Due to cost advantages of widely used technologies the most likely path will be incremental change: Raising efficiency in gasoline cars instead of switching to electric cars, improving insulation in existing buildings instead of erecting passive houses, etc. When it comes to lighting the purchase price is much lower but the number of lamps make a radical break quite costly, and here we have the problem of the norm the warm glow of the incandescent as associated with.

Because sunk costs in stocks are important not only for the large number of units but also for the inertia it represents. IN THE FOLLOWING A CHANGE-OF-STOCK MODEL WILL BE TRIED OUT AS A STARTING POINT FOR THE ANALYSES. A point of departure for the model is the fact that energy is never used directly but always by way of some artefact—a paper machine, a car, a dwelling, a dishwasher, etc. [4]. There is a stock of machines, vehicles, buildings and appliances that demand energy. Every type of such energy converters comes in different models, and they are not only energy converters, they also have other qualities that are important for the buyer and user. A car, for instance, has several "characteristics" [6] of which fuel consumption is just one of many. THUS THE WORD "ARTEFACT" USED HERE STANDS FOR A COMPOSITE, OR COMPLEX UNIT. The stock is renewed through scrapping of old units, and through adding of new units. Additions can be of two kinds basically: Incremental improvements on technologies dominating the stock, or radically different technologies surviving at the margin of the stock.

A challenge for the efficiency strategy is the "rebound effect". It has been debated several times, beginning with Brookes' and Khazzoom's articles 1979 and 1980 (for an introduction see [7]). From an historical, or rather dynamic, point of view, the neoclassical formulation of the theory is limiting. As it stands it says basically that the acting factor (improvements in energy efficiency) causes a counteracting factor (increased use of the service in question or other services requiring energy) to operate. This narrow definition is too limited, for two reasons: First, counteracting tendencies can also work in parallel without direct link to prices and costs of particular type energy use. Increasing population, the decreasing number of people in the average household and new areas of consumption can increase the aggregate consumption of energy. Second, radical changes are associated with such drastic improvements in efficiency that it is impossible to outdo the gain through increased consumption.

WHAT IS TESTED HERE IS THE FRUITFULNESS OF THIS 'CHANGE-OF-STOCK' APPROACH.

2. Method

Three types of artefacts were chosen, all associated with private consumption (households)—cars, dwellings and lamps. Data of aggregate stocks over the long-run were collected from different sources. For cars and multi-dwelling houses the rate of renewal was estimated, and fuel and heating consumption of the average car and dwelling respectively. Counterfactual developments were estimated where certain variables were held constant, such as car-intensity, mileage per car, longer use-life of cars, and no energy-demanding changes in cars. Basically the same thing was done on heating of dwellings in multi-family houses. Due to lack of historical data the development of the residential lighting stock could not be disclosed. Instead data from a monitoring study performed by the Swedish Energy Agency was used for an estimation of the future of the Swedish residential lighting stock during the phase-out of incandescent lamps.

These incremental changes were contrasted with radical changes. In one it was estimated how much had been gained by the factual switch in long-distance domestic travel from air to rail, and in the other the aggregate effects of a counterfactual double-switch from gasoline to electric cars plus a switch from electric heating to district heating. The rationale for these cases is that in the first a radically different transport technology actually had been chosen, and in the other preferred choices of technologies from a sustainability point of view were estimated.

As society is an open system, one factor cannot be isolated as is possible in a laboratory experiment. Thus, whatever method used, the result cannot be unequivocal, and therefore can, and must, be the object of several possible interpretations. Counterfactual studies in social sciences can better be looked at as thought-experiments, in this study closely related to issues of trade-offs and choices of path in energy policy. When such problems and choices are discussed the relative magnitudes of gains in energy efficiency are of interest.

3. Results

3.1. Cars

The stock of private cars has been increasing in the long run, from 250,000 in 1950, to 2.5 million in 1973, and to 4.3 million in 2009. This rate of growth has exceeded the growth of population by far: In 1956 there were 10 inhabitants per car, in 2009 there were 2.2. Growth of the stock stagnated in the late 1970s and in the early 1990s. The age of the average car in 2009 is 9.3 years. [1].

The car is a complex durable commodity with several characteristics. The composition of characteristics of the average car changes through scrapping of old and adding of new cars. Energy efficiency is dependent not only of the energy conversion efficiency of the engine, but of several other characteristics, such as rate of acceleration, engine power, weight, air drag, the quality of tyres, etc. These characteristics, in turn, are connected to usefulness in terms of safety of driving, passenger and luggage space, low noise level and many others.

Sprei et al [16] investigated the conflicting tendencies in the composition of characteristics of new cars in Sweden: Better performance on one hand and lower fuel consumption on the other. New cars in 1975, 1985, 1995 and 2002 were studied in regard to passenger space, luggage space, top speed, time for acceleration, frontal surface area, weight, maximum power, cylinder volume, and fuel consumption. They found that increased space, acceleration and weight had reduced the gains from technical improvements of the engine, air drag and rolling resistance of tyres. About 65 per cent of the possible gains had been eliminated by comfort and acceleration only 35 per cent came out as better fuel economy.

Table 1. Descriptive and counterfactual data on the stock of private cars in Sweden and their fuel consumption 1950–2009.

	1950-59	1970-79	2000-09
A. No of cars in stock, millions	0.62	2.65	4.14
B. Inhabitant per car	11.5	2.9	2.0
C. New cars as share of stock, %	17.9	8.9	6.5
D. Scrapped cars as share of stock, %	4.3	6.7	5.7
E. Mileage, passenger km, billions	16.6	63.8	96.4
F. Mileage per car, km	26774	24075	22419
G. Fuel consumption per car, l/100 km		10.15	8.32
H, a. Total fuel consumption, index		100	115
b. Index when B and F constant		100	96
c. Slower renewal of stock		100	119
d. Only energy-saving features new cars		100	112

The average car consumed 8.32 litres per 100 kilometres when the factual development was estimated, and 8.08 when a possible development of smaller, slower and lighter cars was calculated (index value 112 in the last row). The slower renewal of the stock is estimated as the equivalent to the average fuel consumption of the stock in the period 1990-99. The average car of such a stock would have been very old, about 20 years (index value 119 next to last row). When car intensity and mileage per car is held constant at the 1970-79 level, total fuel consumption in 2000-09 is not only lower than it actually was, but also lower than in the 1970s, despite the fact that mileage was higher in the 1970s [14]. Note that in this counterfactual case the number of cars has been allowed to increase in parallel to the size of the population. The rate of replacement is in the long run slowing down, additions more so than scrappings (row C and D).

3.2. An imagined double switch to and from electricity

What would a double conversion—replacing electric heating with district heating, and replacing petrol cars with electric cars—mean for total energy consumption in Sweden? Assumptions used were 20% efficiency for combustion engine and 70% for electric motor [15], and 95% for electric heating and 84% for district heating [5]. The phase-out of electric heating and phase-in of electric cars were distributed equally for each year over a 30 year-period, 1975-2006. Input data on petrol ("bensin", excluding diesel) refers to total use of petrol in the transport sector, not only for private cars, and is thus exaggerated. It is assumed that electric heating will be replaced by combined heat and power production in district heating systems, but the additional electric energy produced has not been added to the total amount of electricity (which is a measure of consumption, not production). The fuel used in this counterfactual increase in CHP is left unspecified.

Table 2. Estimated changes in energy consumption when gasoline cars are replaced by electric cars, and electric heating with district heating.

	TWh 1975	TWh 2006	Index 2006
Gasoline cars, factual	38.2	45.2	100
Electric cars, counterfactual	10.9	12.9	29
Electric heating, factual	9.3	22.1	100
District heating, counterf.	10.5	25.0	113

Replacing gasoline cars with electric cars would reduce energy consumption with 32.3 TWh, while replacing electric heating with district heating would increase consumption with 2.9 TWh. The net gain would thus be 29.4 TWh.

3.3. Dwellings

The housing stock changes through a combination of building new and scrapping or rebuilding old houses. During a long post-war period, from 1959 to 1975, new build dominated restructuration with more than 60,000 dwellings per year (a peak occurred also around 1991). Since 1993 renovation of existing dwellings has dominated, at least in regard to multi-dwelling houses where reliable statistics is at hand.

Table 3. Descriptive and counterfactual data on the stock of dwellings in multi-family houses 1980, 1990 and 2008.

	1980	**1990**	**2008**
A. No of dwellings in stock, thousands	2043	2171	2440
B. Persons per dwelling	1.70	1.51	1.53
C. Change of stock, %	1.3	2.6	1.9
D. Square meter per dwelling	65	78	*80
E. Heating per square meter, kWh	295	190	145
F, a. Total heating, TWh	39.2	21.1	28.3
F, b. Total heating, index	100	82	72
F, c. Index when B and D constant	100	66	55
F, d. Index when E is constant	100	127	147
F, e. Index when B, D and E constant	100	103	111

Source: [9] [10] [12]. * = guess.

The last census, including housing conditions, was made in 1990. After that date data on housing has not been renewed at the same level of quality. This is the reason why a guess had to be made concerning the size of the average dwelling in 2008. Change of stock (row C) includes demolished, refurbished as well as new built houses. The rate of replacement (2%) is much lower than for the car stock (12-13%). Efficiency of heating has improved considerably since 1980, especially during the 1980s (and probably during the 1970s too, if the trend for multi-dwelling houses followed that of the small houses). Total heating has thus been reduced despite a growing number of dwellings.

When household formation and size of the average dwelling is held constant, total heating is reduced even more (see row F, c). If improvements in heating efficiency would stop at the 1980 level, 47 per cent more energy would have been consumed (row F, d). If changes in household formation and changes in the stock would have been neutral in regard to dwelling size and heating efficiency, then total heating would have been higher than it was in 1980.

3.4. A real switch from air to rail

According to statistics domestic air travel (from and to destinations within Sweden) increased from 1970 to 1990 [14]. After this year domestic air stagnated—in 2008 it was still lower than it was in 1990. Travel by railroad stagnated 1980-1992 but increased quite fast after this period. It seems that a change has occurred in the choice between train and aviation in long-distance domestic travel, in favour of train and thereby a switch from aviation fuel to electricity. If this interpretation is correct the change has lowered energy consumption for this purpose. A CALCULATION HAS BEEN MADE OF THE ENERGY CONSUMPTION IN TWO CASES: One the factual case, and a counterfactual case where rail had followed a stagnating trend while air had increased. In the factual case 13 TWh were used for domestic travel, in the counterfactual case 20 TWh—quite big a difference.

3.5. Lamps

We do not know so much about the lighting stock. The most comprehensive study made so far, is that by the SEA 2005-2008. Data from this source is shown in Table 4.The studies made so far are not representative of the whole household population. The number of households covered is small, from a statistical reliability point of view, due to the fact that data collection is cumbersome as the hours-of-use is essential information to collect.

Table 4. Unweighted averages on Swedish household's use of electric lighting 2005-2008.

	Small houses	**Multi-dwelling houses**
Number of lamps	55.2	31.2
Wattage per lamp (W)	29.3	26.6
Hours-of-use per day and lamp	1.60	1.94
Number of households (000)	1,978	2,238
Electricity for lighting (TWh)	1.87	1.31
Lighting/all electricity (%)	22.7	19.0

Sources: [17], [18], [8]. "Small houses" include detached houses and houses with two dwellings. "Multi-dwellings houses" often contain shops, offices and other non-residential spaces, but the main purpose is residential.

The sample is small in relation to the population of households, and the geographical distribution of the sample is quite narrow. On the other hand data covers several types of households in regard to housing, age, number of people, etc., and it is very detailed comprising observations on each appliance. With this in mind, we can let data give us a hint of what the national consumption of electricity for lighting would look like. From data in Table 4 it can be calculated that there are 179 million lamps in total.

Table 5. The distribution on lamp types in Swedish households, and assumed lifetime and price level for each type. Per cent, hours, Euro.

Lamp type	**Share, %**	**Life time, h**	**Price level, €**
Incandescent	60.5	1000	1
Halogen	16.2	3000	4
CFL	13.1	7000	6
Fluorescent tubes	10.2	10000	6

Sources: [17], [13]. Currency rate assumed: 10 SEK=1€. 1 USD ≈ 0.75€ in May 2010.

The effects of the phase-out [3] can be described as a comparison of the residential lighting stock before and after the transition period. It is assumed that all incandescent lamps will disappear and be replaced by CFL and halogen lamps. Then the replacement rate will decrease from 43 to 14 per cent per year (or from 2.3 years to 7.1 years for the whole stock to be replaced). Average power will be lower and thus electricity consumption for lighting (assuming constant hours-of-use).

Table 6. Economics of the phase-out.

	2010	2013
Replacement rate, %	43	14
Power per lamp, W	28	18
Electricity for residential lighting, TWh	3.2	2.1
Lamp sales, m€	113	119
Electricity sales, m€	483	308

"m€" = millions of Euro.

4. Concluding discussion

The change of stock approach says that the stock consists of mature energy converting technologies with cost advantages in production and advantages of familiarity among consumers and users. Because of these advantages an incremental path of improvements in energy efficiency is often chosen, the path of improvements of dominating technologies. For example higher fuel efficiency of the combustion engine, and additional insulation of existing houses.

Radical changes through the introduction of basically different technologies meet barriers of entry and must overcome the obstacles associated with path dependence. They are implemented only at the margin of the stock and meet increasingly higher barriers as dominating technologies are improved upon. This explains why the electric car has difficulties to gain wide diffusion.

Incremental changes in energy efficiency can be displaced by changes in other characteristics counteracting the efficiency gain. A heavier car, for instance, requires a more powerful engine, which can partially or completely outdo improvements of the engine. The compound effects of all relevant changes are what matters. Nevertheless, estimations of energy efficiency improvements shown in this paper have been quite substantial, more so in heating than for cars. Still, radical changes, such as a double switch from gasoline to electric cars and from electric heating to district heating would not only include a higher gain in efficiency but also a change of path.

The phase-out of incandescent lamps is a special case as it relies on a long period of preparation. The CFL has been around since the 1980s and is now more competitive in terms of purchase cost and familiarity among the public. The phase-out pushes consumers over the last threshold of a somewhat higher purchase price and forcing the user to forget the warm glow of the incandescent.

In the 1990s in Sweden there occurred a switch from air to rail in long-distance travel within the country. Many passengers changed their mode of transportation in favour of the train. This switch was a switch from the use of one existing stock to another, rather than a change of one stock. Energy saved from this switch was considerable.

There are, however, counteracting tendencies of a more purely social nature that partially outdo the gains efficiency in the more purely technological sense. Increasing population, a higher number of cars per head, and fewer people in the average household, are examples of such tendencies. They play a significant role for the total consumption of energy.

The strength of the change-of-stock approach is that it enables us to capture both promoting and offsetting factors, and both details and aggregate effects of changes related to energy efficiency in consumption. Taking the stock into consideration has implications for the future: The stock will be there in the future, it represents decisions of yesterday and today. Old innovations, both conservative and radical, may result in improvements in energy efficiency but are dependent on what is added to and scrapped from the stock and shifts between stocks.

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Households' energy use – which is the more important: efficient technologies or user practices?

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Abstract: Much policy effort focuses on energy efficiency of technology, though not only efficiency but also user practices is an important factor influencing the amount of consumed energy. This paper will explore to what extent energy efficiency of appliances and houses or user practices are the more important, both for understanding why some households consume much more energy than others, and when looking for relevant approaches to a future low carbon society. The paper uses several sources to explore this question, including results from the researcher's own projects, review of other studies and national statistics. Through the presentation of these different projects and examples it is shown how user practices are at least as important as the efficiency of technology when explaining households' energy consumption. The paper concludes that more research in this field is necessary. In relation to energy policy it is argued that it is not a question of efficiency *or* practices, as both have to be included in future policy if energy demand is actually to be reduced.

Keywords: *Households, Consumption, User practices, Energy efficiency.*

1. Introduction

In Western societies households stand for approx. one third of the energy consumption, and throughout the last thirty years efforts to reduce this has included research on and development of more efficient technologies and buildings, as well as policy activities directed at households encouraging them to purchase these more efficient technologies. To a much lesser extent focus and interest have been directed at how the actual use of technologies and houses influence the final energy consumption. However, recently an emerging interest is seen in research documenting the importance of user practices.

A Dutch study documents that building characteristics determine 42% of the variation in energy use for heating (water and space), leaving more than 50% of the explanation for user practices, though only 4.2% extra explanation of the variation in energy consumption can be explained by occupant characteristics [1]. This indicates that user practices are important, though only to a limited degree determined by objective occupant characteristics. A study based on US data concluded in line with this that besides weather characteristics, building characteristics are the main determinant of energy for space heating and cooling purpose followed by behavioral aspects, though in this study they further include the relation between occupant characteristics (like age and income) and building characteristics (like size and type of dwelling) making the indirect effect of the occupants much more important [2]. Besides building characteristics, some studies also include information on type of heat control system, like programmable thermostats, manual thermostats or manual valves and contrary to many assumptions, these studies conclude that those with programmable thermostats have the radiators turned on for more hours than others [3], and do not keep lower temperatures [4], and furthermore they conclude that the type of heating system has an influence on occupant behavior.

In this paper focus will be on presenting and analyzing different types of data which can further enlighten the question of how important user behavior is compared to efficient technology. The final energy consumption in households is a result of the number/size of the technology, the energy efficiency of the technology and the user practice in relation to the technology. In the following a distinction will be made between electricity (for appliances and lighting) and energy for heating (space and water) when exploring the relation between these four elements.

2. Analysis and results

2.1 Danish national statistics on electricity consumption

From the Danish national statistics [5] we have obtained data on the development of energy efficiency of appliances during the last thirty years and the development in the numbers of appliances in Danish households in the same period (see Figure 1). Data in this figure are based on analysis from a bottom-up computer model (ELMODEL-bolig), where input comes from surveys of some thousand households every third year on ownership and use of appliances, combined with information on numbers and types of sold appliances from industry and trade organizations. By combining the left and the right part of this figure, we learn that the growing energy efficiency gained over the last thirty years in the appliances in Danish households is counterbalanced by the growing amount of appliances in use.

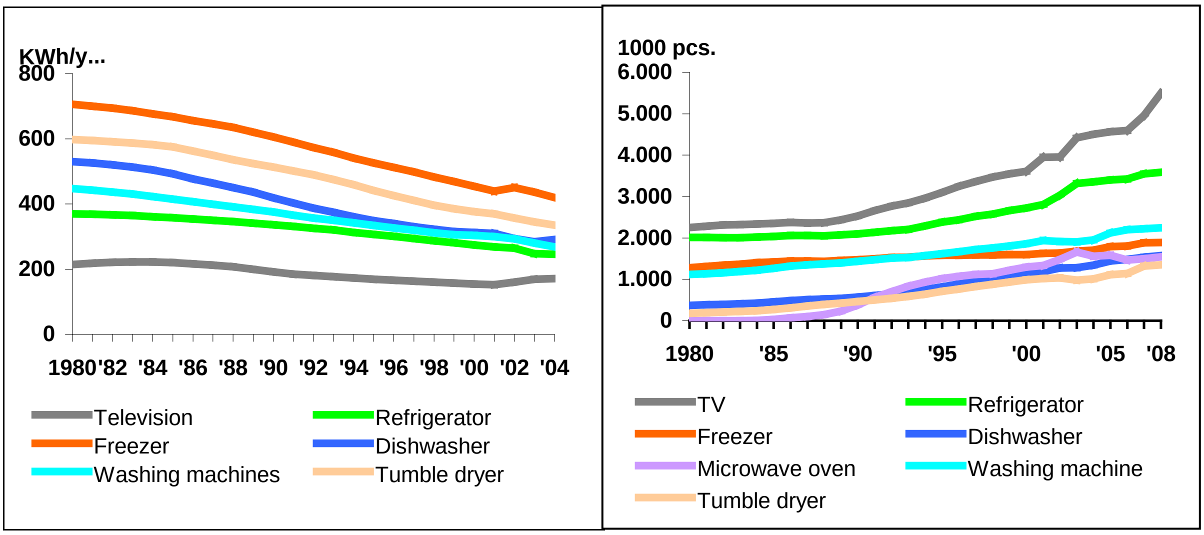


Figure1: Energy efficiency of Danish household appliances 1980-2004, left (KWh/year) and number of appliances in Danish households 1980-2008, right, (1000 pcs). Source [5].

2.2 Different energy consumption in similar houses

The explanatory power of energy efficiency, user practices and the number of appliances to explain energy consumption has been investigated in a study of 1000 quite similar houses, which in spite of similarity show huge variation in energy consumption. Comparing identical houses for heating (space and water) show that those using the least, use less than a third of those using the most, and for electricity (appliances and lighting) those using the most use five times as much as those using the least. The study included among others a survey with a response rate of 50%, combined with heat, electricity and water consumption as delivered by utilities and technical calculations and measurements of temperature and air exchange. The study has previously been reported in Danish [6], and different aspects have been published in English as well [7], [8].

For heat consumption the simple fact that technically completely identical houses can have heat consumption varying with a factor 3, show that user behavior related to heat consumption plays an important role. In this case the size and the energy efficiency of the technology (the house) are identical and variations in energy consumption thus have to relate solely to user practices related to space heating and hot water use.

In relation to electricity the analysis is more complicated as appliances and lighting is bought individually and we have to rely on self-reported data from the survey on number, efficiency and use of appliances. Statistical analysis of data divided households into three equal groups consisting of a third of the households with the highest level of consumption, a third with the lowest and a third with the middle level. Statistical analysis between this grouping and questions of (self-reported) use of appliances, number of appliances and energy efficiency of appliances has been conducted for different types of appliances. As self-reported information on energy efficiency cannot be completely reliable, people are only given the possibility of indicating whether their cold appliances are low-energy or not, or whether they do not know. For light bulbs, they have been asked, whether the share of low-energy bulbs is less than 25%, 25-50%, or more than 50%. In Table 1 it is seen that there is no correlation between people having indicated that their refrigerator is low-energy and the household being among the high, middle or low energy consumers. Correspondingly analysis shows that there is no correlation between the share of low-energy bulbs and which consumer group the household belongs to (not shown in table). On the contrary, there are other factors which do correlate with the energy consumer groups. The question of how many appliances people have show strong correlation as seen in Table 2, where the number of cold appliances per households is shown, and correspondingly analysis for how many televisions and videos the household have also correlates strongly with the energy consumer groups (not shown here). Furthermore the use of appliances also shows strong correlation to the energy consumer group: in Table 3 the correlation between use of tumble dryer is shown, and similar correlation can be found e.g. for the use of washing machine (not shown here).

Table 1. The share of households indicating whether their refrigerator is energy efficient or not is divided into three different energy consumer groups of households. The table should be read vertically. Analysis shows that there is no correlation (n=214, gamma=-0.055, not significant p=0.628).

	Consumer group Low	Consumer group Middle	Consumer group High	Total
Inefficient refrigerator	38%	26%	37%	100%
Efficient refrigerator	26%	35%	29%	100%

Table 2. Households' information on their number of refrigerator-freezer units, compared with the energy consumer group of the household. The table should be read vertically. Analysis shows a strong positive relation (n=286, gamma=0.306, significant with p=0.000).

	Consumer group Low	Consumer group Middle	Consumer group High	Total
1 Refrigerator-freezer unit	41%	31%	28%	100%
2 Refrigerator-freezer unit	21%	37%	42%	100%
3 Refrigerator-freezer unit	17%	35%	48%	100%

Table 3. Households' information on their weekly use of tumble dryer, compared with the energy consumer group of the household. The table should be read vertically. Analysis show a strong positive relation (n=199, gamma=0.334, significant with p=0.000).

Use of tumble dryer	Consumer group Low	Consumer group Middle	Consumer group High	total
1 time a week	28%	33%	38%	100%
2 times a week	13%	39%	48%	100%
3 times a week	14%	28%	58%	100%
4 times a week	8%	28%	64%	100%
5 or more times a week	9%	21%	70%	100%

In general the energy efficiency of household appliances does thus not contribute to the explanation of the huge differences that can be found between the electricity consumption in these households. What does contribute to the explanation is the number and the use of the appliances. However, the number and the use of appliances also correlate to the number of people living in the house. Analysis confirms that number of persons in the household is a strong determinant for the size of the electricity consumption, however, it also shows that it is more energy efficient to live more people together. This will be further explored in the following section.

2.3. Socio-economics in the understanding of user practices

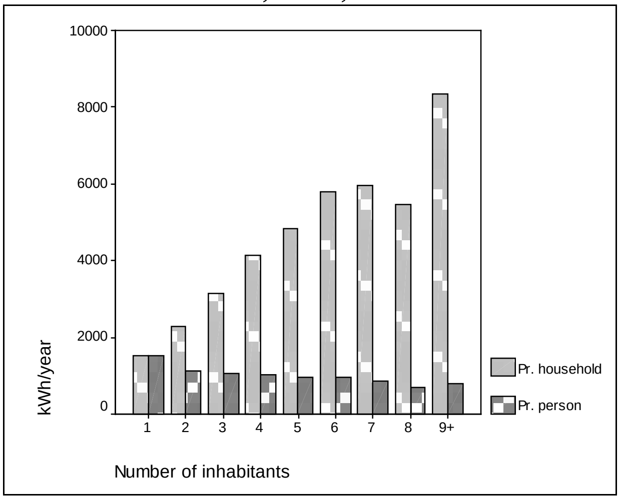
A database with registered data of approx. 50,000 households including socio-economic information on their inhabitants, building information (building type, year, size, installations etc.) and meter readings from utilities on heat (space and water) and electricity consumption (lighting and appliances) show some correlations between users, buildings and energy consumption [9]. Even this type of data does not include any direct information on user practices or energy efficiency, the data can throw light on some of the questions raised in this article. For electricity consumption, regression analysis for 8,500 detached houses is shown in Table 4. The number of inhabitants in the home is the strongest explanation of electricity consumption; income is the second most important and the size of the home the third. Similar relations between socio-economics and electricity consumption have been found in a study using detailed measurements of electricity consumption in Northern Ireland homes [10]. Furthermore Table 4 shows that other variables like age and education of the inhabitants only contribute with little extra explanatory power. Households' electricity consumption is strongly dependent on the number of members of the household. If, however, we compare electricity consumption per person with the number of members of the household, it becomes clear that it is more energy efficient to live more people together (see Figure 2). This is an important result related to user practices as still more people in most Western societies live alone. Today this applies to almost 40% of the population in Denmark, which thus can be seen as a main driver towards still higher energy consumption. From Table 4 it can furthermore be learned that even if we compare households in detached houses of the same size and with the same income, they can have huge variations in the electricity consumption as income and household size together only explain approx. one third of the variation in electricity consumption. The variation in households' electricity consumption can only to a very limited degree be explained by the age of the inhabitants or the level of education of the inhabitants; the greater part of the understanding of this user practice thus has to be understood by applying more qualitative approaches to the understanding of the everyday life of households.
When analysing heat consumption, the database includes type, size and year of construction. The year of construction can to some extent be equated with energy efficiency, especially for

more recent buildings. As the building type is an important factor in the technical description of the houses, analyses has been separated for different types. As an example of the analysis, detached houses will be used. Regression analysis on heat consumption of 22,000 detached single family homes show that the size can explain 28.3% (R^2) of the variation in heat consumption, and the year of construction can explain an added 10.5 % (R^2) of the variation in heat consumption (not shown in tables). When these two factors have been accounted for, other characteristics of the household members such as age, number of persons living in the house and income only contribute all together with approx. 4% (R^2) explanation of the variation.

Table 4. Regression analysis, detached houses: Background variables effect on electricity use, n=8.573

Background Variables	Effect on Electricity Use (kWh/year)	Explanatory Power, Change in R2 (%)
Per person in the household	541	27.6
Per 100,000 DKK in gross income	90	5.8
Per 10 m^2floor area	95	2.5
Per age square of oldest person	-0.35	1.3
Per 0-6 years old children	-158	
Per 13-19 years old children	179	0.5
Long education - primary school	-278	0.02

Figure 2. Average electricity consumption per household and per person compared with the number of inhabitants in the household, including households in detached housing, sem- detached housing and in apartments. 9+ refers to 9 or more inhabitants, n=53,804



In relation to the question of this article it is obvious that heat consumption is much more dependent on building characteristics than electricity consumption is, even though heat consumption also includes water heating which must be considered quite dependent on the number of inhabitants. Related to both heat and electricity consumption it is furthermore apparent that there is a huge variation in energy consumption which must be explained by differences in user practices. Furthermore it can be concluded that these differences in user practices only to a very limited degree can be explained by socio-economic descriptions of the inhabitants.

2.4. Low-energy buildings and user practices

As it seems that heat consumption is more dependent on building physics than electricity consumption is on energy efficiency of appliances and lighting, it is thus relevant to focus explicitly on new low-energy buildings and user practices. In Sweden a comprehensive study of 20 low-energy row houses have been conducted and measurements of total energy consumption (heat and electricity) show that user practices account for a variation of factor 2 as those using the least uses 49.2 kWh/m², and those using the most use 101.7 kWh/m² [11]. In UK similar studies of 26 low energy houses with post occupancy evaluation show that those using the least uses 46 kWh/m² and those using the most use 144.9 kWh/m² for space and water heating, equivalent to a factor 3 in variations in heat consumption depending on user practices [12]. The average in these UK low energy houses was 92.9 kWh/m² and the corresponding average for the local area is 172 kWh/m². In this study there is thus a factor 2 between the average for heat consumption for "normal housing" and the average for low energy housing, which could be interpreted as a factor 2 related to the energy efficiency of the house, whereas the user practices correspond to a factor 3.

3. Discussion

Above the different approaches to answering the question whether energy efficiency or user practices are the most important has been presented. In the following two different discussions will be introduced. First a discussion of the rebound effect, and second a discussion of the future developments in the composition of households' energy consumption.

3.1. Rebound effect and how it relates to discussions on user practices vs. efficiency

There is a huge international amount of literature on the rebound effect indicating that improvements in energy efficiency make energy services cheaper and thereby encourage to an increased consumption within the same services. In a recent review of empirical estimates of the rebound effect within the household sector, it is concluded that the rebound effect of household energy consumption for heating is approx. 20% [13]. This means that 20% of the efficiency gained through technical improvements of building and appliances are turned into increased consumption (higher comfort) following from direct change in user behavior. This understanding of the rebound effect builds on an economic understanding of household behavior i.e. that people consume more because they can afford it, which follows from the reduced energy consumption gained by energy efficiency. It should not be denied that economy can partly explain household behavior related to energy consumption. However, it should be emphasised that there are other relevant explanations than economy, including psychological and social understandings. If people feel they have done something to save energy, like buying an energy efficient appliance, then they might feel that they do not have to think so much about how they use it. Growing consumption however does not necessarily relate to energy efficiency. The growing number of appliances and inhabited floor area must also be understood as a consequence of other societal processes, which have been described as drivers behind consumption, including changing social norms and expectations following from new technical possibilities [14].

3.2. Future development in the composition of household energy consumption

As shown previously, heating consumption seems to be more dependent on the energy efficiency of buildings, whereas electricity consumption is more dependent on user practices including the number and size of appliances. There are, however, good reasons to believe that this relation varies with the different types of appliances. In Figure 1 (left) it is shown that energy consumption of freezers, dishwashers and tumble dryers has been reduced by approx.

one third the last thirty years, whereas no substantial energy reduction has been seen related to televisions. In general it must be expected that households' energy consumption to a still higher degree will be caused by information and communication technology (ICT) in the future. A Danish study showed that ICT from 2000 to 2007 rose from approx. 10% to 20% of a household's total energy consumption and that it can be expected to rise up till 50% of a household's total energy consumption within the coming 5-10 years [15]. These scenarios include assumptions of a continued efficiency of ICTs; however, they also assume that the size and number of ICTs will continue to grow. As it must be assumed that energy consumption related to refrigerators and freezers are more dependent on appliance efficiency than on user practices, compared with the use of ICT, these assumptions point towards a future where it must be expected that user practices as compared with energy efficiency will be even more important for the final electricity consumption in households.

4. Conclusions

This paper has dealt with the question whether user practices or energy efficiency is the most important for the size of a household's energy consumption. The answer to that question is slightly different if it is asked for heating (space and water) or for electricity (lighting and appliances). For heating it is shown that building characteristics, including size and year of construction, can explain approx. 40-50% of the variation in energy consumption, whereas inhabitant characteristics can only explain very little of the variation when the building characteristics has been accounted for. Furthermore studies confirm that completely identical houses can have heating consumption that vary with a factor 2-3 depending on user practices. This means that user practices are at least as important as building physics when it comes to energy consumption related to heating, though the user practices can only to a very limited degree be explained by objective characteristics.

Data analysis on electricity consumption for lighting and appliances suggest that this is more dependent on user practices than on energy efficiency, especially if the number of appliances are counted as part of the user practice. On a national level, a 30-40% increase in efficiency has been gained during the last thirty years. However, in the same period the number of appliances in households has risen more than the energy efficiency. When comparing households living in similar houses, electricity consumption can vary with a factor 5, thus indicating that electricity consumption is less linked with building size and type than with heating consumption. Analysis of data on type, use and number of appliances shows that the number and the use of appliances have a strong correlation to household electricity consumption, whereas information on energy efficiency does not show any correlation. Regression analysis on large databases shows that the number of inhabitants in households is the most important factor for describing electricity consumption; the more inhabitants in a household the higher the consumption. Electricity consumption per person shows the opposite correlation, meaning that it is more energy efficient to live more people together. Data also show that economy correlates with electricity consumption, which corresponds to the fact that the more affluent households can afford to have more appliances.

Even this article raised the question whether efficiency or user practice is the more important, it is relevant to establish that both efficiency and practices are important when seeking to reduce energy consumption. To realise substantial energy reductions, which is an important part of a future renewable energy system, we need consumers who choose efficient technologies, reduce the number of appliances and think about how they use them.

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Energy variations in apartment buildings due to different shape factors and relative size of common areas

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Abstract: A multi-storey residential building includes different sub areas, for example: apartment areas and common areas (corridors, basements, attic etc.). Each sub area may have different specific final energy use. Areas with lower specific final energy use will have a relatively lower contribution to total final energy use of a building. Examples of areas with low specific final energy use are corridors, basement and attics. All these areas are included in the calculation of a building's total final energy use. As a result, there is a risk that buildings designers may fulfill stricter end-use energy requirements simply by constructing buildings with larger areas containing a lower specific final energy use. In addition, the envelope area of the building may vary for a given floor area depending on the shape factor of the building. The heat losses of a building depend on the envelope area, the area that is in direct contact outdoor environment. Thus, buildings with a lower shape factor will have lower heat losses and hence a lower specific final energy use.

In this paper, we study the impact of those two factors on the specific final energy use of similar constructed apartment buildings in Stockholm. We consider 22 multi-storey residential buildings in ten locations that were built in accordance with the Stockholm program for environmental adapted buildings. They were chosen since they have different ratio of common area to total heated area and large variation in specific final energy use. Other characteristics such as energy systems, construction properties and population density were similar.
The analyses showed a high correlation between the shape factor of the buildings and their specific final energy use. An increased shape factor of a building by 0.1 increased the specific final energy use by 5.3 kWh/m^2. The specific final energy use of the studied buildings could vary up to 30 kWh/m^2 only because of the shape factor. Therefore it is recommended that the shape factor is considered in building codes for new buildings especially in cold climates. The energy simulations showed that the specific final energy use in the common areas was about 75% lower than in apartment areas. Hence, including larger common areas in the design of new apartment buildings reduce the specific final energy use significantly while the final energy use per resident will increase. This needs to be considered in energy requirements of buildings. Normalizing the final energy use by the apartment area should be considered as alternative method as it reduces variations in specific final energy use due to the relative size of common areas and increases the quality of using the SFEU for energy requirements.

Keywords: *Specific final energy use, Shape factor, Surface area to volume ratio, Energy variation.*

Nomenclature

SF	*Shape factor*…………………………..m^{-1}	*VHR*	*Ventilation Heat Recovery*
SFEU	*Specific final energy use*...kWh/m^2,a		

1. Introduction

Several programs have been launched in Sweden with the aim of improving the energy efficiency of new buildings. One example is the Stockholm program for environmental adapted buildings [1], which aims to stimulate the construction of buildings with final energy use lower than required by the Swedish building code. The Stockholm program covers apartment buildings constructed between 1997 and 2005, and requires certain limits for the final energy use as listed in Table 1

Table 1. Final energy requirements for the SFEU and final electricity use in kWh/m2,a.

Type of heating system	Total final energy use	Maximum final electricity use
District heating	140	50
District heating with ventilation heat recovery (VHR)	125	60
Electric resistance heaters	90	90

Since the lunch of the Stockholm program, new apartment buildings were built in 77 different locations within the Stockholm municipality. All of these buildings were built in accordance with the program's specifications, yet only 35% of the locations fulfil the final energy use requirements. In addition, the SFEU vary widely between different locations (Fig. 1). In this study, we analyzed the variations in SFEU due to the surface-area-to-volume ratio of apartment buildings (henceforth shape factor) and the relative size of the common area.

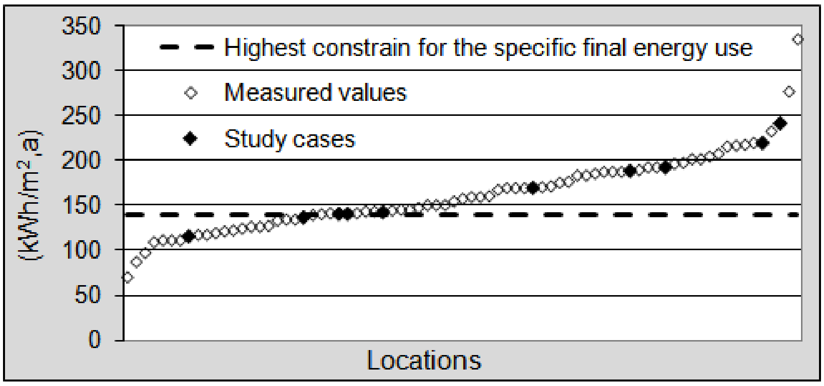

Fig. 1. The SFEU of new apartment buildings built in 77 locations that participated in the Stockholm program. The black points represent the study cases in this study.

1.1. The shape factor (SF)

The shape factor (SF) of a building is its surface-area-to-volume ratio and is a measure of a building's compactness. Buildings with a higher SF are less compact and therefore have a larger surface area for a given building's volume. The surface area of a building is the boundary between heated spaces and unheated spaces, and accounted for large percentage of the heat losses in buildings. Depecker et al. [2] showed that in colder climates the correlation between the final energy use and the SF is strong. Buildings with a higher value of SF have a higher final energy use. China has integrated the SF of buildings into its design standard for energy efficiency of public buildings, which applies stricter values for new buildings in colder climates [3]. Sweden is located in cold climate and the impact of the SF on the final energy use is expected to be significant.

1.2. The specific final energy use

The SFEU, i.e. the final energy use per unit of floor area, is used to compare final energy use in buildings with different sizes, and it is affected by how the floor area size is calculated. According to CEN [4], the floor area of a building can vary by 20% depending on t he measurement method. In Sweden, the area that is used for calculating the specific final energy use in buildings is defined by the National Board of Housing, Building and Planning [5] and is measured according to standard SS 021053 [6]. The area definition is equivalent to the European "overall internal dimension" [4] with a few differences: it excludes unheated areas and adjacent garages. An unheated area is defined as an area with temperature lower then 10°C during the heating season. This is due to the low energy contribution of unheated areas or adjacent garages relative to the relative increase in floor area. Including these areas will result in lower SFEU values [7] without increasing the building's energy efficiency.

The heated floor area in apartment buildings that agrees with the above Swedish definition is not homogeneous and includes different sub-areas including apartments, corridors and basements. The SFEU of apartment building is an average of the SFEU of its different sub areas. Each of these sub-areas has its own functionality and energy characteristics that determine its contribution to the average SFEU of the building. Designing new buildings with relative large sub-areas with low SFEU, for example due to lower temperatures, can reduce the value of the average SFEU of the building.

In this study, we distinguish between apartment areas and common areas. The common areas including: corridors, basements, attics and all other heated areas that are not part of the apartments. We do not consider buildings with integrated areas for commercial purposes, e.g. offices and small shops. Our hypothesis is that the SFEU in the common areas is lower than that in the apartment areas. Thus, the relative size of the common area (common-area-to-total-floor-area ratio) will affect the average SFEU of the building. The reasons for the low SFEU in the common areas are discussed below in the Swedish context.

In Sweden, the indoor temperature in the apartment areas should satisfy the minimum thermal comfort conditions. According to ASHRAE, the comfort zone for the operative temperature is between 20°C and 25°C [8]. In common areas 18°C, can be used to reduce heating costs [5]. Hence the temperature in common areas can be a few degrees lower than in apartment areas.

The energy used for domestic water heating is also higher in the apartment areas. Households in Sweden use 1200 kWh/person,a on average [9]. In common areas, the use of hot water and energy for water heating is negligible. Here we argue that the energy use by central laundry machine located in the common areas should be allocated to the apartment areas. The amount of energy used can be related to the number of residents and therefore to the total size of the apartments' area. Increasing the common area size will not increase the energy use for laundry. It does not matter if the laundry is made in each apartment or in a central laundry room. This argument can be apply to other apparatus that use energy in the common areas for example elevators.

Common areas have a lower windows-area-to-floor-area ratio than the apartment areas because of the natural light requirements in areas that residents visit often. Basements and attics may not have windows at all, whereas corridors that are surrounded by apartments have fewer windows per façade area in comparison with apartment's façade. Due to the higher U-values of windows in comparison with walls, the average U-value of the façade that is in contact with the common area is lower.

The minimum requirement for the ventilation flow-rate in apartment areas is 0.35 litter/sec,m^2 [5]. In common areas it is possible to reduce the ventilation flow-rate to 0.1 litter/sec,m^2 because of the low occupancy, which reduces ventilation heat losses.

2. Methodology

Twenty-two buildings built in 10 locations out of the 77 locations that participated in the Stockholm program were chosen for an in-depth analysis. These buildings have no commercial areas, i.e. offices and small shops, but large variations in SFEU (Fig. 1) despite similar constructions and energy supply systems. Each location consisted of one or several apartment buildings with at least three floors. All of the buildings have concrete foundations and use forced ventilation with fresh air entering through special openings in the façade, located under the windows and behind the radiators. In one location, ventilation heat recovery (VHR) using a heat pump was installed. All of the buildings were connected to the district heating network. The final energy use was measured during 2006 by Fortum-Värme, which is the energy supplier company in Stockholm. The areas in each building were measured manually using the architectural drawings of the buildings. For energy simulations we used the VIP Energy, which is a commercial dynamic energy balance simulation program that calculates the energy performance of buildings using real climate data. It was validated by IEA-BESTEST, ASHRAE-BESTEST and CEN-15265 [10].

2.1. The shape factor (SF)

The final energy use of the case-study buildings was compared to a final energy use of hypothetical reference buildings with similar sizes for volume, floor area sizes, ground floor, roof and windows-to-façade-area ratio but with SF of 1. To meet the lower SF the reference buildings need to be more compact with lower façade area size as illustrated in Fig. 2. The differences in final energy use assume to be related only to the smaller façade area of the reference buildings. Heat losses due to resident behaviour and ventilation heat losses assume to remain constant because of the similar volume and floor area size.

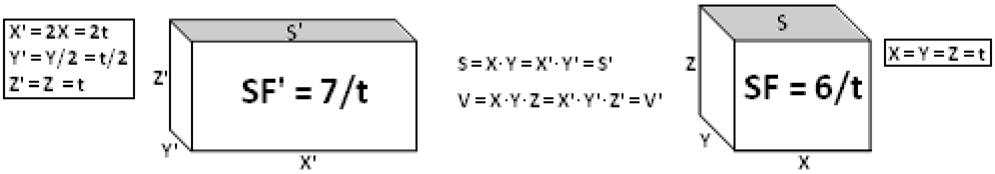

Fig. 2. Two buildings with similar volume, floor area, ground floor area, roof area and different SF.

The difference in final energy use between each case-study building and its reference buildings (ΔE) was calculated according to Eq. (1). Where ΔA_{Wall} and ΔA_{Win} are the area differences of wall and windows respectively between the case-study building and its reference buildings. E_{Wall} and E_{Win} are the difference in heat losses through 1 m^2 of walls and windows respectively between the case-study building and its reference buildings. ΔA_{Wall} and ΔA_{Win} were calculated from the difference in SF and assuming constant windows-to-façade-area ratio. E_{Wall} and E_{Win} were calculated by the VIP Energy simulation program [10] assuming similar values for all the buildings. The volume of the building is equivalent to the floor area multiplied with the floor height, which is 2.7 meters for all the case-study buildings. Therefore we defined the SF as the surface-area-to-floor-area ratio instead of volume.

$$\Delta E = \Delta A_{Wall} \times E_{Wall} + \Delta A_{Win} \times E_{Win} \quad (1)$$

2.2. The relative size of the common area

To determine how the relative size of the common area affects the SFEU of the buildings, five energy simulations were conducted. The following parameters were kept constant to reduce the influence of other factors: 1) the total floor area of the building; 2) the ratio of the glazed area to the floor area: 13% for the common areas and 22% for the apartment areas; and 3) the ratio of the apartment floor-area to the apartment façade-area. In each additional simulation, 75 m^2 of floor-area and 66.8 m^2 of façade area were allocated from the apartment area to the common area, which increased the relative size of the common area by 5% as listed in Table 2. The allocated areas were taken from the first floor in all simulations until the entire first floor was used as a common area. Parameters with values that differ between the apartment areas and common areas are listed in Table 3.

Table 2. Area sizes for each energy simulation. The first value relates to the apartment area and the second to the common area.

	Common area/ Total floor area	Floor area (m2)	Wall area (m2)	Glazed area (m2)	Roof (m2)	Ground floor area (m2)
1	0.1	1475 / 163	805 / 7	472 / 21	404 / 24	376 / 52
2	0.15	1392 / 246	771 / 57	450 / 28	404 / 24	266 / 162
3	0.2	1310 / 328	733 / 116	428 / 29	404 / 24	147 / 281
4	0.25	1229 / 409	710 / 153	405 / 38	404 / 24	73 / 355

Table 3. Parameters related to energy use used in all energy simulations.

Parameter		Apartment area	Common area
Indoor temperature	(°C)	22	18
Ventilation air flow	(litre/sec-m2)	0.35	0.1
Electricity use	(W/m2)	5.4	2
Energy use for domestic water heating	(W/m2)	5.8	0
Body heat from tenants	(W/m2)	1	0

The energy simulations were performed using the Stockholm's climate data and were done by the VIP Energy simulation program [10] for one of the study cases, with a total floor area of 1500 m^2. The roof consists of two layers of asphalt-impregnated felt, on 25 mm polywood board, 300 mm mineral wool between wooden roof trusses, and 150 mm concrete, giving an overall U-value of 0.129 W/m^2,K. The external walls have a U-value of 0.249 W/m^2,K and consist of 8 mm of plaster, 150 mm of mineral wool between wooden studs and 150 mm of bricks. 25% of the façade made up of triple glazed windows and doors and has overall U-value of 1.2 W/m^2,K. The ground floor consists of 20 mm oak boarding on 180 mm concrete slab laid on 150 mm expanded polystyrene and 100 mm macadam, resulting in a U-value of 0.236 W/m^2,K˚.

The final energy use from each simulation was normalized by two different area definitions: 1) the total heated floor area of the building (the current used method) and 2) the total apartments' area. The two area definitions provide two sets of calculated SFEU values for each energy simulation. The energy simulation results were compared to the SFEU of the reference buildings (SF=1).

3. Results

3.1. The shape factor (SF)

A high correlation was found between the SF and the SFEU as illustrated by the trend line in Fig. 3. Buildings with the VHR system were excluded but should follow the trend line as well because they have similar construction properties as the buildings without VHR system. The specific final energy use of buildings with VHR system is clearly noticeable in and is roughly the vertical distance to the trend-line (arrow in Fig. 3).

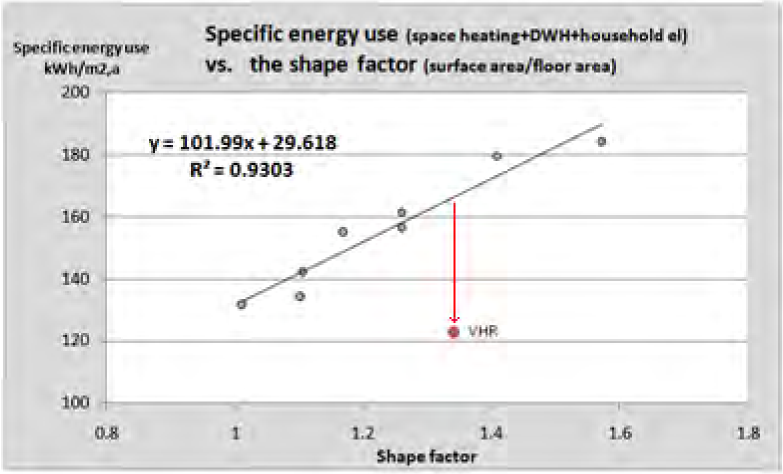

Fig. 3: A correlation between the SFEU and the shape factor of the building.

Fig.3 illustrates the difference in final energy use between each case-study building and its corresponding hypothetical case (SF=1). The SFEU is increasing by about ~5.3 kWh/m^2,a for each increase of 0.1 in the SF up to of 30 kWh/m^2,a.

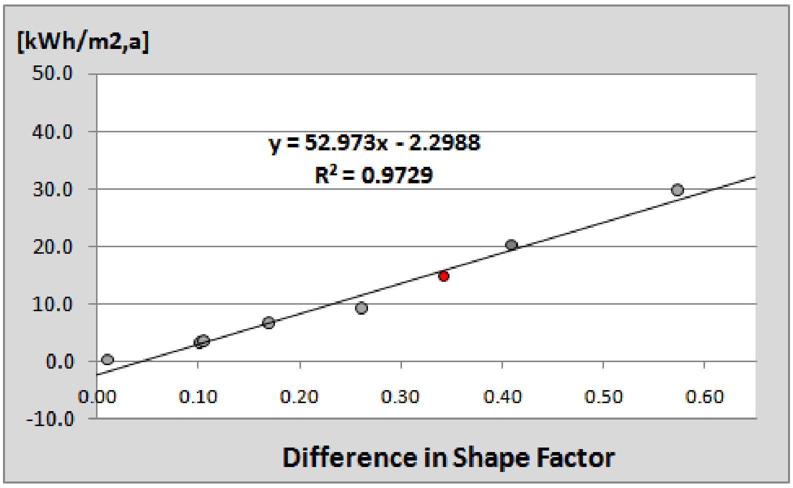

Fig. 4. SFEU losses (Y-Axis) in each study case due to difference in SF (X-axis).

3.2. The relative size of the common area

The SFEU of the buildings and the results from the energy simulations were calculated based on the total floor area (current used method) and the apartment area and plotted vs. the relative size of their common areas in Fig. 5. According to the energy simulation results, the SFEU in the common areas is about a quarter of the SFEU in the apartment areas. Increasing the relative size of the common area reduces the average SFEU of the building calculated by the current used method, although the SFEU in the apartment areas is nearly constant. When normalizing by the apartment area (new method) the average SFEU of the building slightly increases with increased common-area-to-floor-area ratio because the common area contributes more to the final energy (due to its increasing size), which is divided by smaller size of apartment area.

The trend of the specific final use of the study cases, calculated by the two methods, agrees with the simulation results (Fig. 5). Therefore, it is possible to conclude that the constant SFEU in the apartment areas calculated by the energy simulations valid for the study cases as well, and the variations in SFEU in Fig.4 (~30 kWh/m^2,a) are only due to the differences in the relative size of areas with low SFEU (i.e. common areas). The variations reduced by half if applying the new method.

The savings in *SFEU* associated with the VHR system are clear, and are the vertical distance to the trend of the *SFEU* (arrows in Fig. 5 in both methods). However, the savings are questionable if comparing by the current method because the value of the *SFEU* use of the location with the VHR system is only slightly lower than values of other study cases.

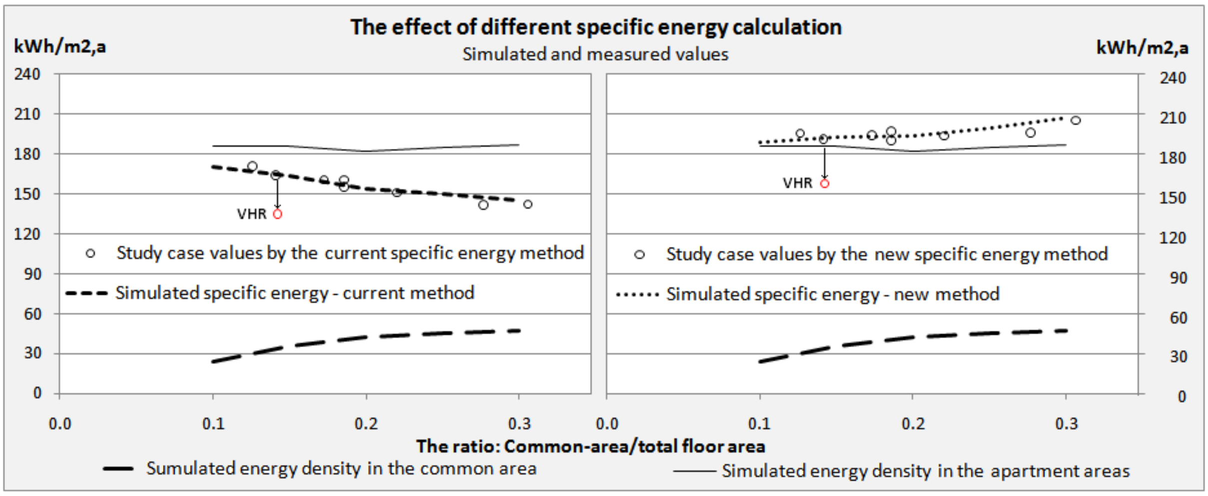

Fig. 5. The energy simulation results (lines) compared to the SFEU (circles) of the different study cases based on the total floor area (left diagram) and on the apartment area (right diagram).

4. Discussion

In this study we analysed the influence the shape factor (SF) of the building and the relative size of the common area, i.e. common-area-to-total-floor-area ratio, on the SFEU. Both parameters are together responsible for a variation in calculated SFEU of more than 50 kWh/m^2,a for the different case-study buildings. As a result reduction in SFEU use due to efficiency measures, as ventilation heat recovery, were not noticeable.

The SF has large effect on the building's final energy use. Buildings designed with large value of SF have larger surface area per floor and larger heat losses. As a result, larger heat losses exists and larger amount of energy is needed during the construction period. Therefore it is recommended that the shape factor is considered in building codes for new buildings especially in cold climates.

When calculating the SFEU based on the total floor area of the building (current used method) the SFEU of the building decrease as the relative size of the common area increases (i.e. corridors, basement, attics etc.) because the SFEU in the common areas is significantly lower than the SFEU in the apartment areas. In addition increasing the relative size of the common areas for a given total apartment's area will increase the final energy of the building because more common area needs to be heated. The final energy used in the common areas is used by the building's residents and the number of residence does not increase with increasing size of the common areas therefore the final energy use per residence will increase. Furthermore, increasing the relative size of the common area increases the building size per apartment area. Consequently, the energy use required to construct the building will increase per apartment area or alternatively per resident. As a result, designing buildings with larger relative size of common areas will reduce the average SFEU of the building, and stricter energy requirements could be achieved without implementing energy efficiency measures. However the final energy use per residence will increase. This needs to be considered in energy requirements of buildings. Normalizing the final energy use by the apartment area should be considered as alternative method because it reduces variations in SFEU due to the relative size of common areas and increases the quality of using the SFEU for energy requirements.

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Energy Consumption In Non-Domestic Buildings: A Review of Schools

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Abstract: The energy consumption associated with non-domestic buildings represents 11% of the UK's total energy consumption, 11% of Europe and 18% of the USA's. A nnual non-domestic building energy consumption is often presented in the form of average benchmarks, such as 450kWh/m²/year for a large air-conditioned building and 200kWh/m²/year for a small naturally ventilated office. Benchmark values give very little insight into how and where a building consumes energy. While some benchmarks provide a breakdown of energy use by energy category (lights, IT, cooling, heating), these data still fails to demonstrate how the energy associated with each category varies throughout the year. To further understand building energy use, a more detailed data breakdown and analysis is required. The electricity demand data for a variety of school buildings (secondary, primary, specialised) in Scotland has been made available for analysis. This consists of half hourly resolution data spanning several years for 50 s chools, allowing key trends and patterns in energy use to be identified. T hese trends can include differences between annual profiles, differences between winter and summer months, and differences in weekday and weekend energy use. Additionally, the effect of other variables such as climate, user behaviour and general building data on the buildings energy consumption can be investigated. A database of half-hourly school energy demand data, with corresponding building details has been set up and a preliminary analysis preformed. Alternative method of pattern recognition in non-domestic energy usage are discussed, and the variables necessary to calibrate this information. This demonstrates the possibility of creating generic energy profiles and hence new benchmarks.

Keywords: *Non-Domestic Energy, Electricity Demand, School Energy*

1. Introduction

Energy consumption is continually increasing throughout the world and a large proportion of this can be associated with non-domestic buildings. In 2007 the UK consumed 157.8 million tons of oil equivalent (Mtoe) or alternatively 1,835TWh of energy [1]. To better understand how energy is used in the UK, it is necessary to breakdown the energy consumption into the different sectors. The total energy distribution of the UK is as follows; domestic consumption: 29.4%, transport consumption: 37.1%, industry consumption: 20.8% and "other" consumptions: 12.7% of total UK energy consumption [2]. The percentage of energy consumption associated with buildings in relation to total energy consumption was 42.3% [2]. The assumption is that the "buildings" mentioned in, [2], consists of both domestic and non-domestic properties.

Non-domestic buildings in 2003 w ere reported to account for 11% of total energy consumption in the UK, 11% in the EU and 18% in the USA [3]. The similarity between UK and EU consumption is probably due to their similar work habits, daylight hours and climate, while the USA's higher proportion may be due to the higher presence of air conditioning, or due to a different proportion of offices to other types of buildings.

Only by collecting and analysing building energy consumption data can an idea into how and when a building uses energy be gained. Introducing other factors such as seasonal demand profiles, both for weekdays and weekends, average daily consumption for each month, and determining any trends in standby/peak power over one year for each school, can ideally identify trends in energy use. With the help of this information, 'generic' profiles can be constructed allowing quick power reference and the creation of newer benchmarks for non-domestic energy use in this particular environment.

2. Current Benchmarks

A key area in the non-domestic sector is education. There have been numerous studies ([1], [4 -11]) into the energy consumption of schools and school energy performance benchmarks, and benchmark data us readily available for schools in the UK (as well as other counties) for the last few decades. Primary schools in the UK typically consume 119kWh/m²/year of energy [4], with the UK one of the few countries that have set energy benchmarks for schools. A target of 110kWh/m²/year is considered as an ideal or "good practice" target [5]. Other school benchmarks are detailed in the "Good Practice Guide 343, or more commonly known as GPG343 [6]. For a primary school, the 'typical' annual consumption target is 191kWh/m²/year where as the 'good practice' value is 135kWh/m²/year. For a secondary school without a pool, the 'typical' benchmark is 196kWh/m²/year and for a secondary school with a swimming pool, the benchmark is 223kWh/m²/year. This guide also divides the benchmarks into either electricity or fossil fuels, and provides a generalised breakdown of energy use in schools represented in a pie-chart.

In comparison French primary schools average 197kWh/m²/year, Greek schools consume 57kWh/m² and Irish primary schools consume 119kWh/m²/year [5]. Hermandez, [5], used 'GPG343' to establish that the typical value for UK primary schools is 157kWh/m²/year whereas the best practice value is 110kWh/m²/year. They used EnergyPlus software for the energy consumption calculations and a grading system based on a methodology outlined in "Energy Performance of Buildings"[12]. This method involved using the schools energy consumption (kWh/m²), a stock regulation value, and a stock reference value (based on either a sample mean or the building stock mean). A table of different conditions involving the three values determined the energy rating and benchmark.

A problem with previous studies and results is that they do not provide sufficient information to give a full understanding of how energy is used in a building. Energy performance benchmarks only provide the total annual energy consumption of a generalised school per floor area. Details such as weekly, monthly and seasonal trends are omitted. However, benchmarks can be used as a quick indication of energy efficiency or a simple tool for quick school comparison but are limited due to this additional detail. This paper discusses the analysis of a sample of schools and the key outputs of the analysis, aimed at providing more detail of school energy consumption than the standard benchmarks. In addition, average electricity demand profiles are analysed and their potential use in explaining energy usage are discussed.

3. Methodology

The interpretation of energy usage in schools is completely dependent on the availability of accurate energy data from a wide range of schools. The first stage therefore is identifying a reliable source or organisation that is willing to provide the data. Several local authorities in Scotland were contacted to allow monitoring of schools in their area to take place. Initially it was decided to select various school buildings and install several non-intrusive load monitoring (NILM) equipment in the schools. There are several advantages of using NILM systems, opposed to introducing equipment into the electricity network. A key advantage is that the buildings electricity supply is not interrupted, minimising disruption to the building. Another advantage is that the equipment can be set up without the need of an electrician or power engineer.

There are several disadvantages to using NILM electricity equipment. The first is that NILM equipment (for a 3-phase electricity monitor) is expensive, (about £4000 per unit). The second problem is the equipment is limited in monitoring the meter side of the buildings electricity supply. Further equipment is needed to monitor each distribution board, to fully understand how the building uses energy. To create a large database of different types of schools, several sets of equipment would be needed, increasing the project costs. Lastly, the data collection phase of the project was relatively short. Ideally several years of data would be needed to ensure it is representative.

An economical alternative was available because several of the authorities, who agreed to participate in the energy data collection, had access to electricity consumption data from their power suppliers. This was in half hourly time resolution that represents the meter side of the building. Having access to this data overcame the possible limitations of using expensive NILM equipment and the short assessment/data gathering period.

Table 1 highlights the studied schools and the associated details, such as year of construction, number of pupils, school type, total energy consumption and whether the school has a swimming pool. This table is used as a reference in determining any trends in energy use. The data presented in table 1 was collected by contacting the schools directly and by referencing the school's website.

4. Normalisation of Data

An important part of analysing the data is comparing the schools energy consumption against other schools. A basic idea of energy consumption can be gained by just comparing kW in terms of load profiles, or kWh in terms of total energy consumption. One hypothesis is that a large school will consume more energy than a small school. By normalising by floor area, this size factor is removed. By introducing pupil numbers, further normalisation can occur. Normalising by pupil number, however, is not as straightforward as normalising by floor area as it is influenced by how the building is used. Floor area and number of occupants are not entirely independent from each other. A school is built to accommodate a maximum number of students. Even with varying number of students, the assumption is that the same number of classrooms, sports halls and even IT facilities will be continually used. This results in similar total energy consumption for the school, regardless of pupil numbers. In contrast, normalising energy consumption of office buildings by occupant numbers appears to be more appropriate, due to the differences in how both schools and offices are used. Office workers generally use their own PC, or their own IT equipment, hence the energy usage associated with IT will vary with the number of occupants. This an important factor to consider when normalising by pupil number. For this reason, the presented results and charts are given in kW/m^2 or W/m^2

5. Categorisation

Table 1- Key School details

School	Year	Floor Area (m^2)	Total Energy use(kWh)	School	Year	Floor Area (m^2)	Total Energy (kWh)
A	1983	8042	667,233	**L**	1960	9561	888,443
B	1960	2535	195,221	**M**	1930*	14909	687,511
C	1980	9835	342,507	**N**	1940*	13559	607,708
D	1989	11430	512,819	**O**	1940*	11052	730,518
E	1991	12349	863,421	**P**	1950	14265	602,720
F	1954	13145	441,056	**Q**	1960	11852	605,890
G	1960	15368	695,154	**R**	1979	10156	492,587
H	1970	11535	643,994	**S**	1975	11927	945,627
I	1893*	11742	565,302	**T**	1960	1225	235,543
J	1978	11436	1,433,075	**U**	1980	7871	354,727
K	1965	11918	584,281	-	-	-	-

*School built at this date, but renovated post 2000

The complete database consists of 48 schools, including 32 Secondary schools, 11 primary schools and 5 specialised schools. Within the secondary school category, 21 schools were built before 2000, and 11 were built after 2000.

To analyse energy usage in schools, it is important to compare schools with similar properties. A large modern secondary school and a old small primary school will have different building characteristics, and differing electricity demands. In order to determine key trends in energy usage, the schools were initially categorised into two key groups: Primary and Secondary schools.

Secondary schools, or High schools, can be defined as premises that educate children from the ages of 11 to 17. High schools have a total floor area from 1,225m² to 15,368m² and total electricity usage between 1,433,075kWh to 195,221 (Table 1). It should be noted that the smallest school (by floor area), school 'T', does not have the smallest energy use (instead school 'B' has) emphasises the importance in normalising the data if comparisons are to be made. This result highlights the need for normalisation of energy use. Within the High/Secondary school category, two additional sub categories can be defined. The new categories are based on age of construction of the school; pre-2000 and post-2000.

The primary schools are defined as the first stages of education, catering for children aged from 5-11. Primary schools tend to be considerably smaller than secondary schools, as well as having smaller pupil numbers and represents 23% of the schools within the database.

Specialised schools are smaller, more focused schools, aimed at helping students with learning difficulties. These schools represent 10% of the studied secondary schools, but because of their small floor area and small pupil number, it is necessary to analyse these buildings separately from the other secondary schools.

6. Results

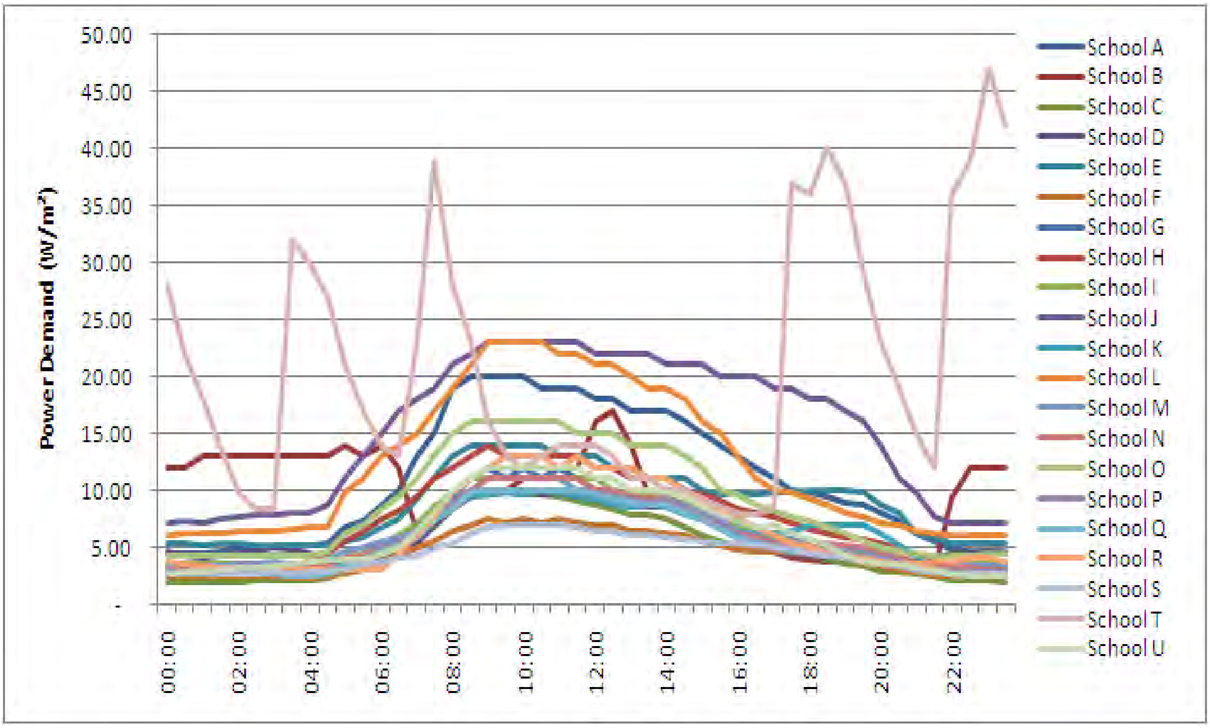

Figure 1- Average Power Demand Profiles

The collected school data was processed automatically by a FORTRAN based analysis program and several output files and profiles were produced. The designed analysis program outputs both a yearly average profile and four seasonal average profiles for each of the studied schools. For this paper, only Secondary schools built before 2000 will be discussed. Figure 1 demonstrates the average daily demand profiles for 21 secondary schools in Scotland, built before 2000. The daily power demand profiles represent the average working day power requirement over the entire year. This eliminates any possible seasonal variation.

School L's power demand profile can be used as an example to describe how a school consumes energy. School 'L' has a standby demand of 6.1W/m² and remains at baseload until 05:00 where it begins to rise. The rise continues until 0600, where the gradient reduces, then increases again. This step in energy use is most likely the result of heating systems (though heating pumps) being turned on. From 06:00 onwards the power demand increases until 09:00 where it reaches a plateau of 23W/m². This second rise is the lighting and IT equipment being switched on, as students and staff start interacting with the school. After 12:00 the power demand starts descending gradually, and at 14:00, the power demand falls from 19W/m² to 10W/m² by 17:00. From 17:00, the power demand steadily falls back to the baseload value by 22:00.

Figure 1 also demonstrates several profiles that have very atypical shapes. Schools 'B','J' and 'T' have power demand profiles that do not appear to resemble other schools. School 'J' has a fixed baseload of 12W/m², and rises slightly to 13W/m² until 07:00. At this point, it then reduces to 6W/m² and proceeds to rise and peak at 12:30 with a peak value of 17W/m². The power demand then falls to 3.1W/m² and sharply rises back to the original value of 12W/m². Although during the time period of 09:00 to 17:30 this profile demonstrates similar characteristics to the other schools in this study (excluding schools 'B','J' and 'T'), the large and constant power demand in the morning and in the evening are atypical. Further investigation has not yet determined why this school has such a profile. Establishing if the demand profile varied from season to season could indicate if the morning/evening demand is heating or lighting related.

The second atypical profile belonged to School ‘B’. The profile initially follows the other schools, in that it rises to a plateau at 08:30. The main difference in profile shape occurs after this plateau. While other schools tend to drop in demand, and return close to the standby value between 1600 and 1800. The profile for school ‘B’ slowly dropped from 22W/m² to 16W/m² from 12:00 to 19:30. After 19:30, the profile returned to the base load value of 7.7W/m² at 21:30hrs. The initial assumption was that this extended power demand outside the normal school hours is due to the school being used for evening classes or for sports activities. However when the profile was compared to other schools that are opened in the evening, School ‘B’ appeared to have a very high power demand that fell only slowly, and did not present the same ‘hill’ of power demand seen between 17:00 and 21:00 (as shown in school ‘L’ for example). On further investigation it was found that the school is part of a larger complex, which includes a large public pool, library and gym. These additional components of the school are open until 22:00 and are used by the local community.

Lastly the atypical profile of School ‘T’ consists of five peaks occurring at 00:00, 03:30, 07:30, 18:30 and 23:30, with peak power demands of 28, 32, 39, 40 and 47W/m² respectively. An interesting observation was that between 12:00 and 15:00hrs, the profile matches the same shape as the other schools. Upon further investigation, it was discovered that school ‘T’ has electric space heating, and not gas heating. The large peaks that occur are the result of the heating being switched on during the morning and evening. The spikes occurring early in the morning and late in the night could be a poorly set-up energy management system or the result of a heating system with a basic thermostat. The full explanation of this profile remains to be established.

7. Discussion and Conclusion

The research discussed in this paper aimed at determining if analysing an energy database can provide information on how buildings use energy, and in turn overcome the current limitations with existing benchmarks. The analysis of the school data to produce average power demand profiles, as shown in Figure 1, helped determine when power is used in a wide range of schools and how much power is required (peaks, and standby loads). The results demonstrate that there is a common shape within the profiles especially within the time period between 07:00 to 16:00. The results also demonstrated that it is possible to group the schools into ‘good’, ‘average’ and ‘poor’ energy/power rating, similar to the system used in the Good Practice Guides [6,13].

Several profiles were identified that did not share a similar shape to schools in the data base. Schools ‘B’, ‘J’ and ‘T’ had atypical profiles that could not be grouped with the other schools. This is an important finding as it highlighted one problem with using ‘generic; profiles and the ‘reliability’ of their widespread application.

This preliminary report of continuing work suggests that it is possible to analyse the different seasonal demand profiles, both for weekdays and weekends, average daily consumption for each month, and determine any trends in standby/peak power over one year for each school. Future analysis will help determine: a) if there are any seasonal trends between the schools, b) how energy consumption varies between each month, c) how the peak values vary throughout the year (highlighting school holidays) and lastly d) if the schools are used during the weekends, and if energy is being wasted. In addition, analysis will be extended on the different categories of schools (primary/secondary). As well as normalising by total floor area and by pupil number (although as already discussed, there may be no additional benefit normalising by pupil number), the data will need to be corrected for local climate. The schools analysed in this study were spread throughout Scotland and variations in local temperature is likely. Analysing local temperature as an independent variable will allow its impact on energy usage profiles to be established. Lastly, user behaviour or interaction will be introduced into the analysis, to help determine when and where energy is being used in the schools. Currently only basic information on pupil numbers for each schools is available. It is unknown how this study will measure, record and normalise pupil behaviour for each studied school.

Generic profiles are of use provided their limitations are recognised. Key information such as peak demands, school type, opening hours, after school use, standby load and construction date can be used to generate generic profiles. A possible approach is to average the school profile data for each school category and produce one profile. A difficulty with this is that atypical profiles, such as for schools B', 'J' and 'T', would be averaged as well, resulting in averaging problems. Additionally, one approach would be taking an average of an average (due to the analysed profiles being constructed using average values). This could lead to errors forming, or incorrect profile shapes. Another possible approach could be creating probability distribution, using every data value in each of the schools. This results in 17,250 data points being analysed, hence 840,960 data points in total for the entire database. The original data analysis program could be altered to include this possible approach. Generic profiles do have several beneficial uses. Energy managers could use a data input screen and enter key building details such as opening times, total area, etc and output a profile that could match their building. Additionally a level of good, average and poor profiles could be outputted as well as new benchmarks. The profiles could be used for determining the impact of renewable energy generation on a buildings daily demand, and could be used by power companies to guide on investment decisions or determining if power upgrades are needed.

The work discussed in this paper is continuing and key outputs, trends and conclusions are being established as the data analysis stage nears completion. This paper has discussed key stages of the methodology, data collection and normalisation. It has also discussed the results of initial analysis of one category of school and one average profile output from a designed analysis program. Lastly this paper introduced the concept of 'generic' profiles, and a possible methodology to gain these profiles. With further research and analysis of the data base, a better understanding of non-domestic energy use can be gained, and new benchmarks created.

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Modeling Building Semantics: Providing Feedback and Sustainability

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Abstract: Even minor changes in user activity can bring about significant energy savings within built space. Many building performance assessment methods have been developed, however these often disregard the impact of user behavior (i.e. the social, cultural and organizational aspects of the building). Building users currently have limited means of determining how sustainable they are, in context of the specific building structure and/or when compared to other users performing similar activities, it is therefore easy for users to dismiss their energy use. To support sustainability, buildings must be able to monitor energy use, identify areas of potential change in the context of user activity and provide contextually relevant information to facilitate persuasion management. If the building is able to provide users with detailed information about how specific user activity that is wasteful, this should provide considerable motivation to implement positive change. This paper proposes using a dynamic and temporal semantic model, to populate information within a model of persuasion, to manage user change. By semantically mapping a building, and linking this to persuasion management we suggest that: i) building energy use can be monitored and analyzed over time; ii) persuasive management can be facilitated to move user activity towards sustainability.

Keywords: *Semantic Modeling, Energy Use, User Behavior, Building Performance, Persuasive modeling*

1. Introduction

The cost and environmental impact of inefficient energy use in buildings, in combination with increased focus on legislation, has increased pressure on users to assess and adjust their behavior in order to lower energy consumption. Whilst users are aware of these issues, and often have a positive attitude towards a change in behavior, they are not provided with sufficient information to manage change towards sustainability. Whilst several standards exist for analyzing building energy efficiency (i.e. BREEAM, LEED, HK-BEAM and GB Tool), they largely focus on building structure and components without taking into account contextual information dynamic building usage, i.e. occupant behavior, organizational culture, etc.

To facilitate positive change, information concerning the building, user energy use and attitude, has to be monitored in order to provide contextually relevant feedback to persuade the user to change behavior towards target behavior (i.e. sustainable energy use). Since existing standards provide insufficient information structures to inform users of their energy usage, in context of building and environmental variation, we must find and use alternative means of informing persuasion techniques. In this paper we propose the use of a semantically rich building model. By storing information relating to building usage (occupant numbers, activities, organizational culture, location etc.) we are able to group and compare energy consumption and energy efficiency of building with similar factors, and/or as a result of user activity. This information can be used to facilitate and inform persuasion management techniques, and therefore supports change in activity toward target behavior.

2. Problems with Building Performance Assessment

Building performance assessment methods and tools have been developed worldwide, to assess the energy efficiency of physical building structures. Current building performance assessment methods can be crudely split into two categories: i) those based on criteria and weighting systems - e.g. BREEAM (UK); or ii) those that use a checklist of building performance aspects - e.g. LEED (US). If such assessment performance is properly applied, they can provide a useful set of tools to identify Key Performance Indicators (KPI) and monitor improvements in the environmental performance of the building structure [1], however such performance assessment often fail to consider energy sustainability in context of building type, location and/or use.

Current building assessment techniques are applied on a voluntary basis, fail to support the full life-cycle of the building, and make it hard to understand the impact of user behavior (i.e. the social, cultural and organizational aspects of the building). Research conducted by Foresight [2] shows that building usage is significant to an individuals overall energy usage. Mackay [3] also argues that minor changes in the way we live and work within buildings, such as personalized heating / lighting settings, can bring variation in energy savings. Users currently have limited means of determining how sustainable they are, especially when energy capture via meter feedback ignores contextual information relating to building type and/or business activity. To facilitate long-term sustainability, buildings assessment must be able to monitor energy use over time in order to determine areas of potential change in context of building type, building structure and user activity. Only by providing feedback in light of live semantic context can appropriate persuasion be provided to users to encourage manageable change.

3. Semantic Building Information Modeling

In order to place building energy assessment in context of building use and user activity, we need to be able to create associations between the data and the specific characteristics (intrinsic) and context (extrinsic) properties of the building. This is important since it allows us to more precisely define acceptable and unacceptable energy usage for buildings based on numerous contextual factors. Buildings in colder climates, for instance, are likely to spend more resources on heating, which will in turn affect their energy efficiency. Publically comparing otherwise identical buildings in different climates will result in a range of energy usage levels.

The more specific we can be regarding the characteristics and use of buildings, the more detailed we can be when considering energy analytics, the better we can support a move towards sustainability that considers both building fabric and building use. By applying MEASUR methods, as proposed in [4], we suggest that the following factors should be considered as KPI when adding contextual information to building space:

- Physical building structure: including building size, floor space, number of floors and size of rooms.
- Building material: old/new building, presence of double glazed windows, energy efficient technologies etc.
- Building Occupants: number, average time spent in the building, average start/end times, occupancy variance.
- Building Usage: common occupant activities, presence and usage of building systems and electrical appliances.
- Social/Organisational: Building occupant usage policies, organisational culture.
- Geographical Context: location, climate, weather, temperature sun-light level variance, seasonal changes.

Assessment of buildings, in relation to their intrinsic and extrinsic properties, allows us to compare and identify buildings with similar properties. This enables us to quantifiably determine energy waste and therefore key areas of change that could improve sustainability. In contrast simple monitoring of energy usage readings, which provide only basic information with no reference to context, we can separate energy consumption and efficiency as being a result of either building structure and/or building use. Energy readings alone are unable to define whether a building is being used in an efficient or inefficient manner, yet the comparison between buildings with similar key properties allows direct comparison of energy performance, indicating whether a particular building is being used well or not. Such information can only be determined by semantically populating a live model of the building with temporal information about energy use.

Semantic building models can be developed through the specification of building property types and activity use definitions. When activity information is linked to as-built CAD drawings, existing building assessment methods, BMS (Building Management System) data streams, energy usage policies etc., a considerably flexible and semantically rich energy model can be developed.

4. Model Data Storage and Temporal Issues

We advocate that semantic building data models, using records to represent buildings along with their properties, should be represented using a historical relational database. The relational functionality supports arbitrary data structures, powerful data manipulation and querying capabilities. Use of a historical database supports temporal analysis of building use.

Most database systems are referred to as ‘snapshot’ databases, since they record the state of their domain at a single point in time. This means that any updates made to a record, results in the previous value being permanently lost. Likewise, any entities that are deleted imply that those entities never existed. In contrast, historical databases never delete records and only update and insert new records in order to maintain an object‘s historical audit trail. This supports data mining and the recognition of trends as a result of object states. Moreover analytics can effectively consider changes to building use over time. Such temporal databases manage time values in one of two ways: i) valid time and ii) transaction time. Valid time denotes the time period during which a fact is true with respect to the real world. Transaction time is the time period during which a fact is stored in the database [5].

The application of a temporal database to the problem of recording semantic building models is appropriate since user attitude and occupant behavior patterns (and therefore energy usage) are likely to change over time; and we need to be able to represent the impact of change or behavior in context of the specific time scale and/or season during which it was deemed accurate.

Whilst the use of a temporal database adds significant complexity to the semantic model, such systems allow increasingly powerful queries of stored information, which supports the provision of contextually persuasive feedback and management of user change towards sustainable energy use. In order to manage positive user change, towards target behavior, we must first understand how persuasion management is facilitated via information provision.

5. Persuasive Management

The issue of user persuasion is becoming increasingly incorporated into systems design, and is used in areas including social networking, online videos, and mobile devices, etc. [6].

Research in this area shows that there are multiple means of changing user behavior and this has a strong relationship with user current activity and attitudes. Fogg [6] stipulates that a change in behavior occurs at the moment at which the user has sufficient motivation, i.e. feels able to make the change; which often occurs as a result of external triggers acting on the individual. By understanding the user's current behavior towards energy use, and by managing triggers by providing relevant stakeholders with appropriate feedback / information, persuasive management can be used to enthuse users towards target behavior. In this work we used the 3D-RAB persuasive model [7] to support persuasive feedback management. To understand this model, and how it relates to energy sustainability and persuasion management, the following sections introduce information concerning: assessment of current behavior, attitude toward target behavior, attitude towards change, and behavior state change.

5.1. Assessment of Current Behavior (CB)

Current behavior is defined as the existing actions of a person in relation to the environment. Such actions may be conscious or subconscious, overt or covert, voluntary or involuntary. In order to measure behavior, and support a positive movement towards target behavior, current behavior must be assessed. This is to say that appropriate user behavioral change, and therefore information feedback, must be personalized. For simplicity, behavior is measured as being either positive or negative, when considered in context of energy sustainability. A user, either a person or organization, is considered to have a positive behavior if current behavior is the same as the target behavior, i.e. actions that make efficient use of energy. CB can be defined as being positive or negative by analyzing BMS energy streams in the semantic model. By looking at specific energy use, i.e. that identified as being related to a specific activity, over the defined time scale of the activity, and by placing this information in context of the building type and fabric we are able to assess energy use against personalized targets.

5.2. Attitude towards Target Behavior (ATTB)

User attitude towards target behavior is defined as the like or dislike of target behavior; and is, for the purpose of simplicity, defined as being either positive or negative in this research. If someone's attitude supports energy sustainability then they are deemed as having a positive attitude towards the target behavior. Interestingly, user's attitude towards behavior is not always consistent with current behavior. ATTB is captured via experimentation, normally involving decision making results and / or questionnaire feedback.

5.3. Attitude towards Changing/Maintaining Current Behavior (ATCMB)

Attitude towards change is a measure of whether, in a particular case, a person is positive, negative or neutral towards change. This measure is considered to be positive when a user agrees to change to the target behavior, or when they are willing to maintain positive current behavior. Aronson [8] argues that changing a user's behaviour can result in attitude change, since new attitudes are formed to justify behavior. He explained that people adjust their attitudes to fit new behaviours in order to reduce or eliminate the "tension of dissonance". The theory of cognitive dissonance proposes that two cognitions are considered to be in dissonance if one opposes the other creating an unpleasant psychological tension [9]. The foundation of this theory is based on the fact that in order to eliminate dissonance, a user changes their belief, action, or perception of the action. ATCMB is captured via experimentation, normally involving decision making results and / or questionnaire feedback.

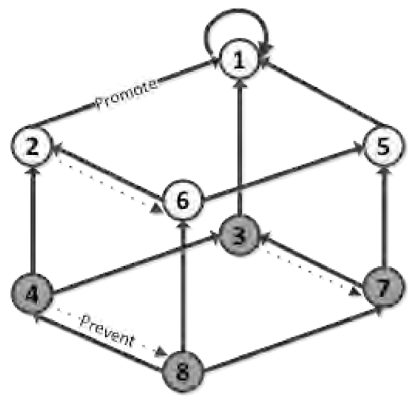

Fig. 1: Transitions in 3D – RAB

5.4. 3D- RAB Model

The 3D-RAB model [7] enables the persuader (i.e. the stakeholder interested in obtaining sustainability) to categorize users into groups depending on CB, ATTB and ATCMB being positive or negative. In total, eight categories of user were identified (see figure 1). The various states are analyzed, in context of energy use, in order to ascertain possible transitions for persuasion. Combining Figure 1 and Table 1, we can see how states are either stable or unstable, and explains how users in unstable states can transfer states as a result of persuasive feedback. The relationship of, and transition route of users, is based on the theory of cognitive dissonance, which is defined as being: i) strong, ii) moderate, iii) weak or iv) absent.

Table 1: Definition of current behavior, attitude and its impact of dissonance

State	Current Behavior	Attitude towards target behavior	Attitude towards changing/ maintaining current behavior	Cognitive Dissonance	Stability of state	Natural State tendency	Targeted state for Persuasion
1	+	+	+	No	Stable (+)	1	1
2	+	+	-	weak	Unstable (+)	1	1
3	+	-	+	moderate	Unstable (-)	7	1
4	+	-	-	Strong	Unstable (-)	8	2 or 3
5	-	+	+	Strong	Unstable (+)	1	1
6	-	+	-	moderate	Unstable (-)	8	2 or 5
7	-	-	+	weak	Unstable (-)	8	3 or 5
8	-	-	-	No	Stable (-)	8	4 or 6 or 7

Strong cognitive dissonance is formed when there is a very strong disagreement between one's attitude and current energy use and it results in a strong unpleasant psychological tension and produces a greater probability that one may change his/her attitude or behavior in order to eliminate the dissonance. At such a state the user experiences a very uncomfortable cognition state that he/she recognizes the need for a change in attitude or behavior. For example, if a user wishes to save energy and/or cost, providing his/her with information about energy waste of equipment being left on overnight, may result in the user turning off the devices at the end of the day. When there is a weak or moderate dissonance the disagreement between one's attitude and behavior is not enough to motivate change. In the case of no cognitive dissonance, user attitude agrees with his/her energy use and there is no psychological tension. Variation in dissonance therefore creates stable and unstable states that can be positive or negatively towards the target behavior.

In states 1-4 (see Figure 1) the user is already performing the target behaviour (i.e. positive and/or sustainable use of energy). Accordingly feedback information should be given to move the user towards, or keep in the state 1 (positive action and attitude, low dissonance). If current behaviour is in states 5-8, then a change is required toward positive activity. This change can be facilitated by providing energy feedback information, either directly to users or, depending on the user state and level of dissonance, to related stakeholders (i.e. user / activity / building managers). Such feedback is likely to increase stakeholder level of dissonance, due to financial and/or energy targets. To remove this dissonance, alternative external triggers can be placed on the user (e.g. loss of bonus, or enforced process change). By changing user incentive (e.g. bonus), which ideally leads to a change in user or user attitude, or by enforcing change in current behavior, a transition in user state occurs towards a more positive stable state. Information provision and regular use assessment, supported by analysis of the semantic temporal model, can be used over time to facilitate positive change, whilst identifying and highlighting existence of negative state transitions.

6. Conclusions

Currently building assessment methods largely ignore building context and / or activity. We are therefore unable to define whether a building is being truly used in an efficient or inefficient manner. In this paper we have discussed how using a dynamic and temporal semantic model, to populate information within a model of persuasion, can be used to manage users towards lasting behavioral change.

If Building Management System, building structure, and activity information can be captured and integrated within a temporal semantic building model, then personalized feedback concerning user energy usage can be used to prompt positive change in either, occupant and / or related stakeholder attitudes or current behavior to minimize cognitive dissonance. By combing physiological principles with information from live semantic temporal building models, we can identify energy waste in context of building, context and activity type. Such modeling approaches, although still largely unsupported by mainstream building modeling and database technologies, would provide huge potential when integrating energy information about building structure, systems, context, and users.

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Energy Cultures - a framework for interdisciplinary research

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Abstract: The Energy Cultures framework aims to assist in understanding the factors that influence energy consumption behaviour, and to help identify opportunities for behaviour change. Building on a history of attempts to offer multi-disciplinary integrating models of energy behaviour, we take a culture-based approach to behaviour, while drawing also from cultural theories, actor-network theory, socio-technical systems, and lifestyles literature. The framework provides a structure for addressing the problem of multiple interpretations of 'behaviour' by suggesting that it is influenced by the interactions between cognitive norms, energy practices and material culture. By conceptualising the research arena, the framework creates a common point of reference for the multi-disciplinary research team. The Energy Cultures framework has proven to be unexpectedly fruitful. It has assisted in the design of the 3-year research programme, which includes a number of different qualitative and quantitative methodologies. In application to a given example, it helps to position the complex drivers of behaviour change. Although the framework has not yet been fully tested as to its ability to help integrate findings from our various research methods, we believe the Energy Cultures framework has promise in furthering interdisciplinary studies of energy behaviours in a wide variety of situations, being relevant to different contexts and different scales.

Keywords: *Household energy behaviour, Theoretical framework, Multi-disciplinary, Research design*

1. Introduction

There is huge potential for greater efficiencies in consumer energy behaviour, but achieving the necessary behaviour changes is proving exceedingly difficult. The International Energy Agency (IEA) advises that energy efficiency improvements across the end-use sector have the potential to achieve 52% of the CO_2 emissions reduction required by 2030 to contain atmospheric CO_2 concentrations at 450 ppm. This is more than the combined contributions of renewable energy systems, biofuels and carbon-capture-and-sequestration. The IEA calls this transition the 'energy environmental revolution', and notes that many nations face challenges in achieving behavior change in the demand-side area [1]. It is well accepted that interdisciplinary studies are likely to offer enhanced insights into the vexed question of energy behaviours [2], but interdisciplinary research itself can be highly challenging especially in the absence of common conceptual agreements.

Our 3-year research programme, 'Energy Cultures' [3], is attempting to achieve an integrated understanding of household energy behaviours, and to identify promising opportunities for behavior-change interventions, by bringing together an interdisciplinary team. The core members are five university-based researchers with backgrounds in consumer psychology, economics, sociology, law and engineering. We share an interest in the behaviour of energy consumers, but approach the concept of behaviour through very different disciplinary lenses. In order to bring some coherence to our interactions and to the research programme as a whole, we developed a theoretical model - the 'Energy Cultures framework'. Here we describe the framework, and how, while it was initially developed to depict the nature of the problem, it has proven to be unexpectedly fruitful in supporting collaboration, designing the research programme, and characterising the complexity of household behaviour.

2. Designing the Framework

Since the 1970s there have been numerous studies of energy consumption behaviours from a wide range of disciplinary perspectives, including microeconomics; behavioural economics; technology adoption models; social and environmental psychology; and sociological theories. No single analytical approach provides a framework for analysing more than a small portion of behaviour, or for providing reliably successful interventions [4-6].

There is clearly value in developing a framework to support more integration across disciplines, but despite a number of attempts to establish unifying models [5-12] they are little used, and in practice single-discipline studies dominate the literature [5]. Wilson and Dowlatabadi [6] suggest that a successful integrating model would need to be relevant across three characteristics of energy behaviour—context, scale, and heterogeneity. In other words the model would need to be applicable to a wide range of determinants of behavior; to different scales (for example from a single household to an industry sector); and would need to be able to account for the wide variability in energy behaviours and responses to interventions.

In developing the Energy Cultures Framework, the initial purpose was to create a model that incorporated all of the potential drivers of household energy behavior as perceived by the Energy Cultures team members, so that we had a commonly agreed notion of the problem and its potential influences. This was crucial because different disciplines have quite different notions of what 'behaviour' actually is, as well as what its drivers are. Behaviour is sometimes characterised in terms of the energy technologies acquired or adopted by the consumer (e.g. is the house well-insulated? does it have a heat pump?); sometimes in terms of the consumer's *use* of energy-related technologies (do they drive or walk to work? do they use a dishwasher?); sometimes in terms of the consumer's aspirations (e.g. cleanliness, a healthier environment), and also as various interrelationships between these factors [5, 6, 13]. From our inter-disciplinary perspective, we felt it was important to include all of these notions of behaviour – technologies, activities and aspirations, and their interrelationships. We also wanted to be able to take into account the very broad range of factors that have been identified as affecting or driving behaviour, including the values, beliefs and knowledge of the consumer, the wider social and cultural values that impact on the consumer, the availability of technologies, the pricing and market conditions, the regulatory and policy environment, incentives and disincentives, and many other influences.

We were influenced by several theoretical streams. Socio-Technical Systems (STS) theories consider the role technologies play in influencing behaviours and expectations, and suggest that ''social practices and technological artefacts shape and are shaped by one another'' [14, p. 351]. We also draw from Bourdieu, who theorises that the practices that make up a social life are largely generated and regulated by 'habitus' – persistent patterns of thought, perceptions and action – which themselves are a response to the objective conditions within which the individual exists. Habitus is self-generative and can constrain an individual's aspirations so that practices that lie outside their habitus may be excluded from consideration as unthinkable. This is not to say that we believe cultures are fixed and immutable (nor does Bourdieu, who discusses the possibilities of strategic action to alter habitus). On the contrary, as is evident everywhere in society, cultural groups change their characteristics and membership, cultural traits are mutable, and they can be rapidly adopted by new groups in conducive conditions. For our purposes, it is how individuals and groups shift from the self-replicating stasis of habitus into the adoption of new practices, new beliefs and aspirations, and new technologies, that are the core of our interest. Our approach is also strongly influenced by 'soft systems' thinking—ways of understanding a particular context in a holistic way through considering interactivities between its attributes. Systems thinking attempts to address the shortcomings of reductionist approaches, recognising the complexity of the real world. We use 'system' not in the sense of a real-world entity, but as a construct to aid understanding [16, 17].

'Culture' is another core concept, and here we are not using the term to refer to any particular pre-defined ethnic or social group, but in recognition of the diversity of values, beliefs, knowledge, practices, technologies, and other cultural determinants that exist within any given society. Our hypothesis is that distinctive clusters of cultural norms, energy practices and material culture will be able to be identified within a given society, and that identifying and studying the characteristics of these 'energy cultures' will give insights into the heterogeneity of energy behaviours. The term 'energy cultures' brings the norm-practice-material culture dynamic to the fore, rather than the more decentred influences that are the focus of much STS literature (although still recognizing the influence of external agents.

Within the energy literature, the concept of culture has generally been more implied than overt. The key exception is in the work of Loren Lutzenhiser [12] who suggests that energy consumption is embedded in cultural processes. Material culture (buildings, furnishings, technologies, etc.) interweaves with "roles, relationships, conventional understandings, rules and beliefs into the cultural practices of groups" (12, p. 54). Our 'energy cultures' framework builds on Lutzenhiser's insights.

3. The Energy Cultures Framework

The Energy Cultures framework (Fig 1) proposes that consumer energy behaviour can be understood at its most fundamental level by examining the interactions between cognitive norms (e.g. beliefs, understandings, motivations etc), material culture (e.g. heating technologies, building form, etc) and energy practices (e.g. activities, processes). These are all aspects of 'behaviour', and using a household as an example, cognitive norms might include social aspirations, expected comfort levels, environmental values and respect for tradition; material culture might include heating devices, house structure, and insulation; and energy practices might include temperature settings, hours of heating, and maintenance of technologies. Each of these three components (cognitive norms, material culture and energy practices) individually affects energy use, yet they are also strongly interactive. For example, the existence of a heat pump (material culture) will result in very different practices from a household with an open fire; or a frugal upbringing (cultural norms) will impact on energy practices and possibly on the choice of technologies (material culture).

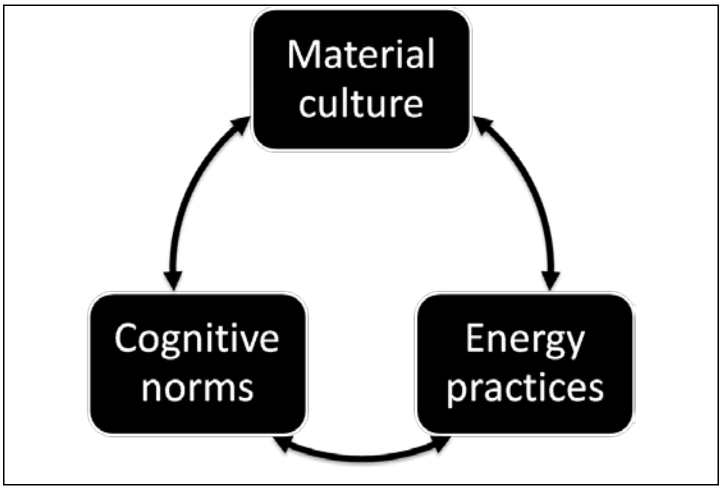

Fig. 1. The core concept of the Energy Cultures framework: cognitive norms, material culture and energy practices and the interactivity between them.

The three components and their interactions form the core of the Energy Cultures framework, but there are also wider systemic influences on behavior (Figure 2). Each aspect of material culture, energy practice or cognitive norm is impacted in some way by these wider influences—for example, cognitive norms around home heating will be affected by such things as upbringing, age and education; choice of home heating technologies may be impacted by such things as income level, availability of technologies, law and regulations and efficiency rating schemes; and heating control settings (if any) may be influenced by such things as the energy price structure and social marketing campaigns.

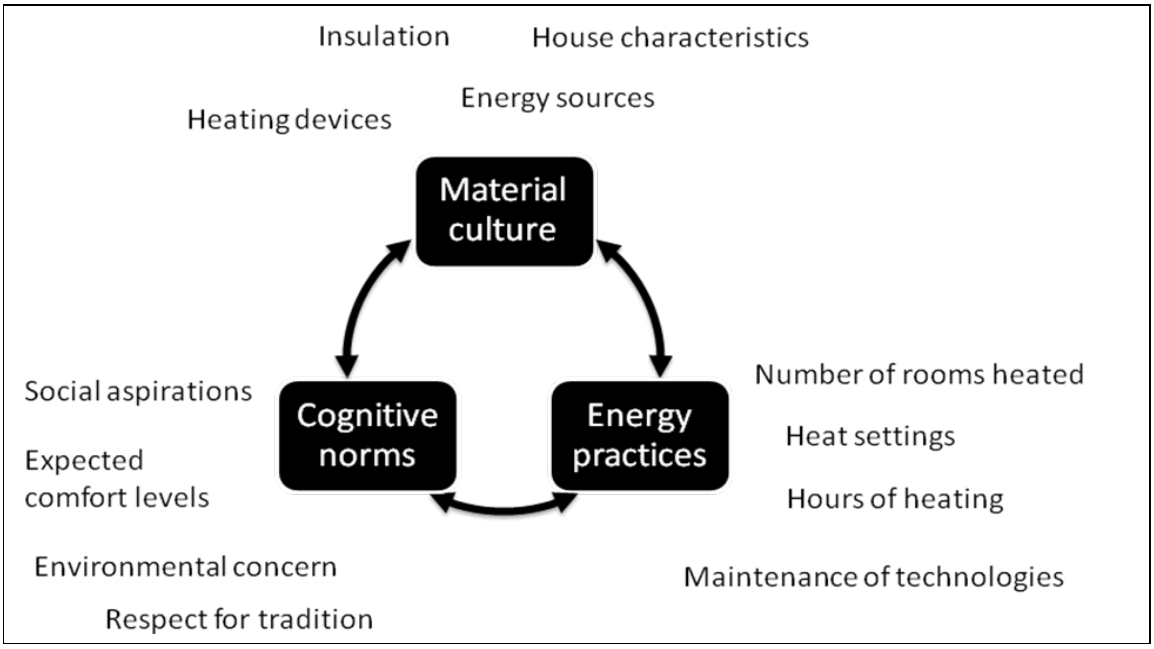

Fig. 2. Using the Energy Cultures framework to depict some of the wider systemic influences on behaviour.

4. Application of the Energy Cultures Framework

Having initially developed the Energy Cultures framework as a commonly agreed depiction of the problem we were seeking to address, we found it had other uses. Firstly, it aided in constructing hypotheses for our research into household energy behavior. For example, we hypothesise that clusters of similar norms, material cultures and/or practices will be observable in a given population, enabling segmentation of the population in terms of reasonably distinctive 'energy cultures'. Characterising these different 'cultures' will assist in both understanding the range and nature of consumer behaviour, and in identifying what sorts of interventions may be effective in achieving a move towards greater energy efficiencies for any given 'culture'.

Secondly, the framework has provided a conceptual structure for the design of the research programme. Each of the disciplines has particular methodologies which can help inform different components of the energy cultures framework, and the interactions between them. To date (at the end of our first year), we have studied cultural norms (and in particular the influence of values on practices and material culture) using 'values laddering', a method from consumer psychology involving in-depth interviews. Households have been surveyed to identify their material culture, practices and cognitive norms, as well as some of the external influences recognized by householders such as information sources and social networks. Choice modelling, an economics method, has been used to identify the tradeoffs that people make in their preferences for household heating and hot water systems, which in terms of the models informs the interactivity of cognitive norms with both material culture and energy practices. The data is being collected at three scales – some households are being subject to all three data collection methods; the latter two methods being applied both within our three case study areas and nationally.

A third use of the framework is as an integrating tool. We use the framework as the basis for staging the streams of the multi-method research project so that one informs the other—for example, findings from values research (cognitive norms) was used to design the choice modelling. By using common case studies (where relevant) for all of the research, data from different research streams can be contrasted across households or groups of households, building up a rich picture of household behaviours. Integrated analysis of this data will start to identify clusters of 'energy cultures', which will then be studied in greater depth in segmented focus groups of householders using soft systems methodology. The wider legal and policy context affecting behavior will be examined through legal desktop investigations. Opportunities for effective interventions will be sought both from the reported experiences of energy culture group members, and from the policy review. In year 3 some interventions will be trialled within culture groups.

A fourth application of the framework has been to understand behavior change in retrospect. The Transition Town movement is a 'vibrant international grassroots movement that brings people together to explore how we – as communities – can respond to the environmental, economic and social challenges arising from climate change' [18]. We have examined the behavioural shifts occurring in a New Zealand transition town, Waitati, using the Energy Cultures framework.

Possibly, the most prominent and far-reaching transition activity that community members are engaged in is known as the Waitati Energy Project (WEP). This is a multifaceted set of proposals to move the community to more sustainable patterns of energy consumption and supply. The Waitati Energy Project had its beginnings when a small group of enthusiasts invited a prominent Green politician to speak to the community on sustainability issues. Building on interest aroused by this meeting, they organised over the next year a series of well-attended events to help develop 'energy literacy' in the community, including a day-long fair with speakers, stalls and hands-on activities like a cycle-powered television.

In terms of the Energy Cultures framework, these activities helped shift the cognitive norms of the community towards an improved awareness of global and local imperatives for greater energy efficiency and more renewable energy supplies, a better self-awareness of the community's own characteristics, and improved energy literacy. This shift paved the way for changes in practices and material culture.

To date, the most significant change in material culture is in home insulation. Most of Waitati's homes are poorly insulated because they were built before mandatory insulation standards were introduced in the 1970s, so there are ready opportunities for improvements energy efficiency. The WEP organisers secured government subsidies for a mass home insulation project in 2009 and facilitated the project. As a result, 53 of the 200 houses in Waitati received subsidised insulation upgrades. WEP's success in gaining the funding, and the significant level of uptake, would have been unlikely if the community had not been cognitively 'primed' (for example a far lower level of uptake was achieved in other areas). Other changes in material culture have been enabled through genuinely cooperative activities such as the exchange of technical advice, the organisation of bulk purchasing to secure discounts and the establishment of partnerships with local suppliers and builders.

On the energy supply side, WEP proposes to build a community owned wind turbine to provide power for the district while feeding surplus electricity into the distribution grid. While community owned turbines are not uncommon in other countries, this would be a first in New Zealand. It represents a significant change in thinking at the local community level that requires changes also to the cultural infrastructure and practice at a national level. Current industry norms are not supportive of locally distributed generation, and the legal and financial structures for ownership and operation of such a venture are untested. Based on the Energy Cultures framework, we anticipate that progress in this area will require harmonisation of community members' cognitive norms and practices, prior to being able to achieve a shift in material culture and an overall transition to a new energy system 'habitus'. Steps have been taken to develop the turbine project with a community planning exercise, the identification of sites, initial evaluation of the generation potential, discussions with the lines company and a turbine manufacturer, as well as gaining Government funding to develop a financial model and business plan take the proposal to the next stage. The fact that the community is prepared to take on such a challenging proposal represents a significant shift in the 'energy culture' of the individuals directly involved and of the community as a whole.

These are all examples that illustrate the ways in which energy behaviours are influenced by the interactions between cognitive norms, material culture and energy practices, and that these interacting components can be examined at both a personal and community/social level. We consider that visualising, and analysing, the system as an interconnecting set of attributes helps to reveal the need, the options and the staging for change strategies. Understanding how Waitati has achieved a significant shift in the direction of household energy efficiency and supply can offer clues as to how change might be initiated in other contexts.

Finally, a further intention with the Energy Cultures research programme is to identify suitable interventions for behavior change. It was clear from the literature [6] and from our own observations that there is surprising variability in energy-related behaviour, even across households or firms with apparently similar characteristics. We suspect that the lack of success with interventions might be related, in part, to their being designed to influence an imaginary typical consumer, rather than selected as 'best fit' for definable behavioural clusters. The research programme aims to describe and characterise this heterogeneity, so as to be in a better position to match interventions to specific energy cultures. This will undertaken and tested in Year 3 of the programme.

5. Conclusions

The Energy Cultures model is fundamentally a conceptual framework to help articulate a particular class of problems relating to why individuals and groups use energy in the way they do. Nevertheless we have found it to have a number of other potential applications, some of which we are only beginning to explore. At an applied level, the Energy Cultures framework has already provided a basis for crossdisciplinary collaboration, and for multi-disciplinary research design. It enables identification of the relative roles of different disciplines in contributing to exploring the research problem, and the linkages between findings, and thus facilitates cross-disciplinary interactions. We are using it as a common point of reference and a tool for integration of research findings from our multi-stream research project.

The adaptability of the Energy Cultures framework is such that it displays Wilson and Dowlatabadi's three requirements for a successful integrating model [6]. It accounts for different *contexts*—the wide range of drivers of behaviour, through its modelling of the interactivities between the three core components of behaviour, and between these and wider societal and structural influences. It works at different *scales*, being applicable to understanding a single household, a group of households, a community (such as Waitati), an industrial sector, or conceivably at a national level (as in potentially considering the difference in 'energy cultures' between one nation and another). And it is particularly designed to characterise *heterogeneity* – the wide variability in behaviours – through the identification of different energy cultures.

The Energy Cultures framework has been developed in part to assist in policy development, regulation and market design to achieve greater energy efficiency through improved understanding of the interactions between context and behaviour. In particular, by identifying clusters of people or households with similar behavioural patterns, it may assist in the crafting of more effective interventions and incentives targeted to specific energy cultures. We also note its potential to help energy supply companies understand different behavioural clusters ('energy cultures') among their customers, so as to better tailor their tariff schemes and products. However, only further application of the approach will show whether it has real utility in helping to understand energy behaviours in a holistic way, and in guiding the development of projects and programmes to achieve greater adoption of energy-efficient behaviours.

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Appliances facilitating everyday life – electricity use derived from daily activities

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Abstract: The purpose of this paper is to present how, using a visualization method, electricity use can be derived from the everyday activity patterns of household members. Target groups are, on the one hand, professionals in the energy sector and energy advisors who need more knowledge about household energy use, and, on the other hand, household members wanting to reduce the energy use by revealing their own habits and thereby finding out how changed activity performance may influence electricity use. The focus is on the relation between utilizing electric appliances to perform everyday life activities and the use of electricity. The visualization method is based on the time-geographic approach developed by Hägerstrand and includes a model that estimates appliance electricity use from household members' activities. Focus, in this paper, is put on some basic activities performed to satisfy daily life needs: cooking and use of information, communication and entertainment devices. These activities appear frequently in the everyday life of households, even though not all household members perform them all. The method is applied on a data material comprising time-diaries written by 463 individuals (aged 10 to 85+) in 179 households in different parts of Sweden. The visualization method reveals when and for how long activities that claim electric appliances are performed by which individual(s). It also shows electricity load curves generated from the use of appliances at different levels, such as individual, household and group or population levels. At household level the method can reveal which household members are the main users of electricity, i.e. the division of labour between household members. Thereby it also informs about whom could be approached by energy companies and energy advisors in information campaigns. The main result of the study is that systematic differences in activity patterns in subgroups of a population can be identified (e.g. men and women) but that directed information based on these patterns has to be made with care and with the risk of making too broad generalizations.

Keywords: *Electricity use, Everyday activity sequence, Visualization, Activity pattern, Load curve.*

1. Introduction

Information is a relatively cheap way to make efforts to influence people to change their everyday life activities in order to better comply with the policies aiming at mitigating climate change from overuse of resources, among them electricity [1,2]. Information as a means to influence people's daily routines is not effective unless the individuals judge the information to be relevant to them. Therefore information must be targeted carefully. Who is to be targeted with information about energy saving and energy efficiency activities? This question has to do with the correspondence between which household members are in the energy company's billing register and which household member(s) utilize the electricity demanding appliances in the home. The aim of this paper is to present how the visualization method *VISUAL-TimePAcTS/energy use*[1] can be used to study energy use in households and can facilitate the identification of the actual users of electric appliances within these households. Thereby relevant information for various target groups can be developed. The method has been developed in an interdisciplinary research group in which scientists from social science, visualization science and physics cooperate on a long term basis [3,4,5,6,7]. The method aids

[1] VISUAL-TimePAcTS: VISUAL = visualization, P = place, Ac = activity, T = technology, S = social companionship; time is, of course, time.

in increasing our knowledge about human daily activities and the use of electric appliances for performing them.

Gram-Hanssen showed that even if households are similar in many respects, their energy use may differ a lot [8]. This has to be handled. A basic assumption is that in order to influence people to change their everyday life habits and routines, the information presented to them must address problems that are relevant to them. This means that they should be able to recognize their own daily situation in the material presented and thereby find substance in the arguments.

2. Method and the models for accounting electricity use

VISUAL-TimePAcTS/energy use is developed in the tradition of time geography [9,10,11,12] and its point of departure is the individual and her daily activities as they are seen in a sequence over the day. If data allows (i.e. if there are diaries from more than one person in a multi person household), the individual is seen in the context of her household. Even when individuals are aggregated to group or population levels the important information distinguishing one individual from another is still visible, figure 1.

The data used for developing the method is collected by Statistics Sweden in a pilot study in 1996. An important and valuable characteristic of this dataset is that it contains individuals in households, i.e. individuals of 10 years and older in the 179 households have written time-diaries. The age span of the total dataset is 10 to 97 years and the household sizes vary from 1 person upwards. The households included in the study are situated in different parts of Sweden and their income, education and accommodation forms vary.

The individuals (N=463) have written time-diaries during one weekday and one weekend day. Their weekday activity sequences forming an activity pattern of the population is shown in figure 1 (right). Members of the same household have written diaries on the same date, which means that it is possible to couple and compare the individuals' activities to each other. For example, which person cooks and which person buys the ingredients for cooking within the same household can be revealed.

The diary data considered in this paper are categorized into 7 main activity categories and each of these categories is broken up into more detailed descriptions of a performed activity. Apart from activity type, information about companionship while performing each activity is also available, meaning together with whom or what appliance an individual is. This makes possible the extraction of information concerning energy use of individuals, households and whole populations.

A model for computing load profiles for household electricity and hot water use based on activities has been presented by Widén [13,14]. In the developed model, activity diary data are converted to energy load profiles by considering an energy-use category and a corresponding energy-use pattern for each activity. Each energy-use category is described by a number of parameter values corresponding to standard powers and runtime of appliances used for performing activities within it (fig. 2, right). There are two main schemes describing how energy is consumed while performing activities (fig. 2, left). The first one includes activities that consume energy while they are being performed, like cooking, watching TV or using the radio. The second scheme refers to activities that start consuming energy for a period of time after the activity has been completed, like starting the washing machine or dishwasher. Based on these energy use schemes and the energy type parameter values for power consumption, power demanding activities can be highlighted within VISUAL-TimePAcTS/energy use and load curves can be computed and drawn.

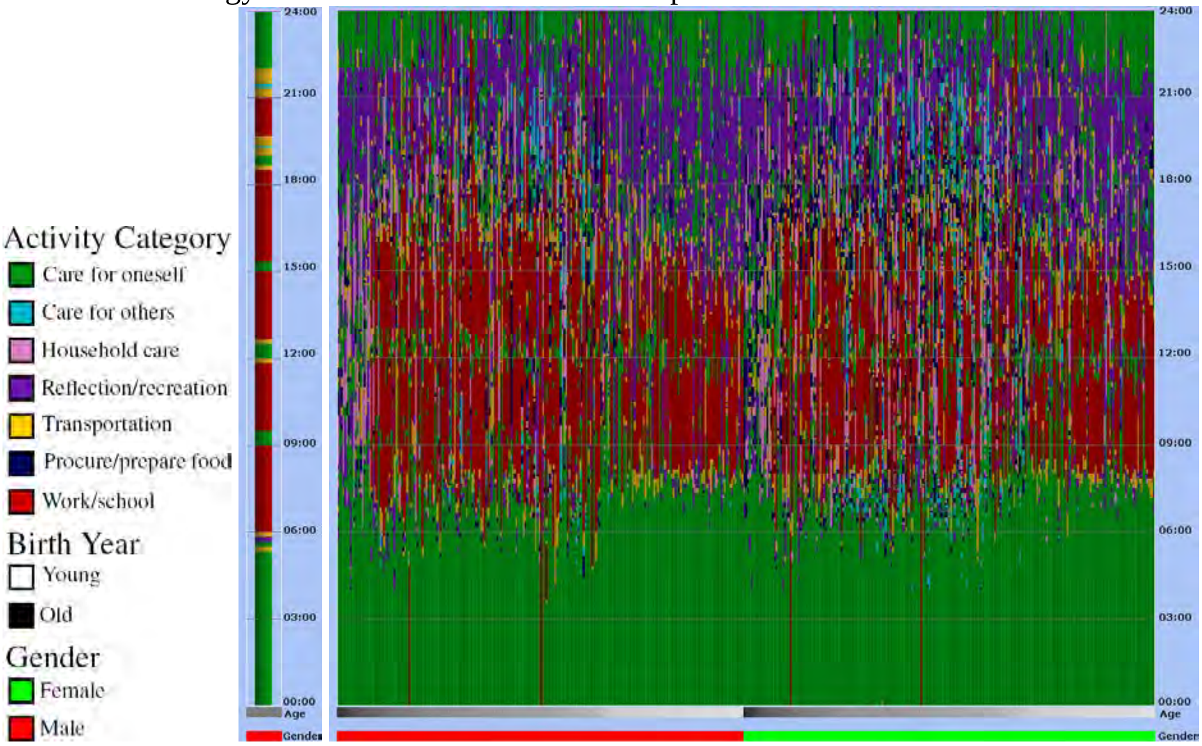
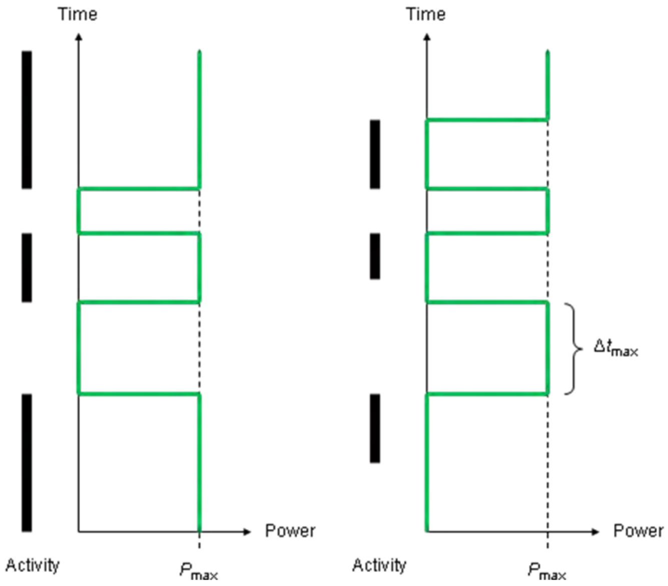


Figure 1. The time geographical representation principle used for visualizing activity diaries. The colour legend to the left shows the colour correspondence of the activities and the sorting variables, a single individual's diary is shown in the middle, and a population of 463 individuals' diaries is shown to the right. Each individual is represented by a stacked bar composed of the sequence of activities she performs during the day (middle). The activities are coloured according to the colour legend (left). Time is represented on the y-axis going upward, and individuals are drawn along the x-axis sorted by gender and age (see legends in the bottom of the figure and colour legend in the left). In the population representation (right) the dominance of sleep during night-time hours (green, care for oneself) and work/school activities (red) during daytime hours is prominent. Travel to work/school in the morning and back in the afternoon is indicated by the yellow parts of the bars representing the individuals. In the evening, reflection/recreation activities (dark lilac) dominate, the most significant of them being watching TV. Dark blue indicates activities to procure and prepare food.

3. Electricity use derived from daily activities

VISUAL-TimePAcTS/energy use makes it possible to reveal the following aspects of electricity use in everyday life of individuals:

- which activities relate to electricity use
- the time of the day when these activities that demand electricity use are performed
- the distribution in the population of these activities (age and gender)
- power load curves displaying the mean electricity use per person in the population



	Power	Runtime	Color
Audio	100	--	
Cleaning	1000	--	
Computer	100	--	
Cooking	1500	--	
TV	200	--	
Ironing	1000	--	
Washing	490	130	
Dishwashing	430	160	
Drying	1650	90	

Figure 2. Left: The left scheme in the left part of the figure shows that a constant power Pmax is demanded during use, while the scheme to the right in the left figure shows that the power demand starts after the activity is finished and goes on until a limiting time Δtmax has elapsed. (Widén 2009). Right: Parameters used for electricity demand and runtime of appliances according to the two schemes, and the colour legend for load curves.

In this paper we investigate the energy use patterns of activities related to “cooking” and “information and communication” using representations created through VISUAL-TimePAcTS/energy use.

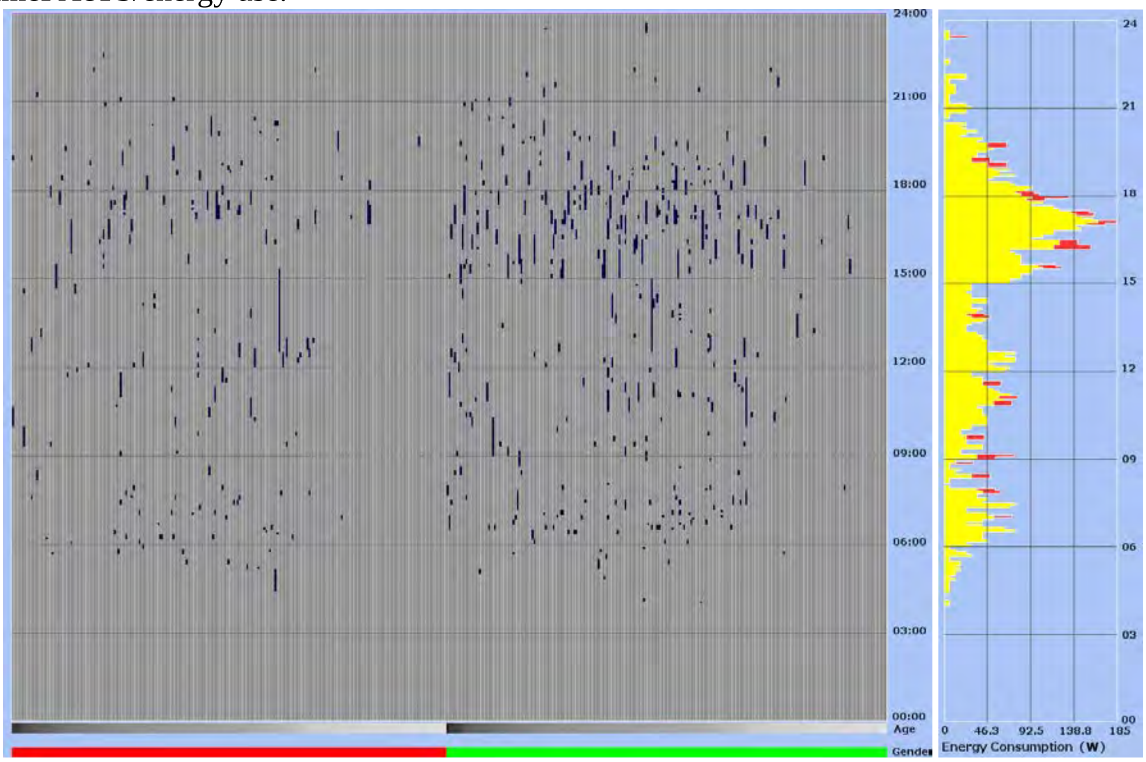


Figure 3. Left: Distribution pattern of cooking and dishwashing activities. Right: Corresponding power load curve showing electricity use in Watt per person in 5 minute intervals (yellow for cooking, red for dishwashing, max ~185 W/person).

Figure 3 shows the distribution of cooking and dishwashing activities (left) and the corresponding load curve (right) of these activities. There is a peak in the late afternoon, smaller peaks in the morning and at lunchtime. These activities are predominantly performed by women, very few children and older men are doing them.

In figures 4 and 5 the activity pattern related to individuals' use of information and communication technologies (TV, computer and radio) is shown. Figure 4 reveals computer use (computer play), which is predominantly performed by younger persons, and especially boys (doing this activity as a main activity). Among women there are some turquoise activity indicators showing that they play with their children who play with the computer (the main category of these activities is "Care for others").

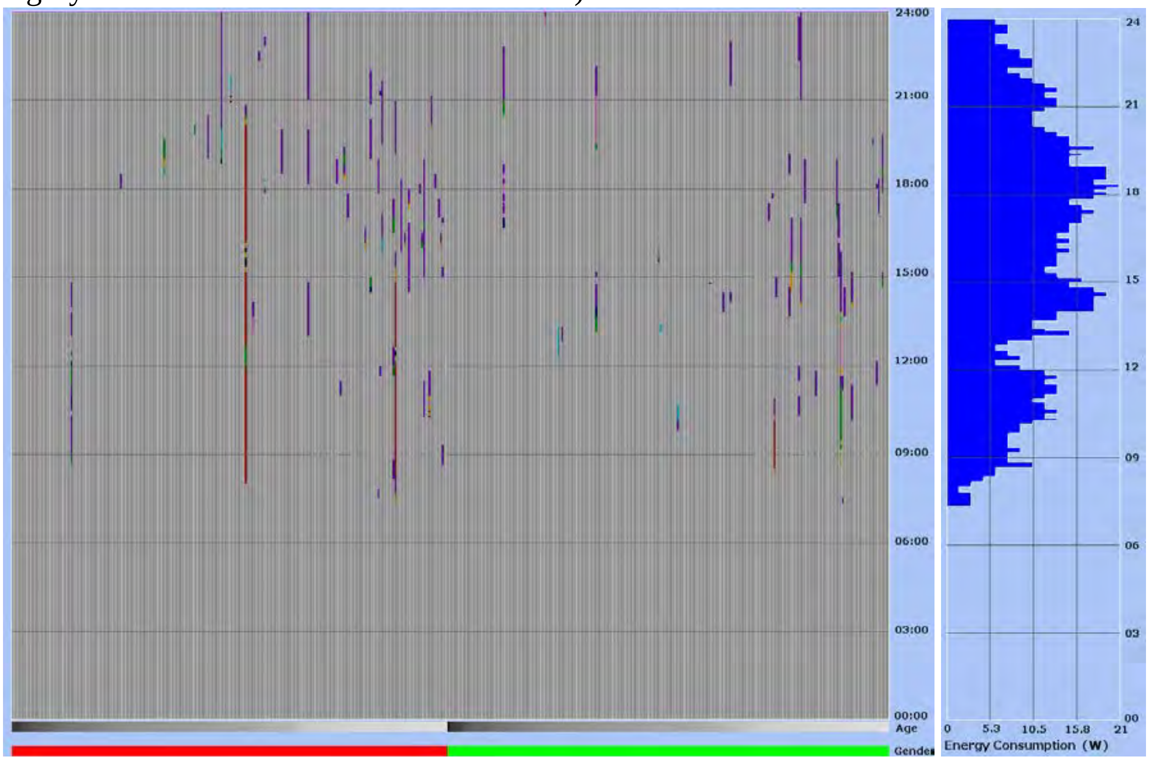


Figure 4. Left: Distribution pattern of activities claiming computer use. Right: Corresponding power load curve for computer use showing electricity use in Watt per person in 5-minutes intervals (max ~21 W/person).

Figure 5 shows the difference between electricity use generated by the activity watch TV and listen to radio (TV and radio as main activity) and electricity use generated by having the TV-set or the radio turned on while doing something else (TV and radio as secondary activities). Most people watch TV as a main activity in the evenings (fig. 5 bottom left), in the afternoon it is mostly girls, boys and old men who watch TV. Among older women and children the TV is also on while they do other things. The frequency curves for TV and radio activities show the total number of people performing them as main activities during the course of the day (fig. 5 left, in dark lilac), while the load curves for these activities show the mean power consumed per person (fig. 5 right, in pinkish for TV and red for radio) and consider also them performed as secondary activities. For this reason the two curves are different. Figure 5 right, also shows what main activity people perform when they listen to radio, which reveals that the radio is, to a great extent, on while working (red) and at breakfast time (green in the morning) – and this goes for people of all ages and both men and women. There is a big difference between TV and radio in this respect: radio is turned on much more than the TV when people do something else.

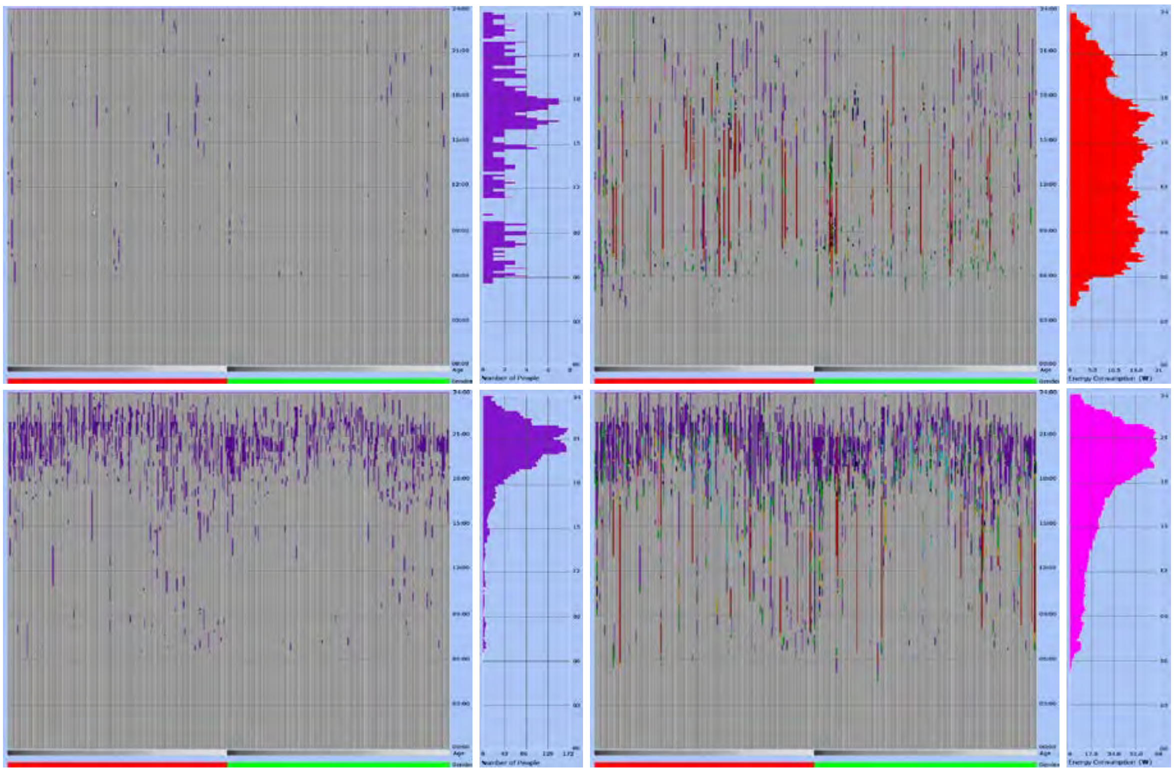


*Figure 5. **Top:** Left: Activity pattern and frequency graph for listening to radio as a main activity (max 7 persons at a time). Right: Activity pattern and power load curve for radio use (main and secondary activity) in Watt per person in 5 minute intervals (max ~ 70 W/person). **Bottom**: Left: Activity pattern and frequency graph for watching TV as a main activity (max 170 persons at a time). Right: Activity pattern and power load curve for TV use (main and secondary activity) in Watt per person in 5 minute intervals (max ~ 70 W/person).*

In figure 6 the total electricity use generated by using appliances for satisfying the need of information and communication (radio, computer and TV) and for food preparation (cooking and dishwashing) is visualized. The max load is about 250 W/person and it appears in the late afternoon, when cooking, TV, computer use and listening to radio appear at the same time. This figure makes it clear that it is cooking activities (the yellow load curve) that demand most electricity. Also clearly shown is that cooking and watch TV have distinct peak hours; especially in the afternoon of weekdays. Due to its mass performance, also watching TV generates a substantial energy demand in the evening hours.

4. Results

The VISUAL-TimePAcTS/energy use method helps reveal collective activity patterns at aggregate level, while at the same time it can help identify differences within groups (here men and women of different ages). In this paper we have demonstrated the potential of the method by investigating the energy consumption patterns generated by activities related to cooking, information and communication.

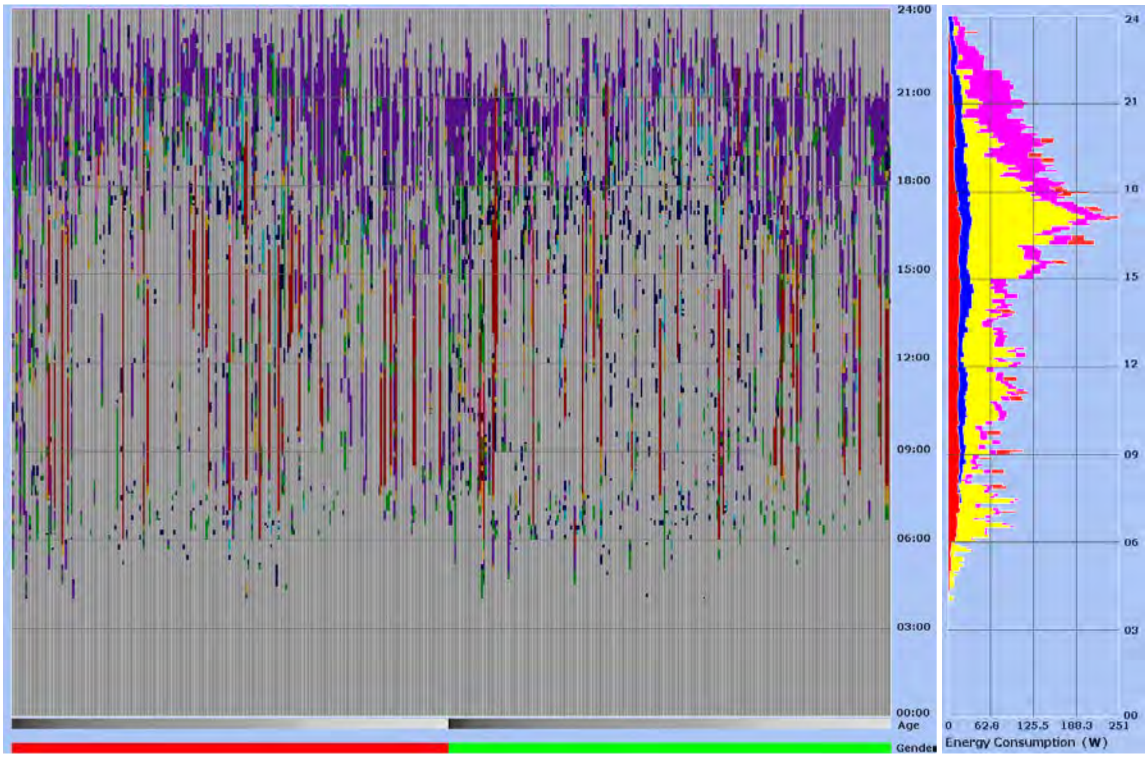


Figure 6. Left: Distribution pattern of all activities claiming the use of the considered electric appliances; TV, radio, computer, kitchen appliances. Right: Corresponding power load curve showing electricity use in Watt per person in 5 minute intervals (max ~250 W/person).

Through this example it becomes obvious that cooking is a daily activity that is to a large extent female gendered. Also shown is that children do not cook. The use of the TV-set is more equally divided between genders and is primarily performed in the evenings, but it differs with respect to age –younger people watch TV also in the afternoon after school. There were big differences between ages when it comes to computer use which was dominated by boys. Listening to radio was more evenly spread over the day, and between ages and gender. Finally, watching TV and especially listening to radio are activities that allow people to do other things and are often performed as secondary activities. This is especially true for listening to radio, an activity that seldom appear in its own right.

5. Conclusions and recommendation

The knowledge that can be acquired from representations created through VISUAL-TimePAcTS/energy use can be useful when policy makers and energy companies try to target information in order to reduce energy use and make it more efficient. For example, in a household with a man and a woman where the man receives the electricity bill, the man might not be the ideal receiver of attached information about energy-efficient cooking because, as we have seen, women cook more often. Information directed to women would perhaps be more effective. However, such directed information faces the risk of being too generalized and not reflecting the diversity between households in terms of both habits and family constellations. This particular analysis is also limited because of the relatively old data.

In general, the visualizations can be used to improve knowledge about what purpose people utilize electric appliances for. At individual and household levels the method can be utilized for communicating energy efficiency advice since it is easy for the individuals to recognize their own daily life in the visualizations of their time-diaries. In order to improve its general applicability, the method will be extended with a module for heating, hot water use and energy use for daily transportation. The method can serve as complement, and maybe also as substitute, to expensive metering studies.

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Providing a Heating Degree Days (HDDs) Atlas across Iran Entire Zones

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Abstract: Considering fossil fuels depletion and increasing of energy demand in Iran, a special attention is required toward the energy conservation. Energy demand of building section in Iran is very high, which is as a result of many factors such as governmental huge subsidies for energy, lack of energy conservation culture in building inhabitants, poor insulation of buildings and poor heating or cooling control systems.
Most of buildings heating control systems in Iran do not respond properly to weather temperature changes during winters, therefore most of the time the interior temperature of these buildings exceed the comfort temperature, thus these buildings are not energy efficient and consume excessive amount of energy. The most important index to identify these buildings across the country is to know HDDs for each point of the country.
Unfortunately, up to now no comprehensive research has been conducted in Iran about HDDs, and thus no HDDs atlas has been provided, therefore it is essential for energy managers, engineers and in particular for the government to be supplied with HDDs for each point of Iran. By taking this fact into account, we decided to prepare a comprehensive HDDs atlas for Iran entire zones.
In this paper authorized temperature databases of 255 meteorological stations in 30 provinces of Iran have been collected from Iran meteorological organization, thereafter HDDs for each station were calculated, then a mathematical modeling (multiple regression analysis technique) was employed in order to simulate the HDDs of other places in Iran. Consequently, a HDDs Atlas across Iran entire zones was provided.
These results can widely be used in energy consumption planning and prediction of the heating energy demand in buildings and enhances the government abilities to manage the rate of energy consumption in buildings.

Keywords: *Iran heating HDDs atlas, Energy management.*

Nomenclature

HDDs	*Heating Degree Days* .... °C·day	*Lat*	*latitude* .... °N
T_b	*base temperature* .... °C	*Long*	*longitude* .... °E
T_{mean}	*daily mean temperature*	*Alt* °C	*Altitude* .... *m*

1. Introduction

Unfortunately, until now no comprehensive research about HDDs has been conducted in Iran. In this paper authorized daily temperature databases of 255 meteorological stations in 30 provinces of Iran have been collected, thereafter the annually HDDs for each station were calculated. Then a mathematical modeling (multiple regression analysis technique) was employed to simulate the HDDs of other places. Consequently, a HDDs Atlas across Iran was provided.

2. Methodology

Fundamentally HDDs are a summation of the differences between the outdoor temperature and base temperature over a specified time period. HDDs are a useful tool that can be used in the assessment of weather related energy consumption in buildings, according to Eq. (1).

Heating energy demand (kWh) =
Overall heat loss coefficient ($kW\cdot°C^{-1}$) × HDDs (°C ·day) × 24 ($h\cdot day^{-1}$)
(The 24 is included to convert from days to hours.) (1)

In current study accessible authorized daily temperature databases have been collected from 255 meteorological stations (Fig. 1) during last 5 years.

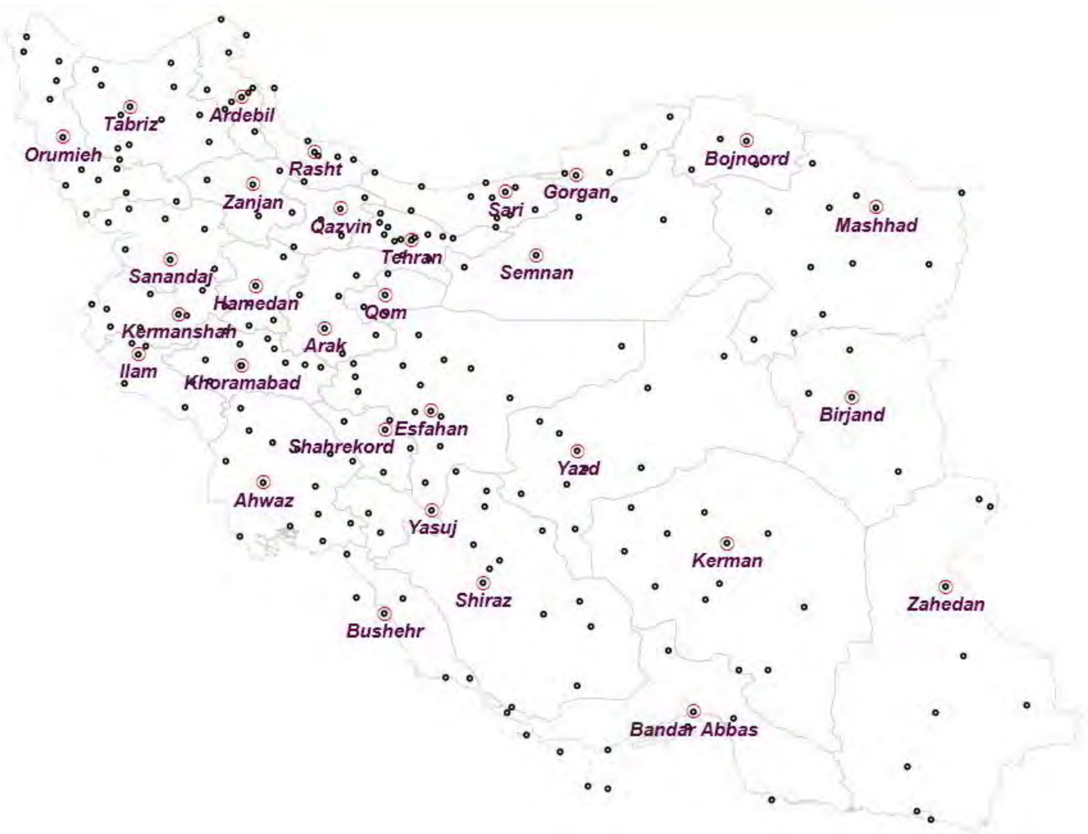

Fig. 1. Location of 255 Iran official meteorological stations in 30 provinces.

In this paper mean daily temperature method has been employed that is generally used in countries, such as USA [1] and Germany [2], where HDDs are calculated from the mean daily temperature. This makes the definition and calculation of HDDs simpler, and makes the reasonable assumption that efficient heating systems do not operate on days where outdoor temperature averages exceed the base temperature [3]. In this method we have applied Eq. (2).

$$\begin{cases} HDDs = T_b - T_{mean} & \text{if} \quad T_b > T_{mean} \\ HDDs = 0 & \text{if} \quad T_b \leq T_{mean} \end{cases}$$

(Based on local conditions, we assume $T_b = 18°C$) (2)

To calculate HDDs, at first the mean temperature was calculated for each day of the year, Thereafter, by applying Eq. (2) HDDs were calculated. Then by summation of HDDs during each year, we obtained annually HDDs during 5 years, subsequently annually HDDs average during this period attained (Table.1.).

Afterwards by computerizing the calculated HDDS, spline multiple regression analysis technique was employed in order to simulate the annual HDDs over each other point of country. In this method, a two dimensional function (surface) has been constructed closely fits range of a discrete set of known data points (HDDS in 255 stations), so we could estimate HDDs values in other points of country. Spline surfaces are very popular in computerized regression because of the simplicity of their construction, their ease and accuracy of evaluation, and their capacity to approximate complex shapes through surface fitting and interactive design [4]. In this paper by constructing spline surface from calculated HDDs, the comprehensive HDDs Atlases were provided (Fig.2. and Fig.3.).

3. Results

In Table 1, for each 255 meteorological stations longitude, latitude, elevation and calculated annual HDDs average have been determined. These results show various kinds of climate zones in Iran.

Table 1. Calculated annual HDDs in Iran meteorological stations.

Station Name	Lat	Long	Alt	HDDs	Station Name	Lat	Long	Alt	HDD
Abadan	30.37	48.25	7	428	Boinzahra	35.77	50.07	1282	2098
Abadeh	31.18	52.67	2030	2076	Bojnoord	37.47	57.32	1091	2319
Abali	35.75	51.88	2465	3544	Bonab	37.33	46.07	1290	2549
Abarkuh	31.13	53.28	1524	1387	Bookan	36.53	46.22	1386	2600
Abbor	36.93	48.97	703	1503	Borazjan	29.25	51.17	90	263
Abumusa island	25.83	54.83	7	5	Borujen	31.95	51.30	2197	2937
Aghda	32.43	53.62	1150	1173	Borujerd	33.92	48.75	1629	2184
Ahar	38.43	47.07	1391	2869	Bostan	31.72	48.00	8	550
Ahwaz	31.33	48.67	23	406	Bostan Abad	37.85	46.85	1750	3533
Alasht	36.08	52.85	190	2820	Bushehr	28.98	50.83	20	253
Aleshtar	33.82	48.25	1567	2476	Chahbahar	25.28	60.62	8	12
Aliabad	36.90	54.87	140	1414	Chalderan	39.07	44.38	1788	3811
Aligudarz	33.40	49.70	2022	2649	Chitgar	35.70	51.13	1215	1737
Amol	36.47	52.38	24	1333	Damavand	35.72	52.07	1960	2928
Anar	30.88	55.25	1409	1337	Damqan	36.10	54.32	1155	1801
Anzali	37.47	49.47	-26	1408	Darab	28.75	54.53	1140	777
Aqdasieh	35.78	51.62	1548	1911	Daran	32.97	50.37	2290	3042
Arak	34.10	49.77	1708	2363	Darehshahr	33.13	47.40	670	1065
Ardebil1	38.33	48.40	1314	3414	Dashtenaz	36.63	53.18	20	1318
Ardebil2	38.25	48.28	1332	3049	Dayyer	27.83	51.93	4	100
Ardestan	33.38	52.38	1252	1466	Dehdasht	30.78	50.55	820	889
Astara	38.42	48.87	-18	1676	Dehdoz	31.72	50.27	1457	1448
Avaj	35.57	49.22	2035	3087	Dehloran	32.68	47.27	232	473
Azna	33.45	49.42	1872	2801	Delijan	33.98	50.68	1524	1964
Babolsar	36.72	52.65	-21	1196	Deylaman	30.05	50.17	4	359
Badrabad	33.43	48.27	1155	1619	Dezful	32.27		83	523
Bafq	31.60	55.43	991	950	Dogonbadan	30.43	50.77	700	711
Baft	29.23	56.58	2280	1837	Dorud	33.48	49.07	1527	1953
Bam	29.10	58.35	1067	628	Doshantappeh	35.70	51.33	1209	1433
Bandar Abbas	27.22	56.37	10	86	Eivane Qarb	33.83	46.32	1170	1675
Bandar Torkaman	36.88	54.07	-20	1314	Eqlid	30.90	52.63	2300	2371
Baneh	36.00	45.90	1600	2459	Esfahan	32.62	51.67	1550	1952
Bavanat	30.47	53.67	2231	2148	Esfarayen	37.05	57.48	1216	2172
Behbahan	30.60	50.23	313	537	Eslam abad	34.12	46.47	1349	2276
Beshruyeh	33.90	57.45	885	1450	Fasa	28.97	53.68	1288	1142
Biarjmand	36.05	55.83	1106	1905	Ferdos	34.02	58.17	1293	1587
Bijar	35.88	47.62	1883	3014	Firuzkuh	35.92	52.83	1976	3479
Bileh Savar	39.37	48.37	90	1937	Gariz	31.30	54.10	2100	2194
Birjand	32.87	59.20	1491	1651	Garmsar	35.20	52.27	825	1444

Table 1 (continued). Calculated annual HDDs in Iran meteorological stations.

Station	Lat	Long	Alt	HDDs	Station	Lat	Long	Alt	HDDs
Geophysics	35.73	51.38	1419	1725	Kish island	26.50	53.98	30	17
Germi	39.05	48.05	749	2222	Komijan	34.70	49.32	1741	2734
Gilaneqarb	34.13	45.93	816	1167	Kuhdasht	33.53	47.63	1200	1818
Golmakan	36.48	59.28	1176	2259	Kuhrang	32.43	50.12	2285	3398
Golpayegan	33.47	50.28	1870	2318	Kushk Nosrat	35.08	50.90	948	1292
Gonabad	34.35	58.68	1056	1646	Lahijan	37.18	50.00	86	1445
Gonbade Kavous	37.25	55.17	37	1252	Lalehzar	29.52	56.83	2775	3127
Gorgan	36.85	54.27	13	1338	Lamerd	27.30	53.12	411	353
Haji Abad	28.32	55.92	931	638	Lar	27.68	54.28	792	561
Hamedan	34.87	48.53	1742	2805	Lavan	26.80	53.38	22	26
Hashtgerd	36.00	50.75	1613	2314	Lengeh	26.53	54.83	23	40
Hendijan	30.28	49.73	3	440	Lordegan	31.52	50.82	1580	1865
Hoseinieh	32.67	48.27	354	494	Mahabad	36.77	45.72	1385	2435
Ilam	33.63	46.43	1337	1776	Mahneshan	36.77	47.67	1282	2305
Imam Airport	35.42	51.17	990	1675	Mahshahr	30.55	49.15	6	409
Iranshahr	27.20	60.70	591	248	Makoo	39.33	44.43	1411	3126
Izadkhast	31.53	52.12	2188	2299	Malayer	34.25	48.85	1778	2459
Izeh	31.85	49.87	767	913	Malekan	37.13	46.10	1300	2501
Jajerm	36.95	56.33	984	1966	Maneh	37.50	56.85	890	1962
Jam-Tohid	27.82	52.37	655	534	Manjil	36.73	49.40	333	1343
Jask	25.63	57.77	5	10	Marand	38.47	45.77	1550	2891
Jolfa	38.75	45.67	736	2363	Maraqeh	37.40	46.27	1478	2445
Kabutar Abad	32.52	51.85	1545	1885	Maravetappeh	37.90	55.95	460	1409
Kahak	34.40	50.87	1403	1884	Marivan	35.52	46.20	1287	2463
Kahnooj	27.97	57.70	470	304	Marvast	30.50	54.25	1547	1415
Kalaleh	37.37	55.48	150	1324	Mashhad	36.27	59.63	999	1904
Kaleibar	38.87	47.02	1180	2540	Masjed	31.93	49.28	321	535
Kangavar	34.50	47.98	1468	2518	Mehran	33.12	46.18	150	711
Karaj	35.92	50.90	1313	2003	Mehriz	31.58	54.43	1520	1319
Kashan	33.98	51.45	982	1498	Meshkin	38.38	47.67	1569	2951
Kashmar	35.20	58.47	1110	1588	Meybod	32.22	53.97	1108	1411
Kenarak	25.43	60.37	12	41	Meymeh	33.43	51.17	1980	2742
Kerman	30.25	56.97	1754	1538	Miandoab	36.97	46.05	1300	2586
Kermanshah	34.35	47.15	1319	2012	Mianeh	37.45	47.70	1110	2359
Khalkhal	37.63	48.52	1796	3566	Minab	27.10	57.08	30	62
Khansar	33.23	50.32	2300	2752	Moallemkelay	36.45	50.48	1629	2325
Khark	29.27	50.33	4	205	Murche Khort	33.08	51.48	1669	1927
Khash	28.22	61.20	1394	914	Nahavand	34.15	48.42	1681	2398
Khodabandeh	36.12	48.58	1887	3037	Nahbandan	31.53	60.03	1211	1179
Khomein	33.65	50.08	1835	2346	Najafabad	32.60	51.38	1641	1798
Khor Birjand	32.93	58.43	1117	1316	Namin	38.42	48.48	1450	3055
Khoramabad	33.43	48.28	1148	1625	Naqdeh	36.95	45.42	1338	2598
Khoramdarreh	36.18	49.18	1575	2584	Natanz	33.53	51.90	1685	1993
Khorbiabanak	33.78	55.08	845	1186	Nayin	32.85	53.08	1549	1692
Khoy	38.55	44.97	1103	2660	Nayyer	38.03	47.98	1600	2932
Kiasar	36.23	53.53	1294	2263	Neyriz	29.20	54.33	1632	1149

Table 1 (continued). Calculated annual HDDs in Iran meteorological stations.

Station Name	Lat	Long	Alt	HDDs	Station Name	Lat	Long	Alt	HDDs
Neyshabur	36.27	58.80	1213	2129	Saravan	27.33	62.33	1195	655
Nikshahr	26.23	60.20	510	91	Sardasht	36.15	45.50	1670	2429
Noshahr	36.65	51.50	-21	1415	Sare Ein	38.17	48.10	1632	3303
Nourabad	34.05	48.00	1859	2798	Sari	36.55	53.00	23	1225
Omidieh	30.77	49.65	35	437	Sarpolezahab	34.45	45.87	545	1075
Orumieh	37.53	45.08	1316	2694	Saveh	35.05	50.33	1108	1600
Parsabad	39.65	47.92	32	1922	Semirom	31.33	51.57	2274	2568
Parsian	27.20	53.03	70	84	Semnan	35.42	53.55	1131	1610
Payam Karaj	35.78	50.83	1261	2153	Shahdad	30.42	57.70	400	447
Piranshahr	36.67	45.13	1455	2513	Shahrebabak	30.10	55.13	1834	1870
Poldokhtar	33.15	47.72	714	899	Shahrekord	32.28	50.85	2049	3020
Polesefid	36.13	53.08	610	1703	Shahreza	31.98	51.83	1845	2067
Qaen	33.72	59.17	1432	2001	Shahriar	35.67	51.02	2986	1817
Qarakhil	36.45	52.77	15	1348	Shahrud	36.42	54.95	1345	1956
Qare Ziaeddin	38.90	45.02	1108	2724	Shiraz	29.53	52.60	1484	1331
Qasre Shirin	34.53	45.60	376	860	Shushtar	32.05	48.83	67	390
Qazvin	36.25	50.05	1279	2168	Siahbisheh	36.22	51.32	2165	2881
Qeshm island	26.95	56.27	13	64	Silakhor	33.73	48.87	1497	2186
Qom	34.70	50.85	877	1553	Siri island	25.88	54.48	4	12
Qorveh	35.17	47.80	1906	2887	Sirjan	29.47	55.68	1739	1419
Quchan	37.07	58.50	1287	2509	Sonqor	34.78	47.58	1700	2568
Rafsanjan	30.42	55.90	1581	1270	Tabas	33.60	56.92	711	929
Ramhormoz	31.27	49.60	151	406	Tabriz	38.08	46.28	1361	2555
Ramsar	36.90	50.67	-20	1376	Tafresh	34.68	50.02	1979	2582
Rasht1	37.27	49.58	-10	1507	Takab	36.38	47.12	1765	3353
Rasht2	37.20	49.65	37	1457	Takestan	36.05	49.70	1283	2199
Ravansar	34.72	46.65	1380	2159	Takhtjamshid	29.93	52.90	1605	1487
Razan	35.38	49.03	1840	2902	Taleqan	36.17	50.77	1857	2920
Robat	33.03	55.55	1188	1378	Tehran	35.68	51.32	1191	1495
Rudan	27.97	57.18	220	84	Torbate Hey.	35.27	59.22	1451	2230
Rudsar	37.13	50.28	-19	1463	Torbate Jam	35.25	60.58	950	1969
Sabzevar	36.20	57.72	978	1669	Tuyserkan	34.55	48.43	1783	2471
Sad Dorudzan	30.22	52.43	1620	1482	Varamin	35.35	51.63	927	1603
Sahand	37.93	46.12	1641	2783	Yasuj	30.83	51.68	1832	1927
Salafchegan	34.48	50.47	1381	1799	Yazd	31.90	54.28	1237	1185
Salmas	38.22	44.85	1337	2955	Zabol	31.03	61.48	489	883
Saman	32.45	50.93	2057	2541	Zahak	30.90	61.68	495	838
Sanandaj	35.33	47.00	1373	2244	Zahedan	29.47	60.88	1370	1093
Saqez	36.25	46.27	1523	3015	Zanjan	36.68	48.48	1663	2884
Sarab	37.93	47.53	1682	3517	Zarand	30.80	56.57	1670	1422
Sarableh	33.78	46.57	1045	1513	Zarineh Obato	36.07	46.92	2143	3814
Sarakhs	36.53	61.17	235	1516	Zarqan	29.78	52.72	1596	1574
Sararud	34.33	47.30	1362	2118					

Then spline method was applied to construct interpolated surface from above discrete set of results, to provide below Atlases (Fig.2. and Fig.3.).

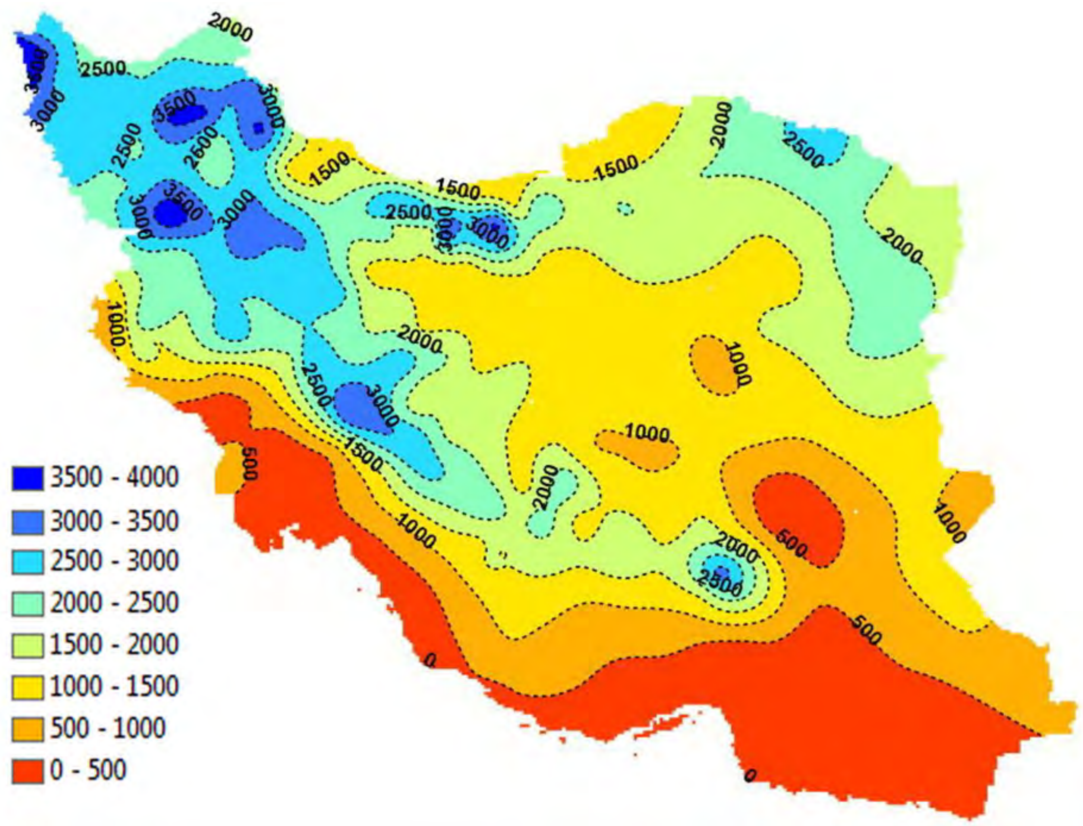

Fig. 2. Annual HDDs contours atlas over Iran entire zones, using spline interpolation

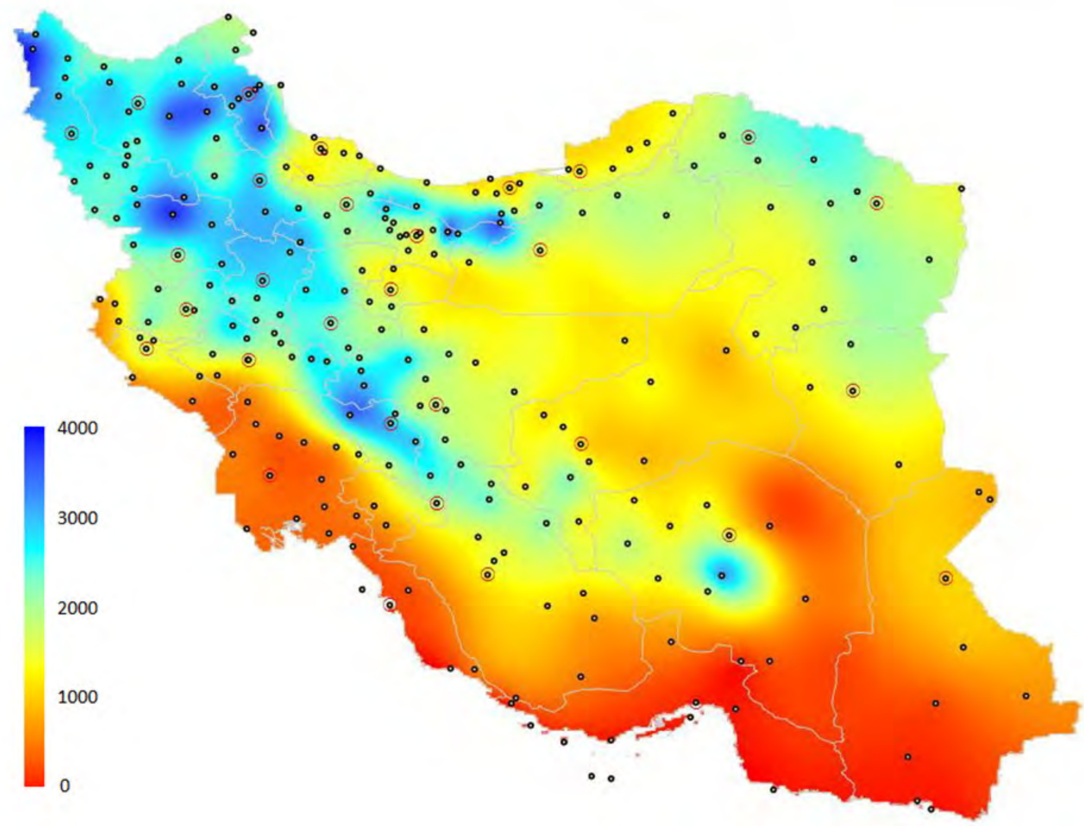

Fig. 3. Annual HDDs spectral atlas over Iran entire zones, using spline interpolation

The highest value of HDDs is in Zarineh Obato mountainous city (3814°C.day), in western region of Iran, and the lowest value of HDDs is in Abumusa island (5°C.day), in the southern region. This large difference in HDDs shows the intense contrast in the climatic characteristics between these two extreme geographic points (The gheographical specifications of each point have been indicated in Table.1).

High values of HDDs can be observed in blue zones, mainly in northwestern regions of country, such as Chalderan (3811°C.day), Khalkhal (3566°C.day), and Ardebil1 (3414°C.day), and some western regions such as Zarineh Obato (3814 °C.day) as mentioned before. All of these points are located beside Zagros mountain range. In addition they also can be observed in northern regions such as Firuzkuh (3479°C.day) because of locating beside Alborz mountain range.

Low values of HDDs can be observed in red zones, mainly in southern regions of country such as Jask Island (10°C.day) and Chahbahar (12°C.day) because of Persian Gulf and Oman Sea climatic effects. They also can be observed in eastern regions of country such as Kahnuj (304°C.day) because of locating beside Lut desert.

Fig.3 shows high contrast values of HDDs in Iran that introduces the exceptional climates over Iran. The uniqueness of these climates originates from several variables such as mountains and deserts especially Zagros and Alborz mountain ranges, Persian Gulf and Oman Sea, in addition unique deserts like Markazi and Lut. In country with these variations of climates, proposing appropriate HDDs can prevent higher escalation in energy consumption.

In Iran with governmental huge subsidies on n atural gas as a predominant heating energy carrier, government can set appropriate subsidies related on HDDs for each point of country.

4. Conclusions

HDDS over Iran entire zones, based on databases of 255 meteorological stations have been calculated and presented in a comprehensive table. Furthermore, contours and spectral atlas using spline interpolation have been demonstrated.

High contrast values of HDDs show the exceptional climates over Iran. In country with these variations of climates, proposing appropriate HDDs can prevent higher escalation in energy consumption.

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Covariates of fuel saving technologies in urban Ethiopia

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Abstract: The current government of Ethiopia has devised supply augmented and demand management strategies in order to reduce pressure on forests and the adverse impact of indoor air pollution. This paper tries to examine and understand the determinants of the speed of adoption of one of the demand side strategies, fuel saving technologies (Mirt and Lakech), in urban Ethiopia. The result of the duration analysis shows that income level is a significant factor in the adoption decision of the technologies. This indicates that households will not shift to other better sources of energy as their income increases, as postulated by the energy ladder hypothesis. Education is positively and significantly related to the speed of adoption of Mirt biomass cook stoves but its effect on adoption of Lakech charcoal stove is insignificant. Electric Mitad (substitute for Mirt *injera* stove) does not have any effect on the adoption of Mirt biomass cook stoves. However, ownership of Metal charcoal stove is negatively correlated with the adoption of Lakech charcoal stoves. This may suggest that there is a need to reconsider the promotion strategy given the better performance of Lakech charcoal stove over Metal charcoal stove. The implications of other covariates have also been discussed.

Keywords: *Improved stoves, Duration, Adoption, Ethiopia*

1. Introduction

The heavy dependence and inefficient utilization of biomass resources for energy have resulted in high depletion of the forest resources in Ethiopia (EPA, 2004). In order to reduce pressure on f orests and plantations and the adverse impact of indoor air pollution, the government has devised supply augmented and demand management strategies. The supply side management deals with increasing the availability of fuel wood through distribution of free seedlings, plantations, supply restrictions, and enforcement of property rights. The demand side management deals with reducing the demand for biomass energy sources by promoting alternative modern fuels, promoting income growth and increasing the availability of fuel saving technologies such as improved biomass cooking stoves (Cook et al., 2008). Large scale distribution of improved stoves will help reduce pressure on biomass resources, increase land productivity by reducing crop residue and dung usage for fuel, and improve family health. The intervention benefits women and children in particular, minimizing their high workloads to collect and supply fuel wood, and their exposure to flame hazard, high smoke emission and harmful pollutants (EPA, 2004).[1] It is assumed that if all rural and urban households (estimated to be about 14.44 million) in Ethiopia shift to the improved *Lakech* and *Mirt* stoves[2], a saving of about 7,778,800 tones of fuel wood which requires clear cutting of 137,192.24 ha of forest will be achieved on an annual basis (EPA, 2004). This implies that

[1]The World Health Organization estimates that, each year, 1.6 million women and children in developing countries are killed by the fumes from indoor biomass stoves (IEA, 2004).

We are very grateful to Ato Melesaw Shanko, managing director of MEGEN Power Ltd, and W/t Hiwote Teshome from GTZ for making available the data analyzed in this paper. We also gratefully acknowledge their kind explanation for questions related to improved biomass cook stoves in Ethiopia. Thanks also go to Dr. Alemu Mekonnen who helped us in facilitating the process of getting the data used for this paper.

[2]Lakech and Mirt are local words which mean ‘excellent’ and ‘best’, respectively.

sufficient distribution of these improved stoves will have significant contribution to save the biomass resources of the country in general and forest resource in particular and to combat land degradation and mitigate the effects of drought (EPA, 2004).

By recognizing the benefits of improved stoves, a number of governmental and non-governmental institutions have been involved in the development and dissemination of different types of biomass stove technologies since early 1970s in the history of Ethiopia (EPA, 2004). However, the efforts by these institutions to disseminate various types of fuel saving technologies have faced different problems at different times. Some introduced improved biomass cook stoves were not successful due to problems related to the stove itself (technical problems), lack of understanding of consumer's taste, lack of appropriate promotion strategy, etc. Most of these inferences are based on qualitative assessments by various stakeholders and scholars working on the area of natural resource conservation and energy. Moreover, the available limited studies on technology adoption in general and improved biomass cook stoves technologies in particular in most developing countries have generally focused on applying the limited dependent variable models such as probit or logit models. Although informative, these types of specifications are static and ignore the dynamic nature of the adoption process. That means, the binary dependent variable (adoption or non-adoption), which is commonly applied in empirical works, does not pick up adoption over time, as it does not allow for household's different waiting times. In general, the available studies failed to examine and understand why some households take some time to adopt the technology while others are quick to adopt and exploit the benefits of using the technology. Therefore, this paper has tried to address this gap and employs a duration analysis. To our knowledge, this technique is applied for the first time in fuel saving technology adoption studies. The next section deals with explaining the methods of analysis. Section three presents the data and some descriptive statistics. The results of the empirical analysis are presented in section four. The last section is the conclusion.

2. Duration analysis

Analysis of duration data is often referred to as survival analysis. This term is mostly used in the medical research, analysis of child mortality, and unemployment. It has also been applied in the area of technology adoption (i.e. Hannan and MacDowell, 1984; Dadi et al., 2004 and Burton et al., 2003). The purpose of Duration Analysis is to statistically identify those factors which have a significant effect (both positive and negative) on the length of a spell. A spell starts at the time of entry into a specific state and ends at a point when a new state is entered. For details on duration analysis see Kiefer (1988) and Green (2003).

The presence of unobserved heterogeneity leads to bias in the estimates of duration dependence. Following Gutierrez (2002), we fit a Weibull regression model with gamma-distributed heterogeneity using the frailty (gamma) option to streg. One can estimate frailty models and test whether unobserved heterogeneity is relevant using likelihood ratio tests based on the results from a likelihood ratio test that STATA reports.

3. Data and descriptive statistics

3.1. The nature and source of data

The data for the empirical analysis come from the survey on 'Mirt Biomass Injera Stoves Market Penetration and Sustainability' study conducted by Megen Power Limited in 2009. The survey was conducted in Amahra, Oromiya and Tigray Regions. Three towns from each region were selected for the survey. The sample size for each region and town was determined proportionately based on the total number of households. Finally, based on sampling frames (lists of households) obtained from the respective Kebeles[3], households were selected using a simple random sampling technique. Accordingly, Oromiya region was allocated 667 households (42.3%) followed by Amhara with 580 households (36.8%) and Tigray with 330 (20.9%). Therefore, the total number of sample households was 1577.

3.2. Description of covariates and descriptive statistics

Table 1: The descriptive statistics of covariates of fuel saving technologies and their expected signs (N=1557)

Variable[4]	Mean	S.D.	Min	Max
GENDER(Gender of household head) (-)	0.68	0.47	0	1
AGEHH (age of household head at the time of the survey)(+)	44.88	13.50	18	102
EDUCATION				
EDilliterate (if the household head is illiterate)(-)	0.21	0.41	0	1
EDreadelm (if the head can read and write or grade (1-8)(+)	0.42	0.49	0	1
EDsecond (if the head is between grade 9 & 12)(+)	0.20	0.40	0	1
EDhigher (if the head has a certificate or above)(+)	0.17	0.37	0	1
CHILD15(No. of children and youths whose age ≤ 15 (+)	1.75	1.54	0	14
ADULTS15(number of adult members of the family)(+/-)	3.38	1.87	1	15
HOWNERSHIP(Ownership status of the house, 1 if privately owned and 0 otherwise)(+)	0.72	0.45	0	1
COOKINGPLACE (1 if the HH has a separate kitchen, 0 otherwise)(+)	0.75	0.44	0	1
INCOME (+)				
MONINCOME1(if monthly income is less than 500 Birr*)	0.57	0.49	0	1
MONINCOME2 (if Monthly income is between 501 & 1499)	0.30	0.46	0	1
MONINCOME3 (if monthly income is between 1500 & 2499)	0.09	0.29	0	1
MONINCOME4 (if monthly income is above 2500)	0.04	0.20	0	1
DELEMITAD (dummy for electric Mitad) (-)	0.08	0.27	0	1
DMETALSTOV (dummy for Metal stove)(-)	0.48	0.50	0	1

NOTE: The signs on the second parenthesis show the expected sign. Birr is the national currency of Ethiopia and the exchange rate was 1 USD ≈ Birr 12.615 during the survey period

The majority of households are highly dependent on biomass energy sources for baking *injera* which is the main staple food in most parts of the country. The descriptive statistics in table 1 above show that only 7.8% of the sampled households use electricity for baking *injera*. More than 85 % of the household heads who are using electric *Mitad*[5] have secondary education or above. This may suggest that education is important for households to move up the energy ladder.

[3]Kebele is the lowest administrative unit in Ethiopia.
[4]Except for the variables AGEHH, CHILD15 and ADULT15, the rest are dummy variables. This is because of the nature of the data. For example, since the data do not have information on income as a continuous variable, we considered it as a categorical variable.
[5]The preparation of the traditional pan-cake like Ethiopian food, *injera*, requires an appliance known as Mitad. 'Mitad' is a clay-made circular pan used for baking '*injera*'

The dependent variable used in the analysis was the time (in years) households waited before adopting Mirt and Lakech improved stoves, measured by the number of years elapsed since their introduction, which was taken to be in the year 1991 and 1994 for Lakech and Mirt biomass cook stoves, respectively. For those households who had not yet adopted, the duration was right-censored at the year of data collection.[6] That is, we know the period of introduction of the technology (the beginning of the duration), but we do not know the end for some observations. The start date is the time when the improved biomass cook stoves were first introduced and the exit date, or the end of a spell, is the time a household adopts the fuel saving technology (Mirt improved biomass cook stove or Lakech Charcoal stove).

4. Results of duration analysis

4.1. Non parametric results

When the data is censored the density and cumulative distributions are not appropriate. An alternative non parametric approach called Kaplan Meier-Estimator has been developed for non-parametrical estimation of survival functions and the related distributions. This is a non-parametric approach, making no assumptions regarding the underlying distribution of survival times. The figure below shows the survival functions for the Mirt biomass *injera* stoves by income level. The survival function for income category 1 is higher than category 2, which in turn is higher than category 3. T he survival function for income category 1 suggests that households in the lower income groups have higher probability of survival than those households from the relatively high income groups. We used both the logrank and Wilcoxon test to test whether the above graphs are statistically different or not. Both tests for equality of survivor functions show that we reject the null hypothesis of equality at 1% level of significance. In other words, we can reject the null hypothesis that the four groups face the same hazard of failure. The results of both tests are also the same for Lakech charcoal stove.

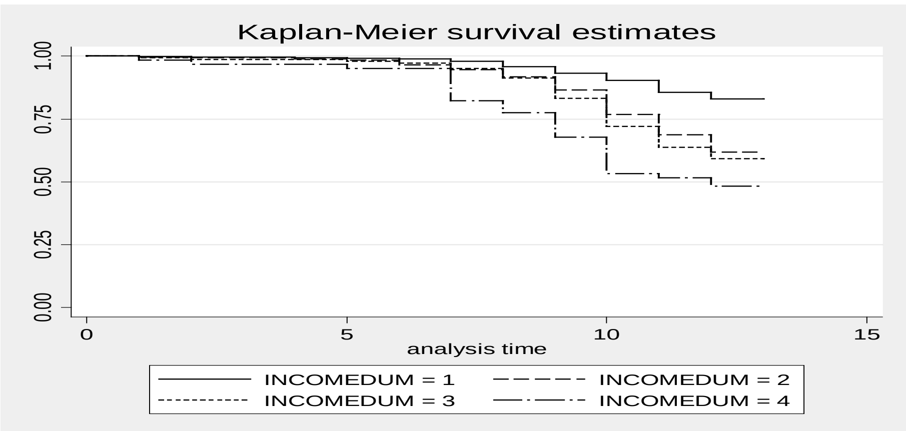

Figure 1. Survival function for MIRT improved biomass cook stoves

When we see the nature of the graphs it seems constant for the first 6 or 7 years. The Kaplan-Meier survivor function does not change indicating that there are no adoptions of the stove at the beginning, irrespective of the level of income. Then the values of the function fall quickly

[6]Lack of consistency in the various reports was our main problem in setting the period of introduction of the fuel saving technologies. Moreover, there is no information on the specific year for the introduction of each technology in each region. So we take the same year for all surveyed households.

from year to year. That means there are adopters of Mirt biomass cook stove every year. We did not report the survival function for Lakech charcoal stove since it is more or less similar with Mirt *injera* stove. That of Lakech charcoal stove falls quickly at a later stage (after 10 years) compared with Mirt.

4.2. Results of parametric regression

The results of the Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC) model selection criteria show that the Weibull model is preferred to the exponential model for both kinds of stoves. Hence we report the results of the Weibull model only. Another issue in duration analysis is the issue of unobserved heterogeneity. The 'theta' value reported in table shows that the frailty model is preferred to the reference non-frailty model according to the likelihood ratio test (for Mirt). For lakech charcoal stove, we estimated without taking the issue of hetrogenity since convergence was not achieved. Table 2 presents the results of the Weibull estimation for Mirt and Lakech stoves.

Table 2: Determinants of covariates of Mirt injera and Lakech charcoal biomass cook stove

	MIRT			Lakech		
Variables	Coef.	S. E.	*p*>z	Coef.	S.E.	*p*>z
GENDER	-0.321	0.151	0.034	0.114	0.111	0.307
AGEHH	0.006	0.006	0.296	-0.036	0.005	0.000
EDreadelm	0.636	0.220	0.004	-0.039	0.138	0.777
EDsecond	1.240	0.253	0.000	-0.015	0.164	0.927
EDhigher	1.085	0.267	0.000	0.156	0.172	0.365
CHILD15	-0.042	0.040	0.292	-0.043	0.031	0.165
ADULTS15	0.088	0.033	0.008	0.069	0.024	0.005
HOWNERSHIP	0.296	0.153	0.053	0.117	0.109	0.286
DELEMITAD	0.206	0.198	0.297			
DMETALSTOV				-0.906	0.107	0.000
COOKINGPLACE	0.486	0.170	0.004	-0.053	0.111	0.634
MONINCOME2	0.695	0.152	0.000	0.378	0.111	0.001
MONINCOME3	0.692	0.219	0.002	0.351	0.165	0.033
MONINCOME4	1.303	0.297	0.000	0.541	0.215	0.012
DTigray	-1.184	0.216	0.000	-0.045	0.165	0.786
DAmhara	-0.447	0.137	0.001	0.044	0.102	0.668
_cons	-11.995	0.765	0.000	-11.391	0.523	0.000
/ln_P	1.287	0.071	0.000	1.481	0.039	0.000
/ln_the	-0.343	0.610	0.574			
P	3.620	0.257		4.398	0.173	
1/P	0.276	0.020		0.227	0.009	
Theta	0.710	0.433				

Likelihood-ratio test of theta=0: chibar2(01) = 3.05, Prob>=chibar2 = 0.040

In the Weibull model, P >1 means that the hazard is monotonically increasing. That is the observations are failing at a faster rate as time goes on. The value of P for Lakech charcoal stove is also greater than one, showing that the hazard, like in the case of Mirt, is monotonically increasing. Stata also estimates the log of P (for computational reasons) and provides a test of the hypothesis that the log of p is equal to zero (which is equivalent to testing for P=1), which is rejected as indicated in the table above. That means the test also rejects the null hypothesis of no duration dependence; i.e log of P is equal to zero.

Note that a negative value of a coefficient β implies that the variable increases the time until adoption whereas a positive coefficient means that the times taken to adopt the fuel saving technology were shorter. Our result shows that education will speed up the adoption of the Mirt biomass *injera* stove compared with illiterate households. Surprisingly, education has no effect on the adoption decision of Lakech charcoal stove. For Lakech charcoal stove income is more important than education. Compared with households earning monthly income of Birr 500 or less, the probability of adopting Lakech charcoal stove increases for those households whose monthly income is 501 and above. The effect of income on the speed of adoption of Mirt biomass *injera* stove is not different from Lakech charcoal stove. The result implies that the design and price of new improved biomass stoves should take into consideration the capacity of households to pay for it. This is very important given the nature of households who are highly biomass dependent. Poor households are usually dependent on bi omass sources for cooking. In general, the higher the income, the higher the probability of adopting improved stoves in urban Ethiopia. According to Jones (1989), cited in Barnes et al. (1994), middle-income families have adopted improved stoves far more quickly than poor families in most African countries. In our case, even high income households are using the improved biomass stove. This also shows that households may not necessarily shift to other better sources of energy as their income increase, as postulated by the energy ladder hypothesis. This is because the process depends on many other factors such as affordability, availability, and cultural preferences.

The estimated coefficient for the variables 'ownership of private house' and 'separate kitchen' suggests that households who possess these basic facilities are more likely to adopt Mirt Biomass *injera* stove. Mirt is a domestic appliance which requires some space and larger in size than many modern and improved-biomass cook stoves. Hence, its installation and proper utilization requires access to basic facilities (Shanko et al., 2009). However, these variables do not have any significant effect in the case of Lakech charcoal stove. This is for the simple reason that the stove is simple and easily mobile. Similarly, Lakech does not require separate kitchen. It is usually used in the main house since it is small, light and convenient for cooking. As a result, the ownership of house and possession of separate kitchen may not be significant factors in adopting Lakech charcoal stove.

The negative sign of the variable 'Gender' suggests that the conditional probability of adoption of Mirt Biomass stove declines if the household head is male. The result is expected because female headed households can appreciate the importance of the stove more than male headed households. This variable is, however, not significant in the case of adoption of Lakech charcoal stove. Age of the household head is negatively related to the speed of adoption of Lakech charcoal stove suggesting that younger households are more likely to adopt the technology compared with households with older heads. The number of adults is positively and significantly correlated with the speed of adoption of both types of stoves. The number of children and youths with age less than 15 does not affect the speed of adoption of both types of stoves. This result may not be reliable as the variable includes household members whose ages are less than 15 years old. The data do not have separate information for children and youths. It is known that availability of children (less than 5 years) usually increase the probability of adoption of the improved biomass stove technologies.

The impacts of substitute technologies were also examined. Electric Mitad is considered as a substitute for Mirt *injera* stove. Metal charcoal stove is a substitute for Lakech charcoal stove. The coefficient for electric Mitad is not significant suggesting that households are not using electric Mitad for baking *injera*. The reason might be the relative cost of using electric Mitad is so expensive compared with Mirt *injera* biomass cook stove. The availability of metal charcoal stove, however, negatively and significantly affects the probability of adopting Lakech charcoal stove. Given the better performance of Lakech charcoal stove over that of Metal charcoal stove, we need to understand why households with metal charcoal stove take longer time to adopt the Lakech charcoal stove than those without metal charcoal stove. The role of marketing and promotion strategies may be significant here. We need to design marketing strategies that attracts households who already possess other kind of stoves, serving the same purpose.

Location variable shows that the speed of adoption of Mirt *injera* stove decreases for a household in Amhara and Tigray region compared with households residing in Oromiya region. We would have expected a different sign as the level of biomass in these areas is usually low (relatively degraded compared with Oromiya region). The result may be justified by the fact that households in Oromiya region are better exposed to the technology than households in Amhara and Tigray regions. Moreover, differences in other factors such as price and level of involvement of NGOs could result in differences in the adoption decision of households between the regions.

5. Conclusions and policy implications

This paper deals with one of the demand side strategies, distribution of improved biomass cook stoves, which will help reduce pressure on biomass resources, save fuel, reduce time for cooking, and reduce the risk of fire hazards. The paper tried to find out the determinants of adoption of two different types of fuel saving technologies (Mirt and Lakech) in Ethiopia by using data collected from selected towns in three regions of the country. We applied a duration analysis to examine the impacts of different socioeconomic variables on the speed of adoption of both types of stove technologies.

The result of the analysis shows that income level is a significant factor in the adoption decision of the improved biomass cook stoves in urban Ethiopia. This may suggest that households will not shift to other better sources of energy as their income increase, as postulated by the energy ladder hypothesis. Moreover, since poor households are highly dependent on biomass sources for cooking, the design and price of new technologies should take into consideration the interest of the lower income groups.

Education (increasing awareness of the people) might increase the probability of adopting the Mirt biomass *injera* stove. We also found possession of Electric Mitad (a technological substitute for Mirt *injera* stove) does not have any effect on the adoption decision of Mirt biomass cook stoves. This may be due to the better performance of Mirt in reducing the energy cost of preparing the staple food, *injera*. Therefore, ownership of electric Mitad does not necessarily mean that households will substitute it for Mirt. This requires the attention of policy makers or energy planners to further assess the potential impact of electric Mitad on household's overall welfare and biomass use (forest pressure). However, ownership of Metal charcoal stove is negatively correlated with the adoption of Lakech charcoal stoves. This may suggest that there is a need to reconsider the promotion strategy given the better performance of Lakech charcoal stove over Metal charcoal stove. The findings further show that access to basic facilities such as private house and separate kitchen for cooking increases the probability of adopting Mirt biomass improved stove. Given the importance of the improved biomass stoves in saving biomass, money, reducing indoor air pollution, etc. future study should give more attention to collecting more information such as prices and subsidies (if any) and examine their impact on the adoption decision. Second, this study examined the adoption of improved stoves technologies, but not the efficient use. We need to see how much fuel wood and charcoal were saved due to these improved biomass cook stoves. Some studies (for ex, Muneer and Mohamed, 2003) also shows that convenience of new stoves over the traditional stoves has increased consumption of fuel wood or charcoal (rebound effect). Future study on this area should also address this issue.

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Energy performance of Portuguese and Danish wood-burning stoves

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Abstract: In Europe, considerable amounts of renewable energy resources are used for residential heating with wood-burning stoves, which can cause considerable energy losses and environmental impacts. A better understanding of its operating characteristics will permit to improve the buildings energy efficiency and indoor climate, and to reduce the emission of air pollutants to the environment.
This study aimed to analyze the operating conditions of a Portuguese made stove and compare it with the most efficient Danish made stoves tested at the Technological Institute.
The combustion experiments were carried out through the measurement of the main operating parameters: flue gas temperature and composition, combustion air flow rate, and fuel consumption rate. The results showed that the appliances emitted energy intermittently, with a mean heat flow rate into the indoors of 5 kW_{th}, representing mean thermal energy efficiencies of 70% and 76%, respectively for the Portuguese and Danish stoves. The Carbon Monoxide concentration in the flue gas was lower than 0.4 % (v/v; 13% O_2) for all stoves.
There is still a need for more accurate knowledge the relationship between the energy and the environmental performance of the appliances. A dynamic analysis of the problem will permit to increase the households energy savings.

Keywords: *Wood-burning stoves, thermal energy efficiency, heat flow rate, flue gas composition.*

Nomenclature

η	energy efficiency	%
h_a	ambient air specific enthalpy	$kJ\ kg^{-1}$
m_b	fuel consumption rate	$kg\ h^{-1}$
n_i	molar flow rate	$mol\ s^{-1}$
Q_g	thermal energy gains	kW
T_{EG}	flue gas temperature	K
w_{wF}	fuel moisture	$kg_{H2O}\ kg^{-1}$
c_{pi}	mean calorific capacity	$kJ\ mol^{-1}K^{-1}$
h_{fg}	latent heat of H2O	$kJ\ kg^{-1}$
m_{ca}	combustion air flow rate	$kg\ h^{-1}$
PCI	lower heating value	$kJ\ kg^{-1}$
Q_l	thermal energy losses	kW
T^0	reference temperature	K

1. Introduction

Nowadays, a great amount of energy is used for residential heating and even in the European modern houses is possible to save considerable amounts of thermal renewable energy. Among the existing sustainable energy systems are the wood-burning stoves that are still commonly used for space and sanitary water heating.

In Portugal, it is estimated that 32% of the houses are using either wood-burning stoves or open fireplaces for space heating, whereas in Denmark 26% of the households are using wood-burning stoves being estimated that wood share is estimated to 18% of the total amount of fuel used for heating in single family houses, and amounts to 60 % of renewable energy contribution in this category of houses [1;2].

However, these equipments can reveal low thermal energy efficiency when operated under deficient conditions also causing considerable impacts in the environment. During the last few years there was an effort to improve both the energy and environmental performance of such equipments, through the establishment of national and international guidelines and standards.

The international standard EN 13240 for "room heaters" and EN 13229 for "insert appliances and open fire places" establish requirements concerning the thermal energy efficiency and operating conditions of the equipments [3;4]. The standards determine the laboratory test procedures and required emission factors concerning the appliances certification. At the same time the new version of the Energy Performance Building Directive (EPBD 2010) is asking the member states to implement an integrated building certification system and that means the energy analysis must consider both the thermal efficiency of the households and its elements, through the establishment of labeling systems for the building equipments. Moreover, the certification of energy systems should take into account its impacts on thermal comfort and indoor air quality [5].

Some countries have been developing national standards for wood-burning stoves, namely the Swan Labeling created in the Nordic countries that present tighter requirements concerning for example the emission factors of total particle matter (PME). In Denmark, most stove manufactures are applying this labeling system through tests in certified laboratories such as the testing laboratory of the Technological Institute [6]. During the last decades, these regulations have been adopted by European stove manufacturers and sellers and this has contributed to the improvement of the energy performance of the marketed wood-burning stoves. The problem and hypothesis is that the increase of the equipments thermal efficiency can in certain extend be related to a decrease in the environmental performance of the biomass stoves, namely concerning its impacts in both the ambient and indoor air quality [7;8].

There is still a lack of knowledge about the relation between the wood-burning efficiency, the heat transfer processes from the combustion chamber to the indoors and the emission of pollutants to the environment. In this context, the aim of this study was to analyze and compare the operating conditions of wood-burning stoves made in two different European countries with distinct energy demands but where the use of wood-burning stoves are still a solution for residential heating. The objective is to contribute to the increase of knowledge about processes involving wood-burning stoves in order to identify practices that can promote higher energy savings in buildings and a cleaner wood-burning process, as well as the creation of guidelines for manufactures, sales men and stove users.

2. Methodology

The present study was carried out in a laboratory test installation at the University of Aveiro (Portugal) projected and implemented for monitoring several operating parameters of the typical Portuguese made wood-burning stove. The project carried out at the Portuguese university aims to increase the knowledge about the test methods used to evaluate the energy and environmental performance of such appliances. The experimental results obtained were compared with the data acquired during similar tests carried out for a Danish made stove - tested at the testing laboratories at the Technological Institute (Denmark), following the European standard EN13240. In both cases, it was considered that the studied equipments are representative of the commonly used wood-burning stoves in Portugal and in Denmark, respectively. The biomass used in this comparative study was wood commonly collected in the Portuguese forest (used for residential wood-burning), for example the ash tree (*Fraxinus Angustifolia*) and for the Danish stove birch wood following the requirements of the EN

13240. The general information about the experimental conditions used are presented in the Table 1.

2.1. Experimental installation and test conditions

In Portugal, the experimental installation integrated a wood-stove (insert appliance) with a mechanical ventilation system used for forced convection, a set of on-line gas analyzers, temperature sensors, a combustion air flow meter, a weight sensor and an automatic control and data acquisition system operated by a computer. During the experiments the following parameters were monitored continuously: the temperature in the combustion chamber and on the stove walls, the flue gas temperature at several locations along the reactive system (at the chimney entrance and exit), the flue gas composition, the combustion air flow rate and the rate of biomass combustion.

The temperature in the different points along the experimental installation was measured with K-type thermocouples while the flue gas composition was determined applying the following continuous measurement methods: a paramagnetic analyzer (ADC model O_2-700 with a Servomex Module) for O_2, and a non-dispersive infrared analyzer (Environnement, MIR 9000) CO and CO_2. The composition of the combustion gas was measured in the chimney at 2.8 meters above the combustion chamber exit. The combustion air flow rate was determined using a mass flow rate meter (Kurz, series 155) while the biomass consumption was monitored through a weight sensor (DS Europe 535 QD – A5) [9].

In Denmark, the stove was tested under the operating conditions established by the European standard, through the determination of the CO and CO_2 concentrations by means of IR spectroscopy using an ABB AO 2020 gas-analyzer. The flue gas temperature and other temperatures were measured with K-type thermocouples. The test laboratory is accredited by the European standard EN 17025 by DANAK (with accreditation number 300 and notified body with notification number 1235). The measurements in the flue gas of both the CO and CO_2 concentrations were carried out at 1.43 meters above the combustion chamber using the test section specified by the EN 13240 Fig. A.9.

Table 1. Operating conditions during the wood-burning stoves monitoring (mean values for the 60 minutes period).

Appliance (country)	Type of appliance	Fuel consumption (kg h^{-1})	Combustion air flow rate ($Nm^3\ h^{-1}$)	Forced convection rate ($Nm^3\ h^{-1}$)
Portuguese	Insert	1.7	29.97	40.00
Danish	room heater	1.6	27.30	N.A.

The laboratory experiments were carried during the heating season of 2010 using typical operating conditions for the studied wood-burning stoves. The duration of each laboratory experiment (wood-burning cycle) was 60 minutes, according to the European standards EN 13240 and EN 13229, respectively for the Danish (wood stove) and Portuguese (wood stove, insert appliance) equipments.

The experimental results obtained were considered in both the mass and energy balance to the wood-burning stoves in order to calculate the thermal energy efficiency of the appliances during a typical wood combustion cycle.

3. Results

The behavior of the monitored operating variables (flue gas temperature in the combustion chamber, both the CO and CO_2 concentrations in flue gases, and mass of fuel in the grate of the stove) during the combustion of biomass is shown in the Figures 1 and 2, respectively for the Portuguese stove and Danish stoves.

The combustion of wood in both equipments shows some major differences. For example, in the Danish stove both the flue gas CO_2 concentration and temperature increased in the initial stages of the combustion cycle, whereas in the Portuguese stove those variables achieve maximum values only after 20 minutes after to the fire lightning (Figures 1 and 2).

An increase in the flue gas CO concentration at the initial stages of combustion was observed for both stoves, although in the case of the Portuguese insert appliance the CO concentration value is higher than for the Danish stove, and lasts for a longer time period. For both cases it is possible to observe an increase in the concentration of CO in combustion gases during the final stages of wood combustion (Figures 1 and 2).

The temperature in the combustion chamber varied between 200 and 600 ^{o}C in the Portuguese wood stove – similar to the temperatures expected for the Danish stove based on thermal calculations.

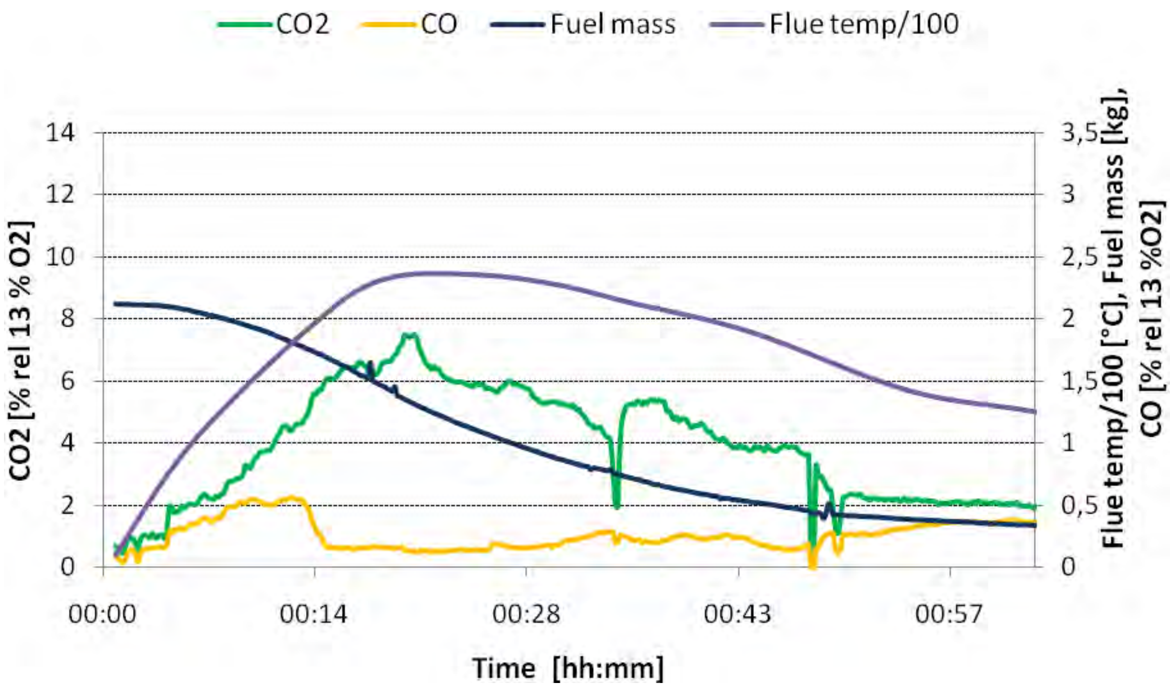

Figure 1. Fuel consumption, CO and CO_2 concentration (13% O_2, dry gases) in the exit flue gas, and temperature of the flue gas over the test period in the Portuguese stove.

The Figure 1 shows that there was a rapid decrease in both the flue gas CO concentration and temperature, respectively 35 and 48 minutes after to light the fire in the stove. The first case is associated to the door opening after 35 minutes of sampling, due the verified problems with the combustion bed. The second situation is related to the automatism of the software sampling systems, since it was programmed for a certain period of measurements and as a consequence it was not registering any values at the 48 minutes time instant.

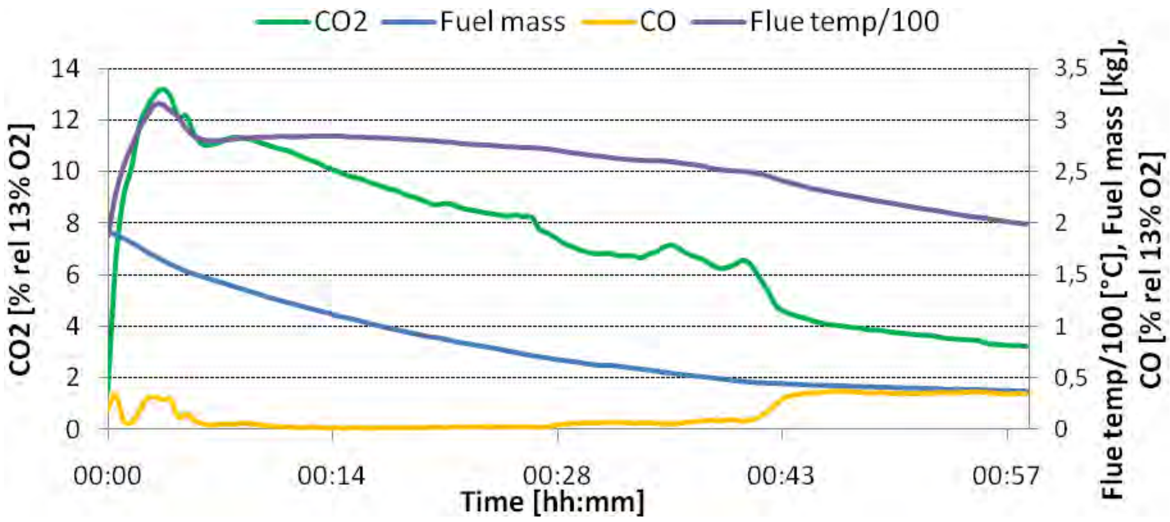

Figure 2. Fuel consumption, CO and CO_2 concentration (13% O_2, dry gases*) in the flue gas and temperature of the flue gas over the test period in the Danish stove.*

For the Portuguese stove, the mean CO concentration in the combustion flue gas over the test period was 0.27% (v/v, dry gases), while the mean CO_2 concentration was 3.6% (v/v, dry gases), and the mean flue gas temperature was 173 ºC. The biomass combustion rate was around 1.7 kg/h. Important is to point out that during the wood combustion experiment it was necessary to handle one of the wood logs in the stove grate in order to maintain the combustion process under satisfactory conditions; this handling interventions are reflected in Figure 1 by the decrease in both the flue gas CO_2 concentration and temperature around 35 minutes after the beginning of the wood combustion cycle.

For the Danish stove, the mean CO concentration in the flue gas was 0.10 % (v/v, dry gases) while the mean CO_2 concentration was 7.3 % (v/v, dry gases), and the mean flue gas temperature was 250 ºC. The biomass combustion rate was around 1.6 kg/h.
Important is to point out that, the gas flow rate throughout both of the stoves is varying in same range (25 to 30 $m^3 h^{-1}$).

The mean thermal efficiency of both wood-burning stoves was determined for each testing period (60 minutes) in order to compare the energy performance of the studied equipments.

The thermal efficiency was calculated considering two European standards, namely the EN 13240 (insert appliances) and EN 13299 (room heaters) that establish a minimum testing period of 45 minutes [3;4]. The calculation of the energy efficiency of each stove was carried out through an energy balance to the equipments. The system boundary considered for the calculation of the energy loss from the stove to the outdoors was the top of the chimney in both equipments.

The amount of energy losses was exclusively associated to the sensible and latent heat of combustion gases leaving the chimney.

The Equations 1 to 3 were used for the calculation of the thermal efficiency of the two stoves. The obtained results are presented in Table 2.

$$\eta = \frac{\dot{Q}_g - \dot{Q}_l}{\dot{Q}_g} \cdot 100 \tag{1}$$

$$\dot{Q}_g = \dot{m}_b \cdot PCI_b + \dot{m}_{ca} \cdot h_a \tag{2}$$

$$\dot{Q}_l = \sum_{i=1}^{i=n} \dot{n}_i \cdot \bar{c}_{p_i} \cdot \left(T_{EG} - T^0\right) + m_b \cdot w_{wF} \cdot h_{fg} \tag{3}$$

Table 2. Nominal heat output and energy efficiency of the Danish and Portuguese tested wood stoves.

	Danish *	Portuguese **
Nominal heat output (kW)	5.2	5,2
Nominal burn time (min.)	60	60
Efficiency (%)	76	70
Mean flue gas temperature (ºC at 20ºC ambient temp.)	250	180

**) Claimed values from the CE-dataplate – Tecnological Institute.*
***) Experimental values obtained at the University of Aveiro laboratory.*

4. Discussion and conclusions

The knowledge about the energy and environmental performance of wood-burning stoves is still insufficient and there is a need to improve them concerning the sustainability of the integration of such a kind of energy conversion systems in the modern energy efficient households.

The development and implementation of testing methods and laboratories is a step stone towards a better knowledge about the operating conditions of such equipments, and the consequent improvements on both its energy efficiency and environmental performance all over Europe.

During the last few years, there was an effort to improve the thermal efficiency of the wood combustion appliances from 50% to more than 80%, however, it is well known that the use of such energy systems continue to cause considerable impacts on the environment.
The presented work revealed that the thermal efficiency of the studied stoves varied between 70% and 76%, respectively for both the Portuguese insert appliance and Danish stove; the nominal thermal heat output considered was around 5 kW_{th}. Regarding the energy efficiency, it can be concluded that the two equipments have efficiencies in the same range, even though the combustion characteristics are pretty uneven, as indicated by the behavior of the operating variables along the time and its mean values. The background is that the energy efficiency is

derived from the ratio CO_2 concentration / Flue gas temperature. So offsetting the two parameters in parallel upwards or downwards will return no change in the actual efficiency.

Normally, one cannot avoid a CO peak in the beginning of the burn cycle (devolatilization), and neither a moderate increase of CO concentration at the end of the burn cycle, due to incomplete combustion (associated to low temperatures) once the flame did extinguish.

However, the presence of CO concentrations varying from 0.2 to 0.4 % (Portuguese insert appliance) in between the peaks at the beginning and at the end of the combustion cycle indicates incomplete combustion conditions, also indicated by the relatively low CO_2 concentration (inserts having an air excess rate of approximately 250% indicates that theoretical mean CO_2 concentrations of up to 8.3 % are achievable).

Thus it ought to be possible to improve the combustion conditions, leading to higher CO_2 concentrations, higher flue gas temperature (and consequently more or less unaffected thermal efficiency), and lower CO concentrations, for benefit of the external environment, as the stove would emit less organic carbon residuals in the flue gas.

However, in comparing the two appliances one should bear in mind that the Danish stove was tested at ideal test conditions and settings during a type test, whereas the Portuguese insert appliance was tested in a university environment (testing conditions similar to that established by the European standard), and considering normal user operating conditions.

As a consequence, there is still a demand for improving the test methods and developed a mathematical tools (numerical models) that will integrate and describe both the combustion and heat transfer processes involved. The use of numerical models will permit to identify solutions to save considerable amounts of energy in households, for example through both a more efficient energy utilization and storage.

The develpment of a new energy simulation computerized tool will help the manufactures and technical consultants to design more efficient wood-burning stoves adapted to different types of building constructions and wood fuels all over the world.

Aknowlegements

The experimental work developed in Portugal was funded by the Portuguese Science and Technology Foundation (FCT) through the project with reference PTDC/AGR-CFL/64500/2006.

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Field study of energy performance of wood-burning stoves

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Abstract: In Europe, large amounts of renewable energy are lost when residential buildings are heated by means of wood-burning stoves. Still, too many wood-burning stoves are energy inefficient, the knowledge of their operation is insufficient and the interaction between the stove and the house to be heated is not adequate. This applies in particular to old wood-burning stoves in old houses. However, this field study, the first ever dealing with new stoves in new houses, revealed that even in new houses with new wood-burning stoves of today the interplay between stove and house can still be improved as well as the modern wood-burning stoves could be designed to perform even better. However, calculation of heat balances and measurement of temperature in a series of single family houses showed that wood-burning stoves actually contribute considerably to the heating of new houses, although their intermittent working led to overheating and conflicts with the primary heating system. Moreover, measurements of particles showed that emission of fine and ultrafine particles to the indoor climate can easily occur.
The study made it clear that information and guidelines to be disseminated among stove manufactures, salesmen, and home owners are needed regarding dimensioning, installation of wood-burning stoves and their lighting and operation as well.

Keywords: *Residential heating, wood-burning stoves, energy performance, particle emission, ultrafine particles*

Although wood-burning stoves are mostly used as a supplementary heating source, they represent a notable part of the carbon-free heating. In Denmark, which has a well-developed gas and district-heating net, the share of wood is estimated to be 18 % of the total amount of fuel used for heating in single-family houses, and amounts to 60 % of the renewable energy contribution in these houses [1]. The large share of wood, mainly consumed in wood-burning stoves, can be ascribed to the fact that firewood is cheaper than other fuels and that Danish wood-burning stoves are popular due to their high efficiency, their certificates of low particle emission [2] and their design - not to forget their ability to create a cosy atmosphere. Therefore, when developing new models, the manufacturers have in turn focused on efficiency, environment and design. The focus on these elements has made it possible to meet the demands of a wide customer segment, including owners of new single-family houses with low energy demand.

So far, new single-family houses continue to have a decreasing demand of energy for heating. This is encouraged by the European Directive on the Energy Performance of Buildings (EPBD), which led to national legislation on better energy performance, i.e. better insulation and airtight building envelopes combined with ventilation systems with heat exchanger [3]. On this background, the aim of the field study was to:

- Investigate the energy performance of stoves in operation, the overall efficiency and utilisation of firewood.
- Determine the impact of wood-burning stoves used on the indoor environment in terms of particle pollution and thermal comfort.
- Give recommendations, guidance to manufacturers and users of wood-burning stoves.

1. Study design

A study design was chosen where seven residential buildings were selected for case studies. The criteria for selecting the houses were that they were built after 1995, i.e. within the period covered by the last two editions of the Danish Building Regulations and that they were equipped with a certified wood-burning stove. However, one house built in 1977 was included the study, because it was equipped with a masonry stove and because one elderly house would probably clarify the study.

A total of seven families with single-family houses hosted the surveys. The specifications concerning the selected houses are shown in Table 1. The experimental hosts were identified by addressing stove manufacturers and suppliers. This resulted in five cast-iron stoves, certified according to Danish Standard, four of which were certified according to the Nordic Swan standard [4]. Two masonry stoves built on location were not certified. Instead similar masonry stoves were known for their quality and tested for their high energy efficiency.

Table 1. Hosts for the field study with type of house and type of stove listed with certification of house and stove included. Building energy class A refers to the most energy efficient buildings. DS (Danish Standard) + Swan (Nordic eco-label) refers to certified clean and energy efficient wood-burning stoves.

Hosts	Type of house	Building year	Energy class	Type of stove	Certification
Espergaerde	detached	1977	D	masonry	(Solbyg)
Ringsted	detached	2006	B	masonry	(Helbro)
Hilleroed	detached	2001	C	cast iron	DS + Swan
Virum	detached	2007	B	cast iron	DS Plus
Værloese	row house	2008	B	cast iron	DS + Swan
Esrum I	detached	2009	A2	cast iron	DS + Swan
Esrum II	detached	2009	A2	cast iron	DS + Swan

2. Measurements

The experimental hosts were visited in the heating seasons 2008/2009 and 2009/2010 respectively. The houses in Ringsted and Virum were not included in the first series of measurements. In turn, Esrum II was not included in the second series of the field study. In the first series, particles, gases and air-change rates were measured, before, during and after lighting. In these cases, the host lighted the fire in the stoves. In the second series also particles, gases and air-change rates were measured. This time also the temperature close to and at some distance from the stoves were measured. To ensure uniform lighting, a stoking expert was engaged to perform the lighting in the second series. In addition, programmable data loggers (TinyTags) recorded temperature and humidity continuously for the following months.

Each of the hosts was interviewed and questionnaires were distributed. The interview was conducted in order to clarify the occupants' habits concerning their use of the stove, the family's experience with using the stove, techniques for lighting etc. The survey was aimed at quantifying technical issues, including consumption of firewood, the type of any primary heating, preferred room temperature and bathing habits, etc.

3. Energy performance

Energy performance has become the mantra of energy supply. Focus has been directed at electric appliances, cars and buildings, but also at the way we produce energy. This demand has reached the energy performance of wood-burning stoves as well. Their energy performance has bee increased and as a consequence the new wood-burning stoves have reached an efficiency rate of 75-80 %. At this level, however, the energy performance of wood-burning stoves cannot be seen in isolation from the building that is supplied. Therefore, the first move was to chart the heat balance of the system. The second move was to detect instances of overheating

3.1. Heat balances

For each of the houses involved in the field study, a heat balance was drawn up. One side of this balance gave the total of all inputs of fuel converted to a net heat production (excluding conversion loss). The other side of the balance gave the annual heat loss adjusted for the actual indoor temperatures, and the domestic hot water consumption. The total was termed gross heat consumption (including hot water etc.)

On the production side of the balance, the conversion of wood was rather uncertain. First the volume of firewood, the type of stack and the type of wood, included moisture content, must be known to estimate the dry firewood mass. Next, the heating value of the wood and the efficiency of the stove were needed for the calculation. Finally the extra heat loss caused by the additional air change of the wood burning must be taken into consideration, see Table 2.

Table 2. Firewood converted to heat production. The efficiency of the stoves is determined from test results field studies [5]. The calculation of the ventilation heat loss is based on the need of 11 m^3 air to convert 1 kg of dry wood.

Host	Firewood (kg)	Calorific value (kWh/kg)	Efficiency (%)	Ventilation loss (MWh)	Net heat contribution (MWh)
Espergaerde	2520	4.,1	80	0.16	8.1
Ringsted	980	4.1	85	0.06	3.4
Hilleroed	1750	4.1	75	0.11	5.5
Virum	350	4.1	70	0.02	1.1
Værloese	350	4.1	75	0.02	1.1
Esrum I	875	4.1	75	0.06	2.7
Esrum II	1400	4.1	75	0.09	4.4

Altogether the different fuels contributed to the net heat production of the houses as seen in Table 3.

Table 3. Merging the heat production of firewood with the heat production of other energy sources.

Host	Firewood (MWh)	District heating (MWh)	Natural gas (MWh)	Heat pump (MWh)	Net heat production (MWh)
Espergaerde	8.1		31.7		39.8
Ringsted	3.4	7.8			11.2
Hilleroed	5.5		9.9		15.2
Virum	1.1		15.3		16.3
Værloese	1.1		12.0		13.1
Esrum I	2.7			8.5	11.2
Esrum II	4.4			12.0	16.3

On the consumption side of the balance, the gross heat consumption was determined by the energy class of the house, as stated in the energy performance (EP) certificate. The net heat consumption is defined as the maximum of heat per square meter per year that is allowed to pass through the building envelope set off against heat gained from solar radiation and internal loads such as people and appliances. Applied to the area of the house this loss must be added to the hot water consumption and adjusted for a possible indoor temperature other than 20°C, see Table 4. The supplement for higher indoor temperature is 7-10 % per degree, lower for old houses and higher for new houses. The domestic hot water consumption was measured or stated to be 1 MWh per person.

Table 4. The gross heat consumption as a total of the standard loss for the building adjusted for indoor temperature and hot water consumption.

Host	Energy class	Maximum heat loss (kWh/ m^2)	Building area (m^2)	Net heat consumption (MWh)	Gross heat consumption (MWh)
Espergaerde	D	134	226	30.3	43.5
Ringsted	B	76	170	12.8	17.7
Hilleroed	C	76	188	14.1	18.8
Virum	B	65	175	11.4	15.7
Værloese	B	65	126	8.2	14.0
Esrum I	A2	65	132	8.6	13.3
Esrum II	A2	65	120	7.8	11.7

The resulting heat balance showed that in most cases the net heat production (excluded transformation loss) was lower than the expected gross heat consumption (included hot water consumption). This could be ascribed to low estimates of the amount of firewood consumed. However, in two cases the net heat production was higher than the expected heat consumption. In Esrum II this was presumably related to an inefficient heat pump, so that the yearly coefficient of performance was even lower that stated.

The energy balances also showed the share of heating resulting from wood burning as a total of the yearly energy production and as at total of the yearly consumption (see Figure 1). In these balances it was found that the share of heat production from wood burning was rather small. So far, an old house, like Espergaerde, with a masonry stove only had a wood-burning share of 20 %. Nevertheless, two new houses, Hilleroed and Esrum II reached a rather high share of 35 % and 26 % of the total energy consumption respectively. Still, the amount of wood used in Espergaerde was 2500 kg and by far the largest amount of wood used by any of the hosts. This showed that it was less demanding to cover the need for heating by use of a wood-burning stove in a modern house than in an elder house. By consuming a smaller amount of wood, a larger amount of fossil energy could be replaced and at larger amount of carbon circulation could be sustained. In that perspective it seemed promising to use firewood in new houses.

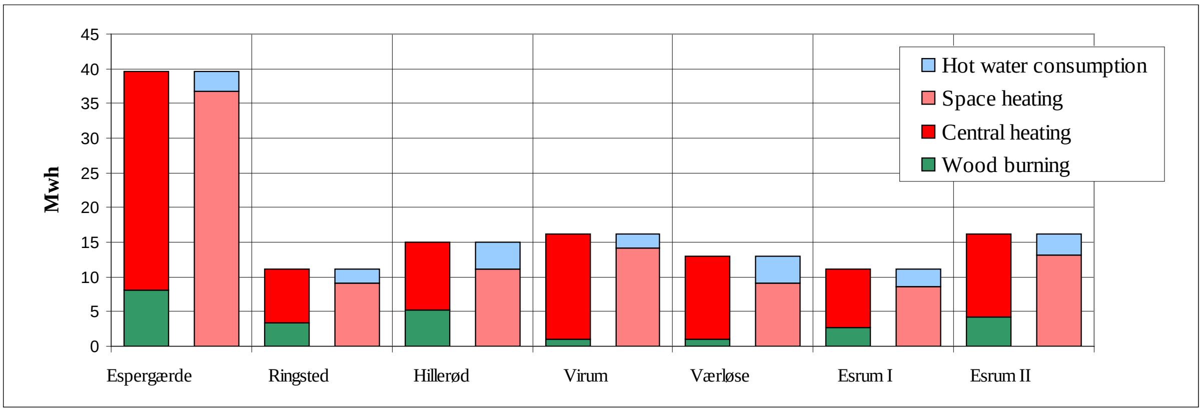

Figure 1. The heat balance based on the figures of net heat production, on one side divided into wood burning and central heating and on the other side into space heating and hot water production.

3.2. Over heating

An adjustment was made in the calculation of the gross energy to compensate for a possible indoor temperature other than 20°C. In any case an average higher than 20°C was found, and as a consequence an adjustment of 3 MWh per house on average was made (see above). This indicated that periods with high comfort temperature or even excessive temperatures might take place in houses heated by means of wood-burning stoves. To investigate the character of possible excessive temperatures, in the second period of measurement, the indoor temperature was logged every hour during the field measurements. In a few cases, temperature loggings were made in steps of two minutes. In short, the loggings showed that excessive temperatures, i.e. temperatures higher than 22°C often occurred. Usually the excessive temperatures happened once or twice a day during the heating season solely in houses with cast iron stoves. In contrast to houses with masonry stoves, the indoor the temperature in houses with cast-iron stoves often oscillated up and down once or twice a day, and sometimes more than 5 degrees in the heating season, see Figure 2.

The biggest adjustment for a high comfort temperature was made in the Espergaerde house. Here an average indoor temperature of 24.8°C was measured. However, in this house heated by masonry stove the temperature around the clock was rather constant.

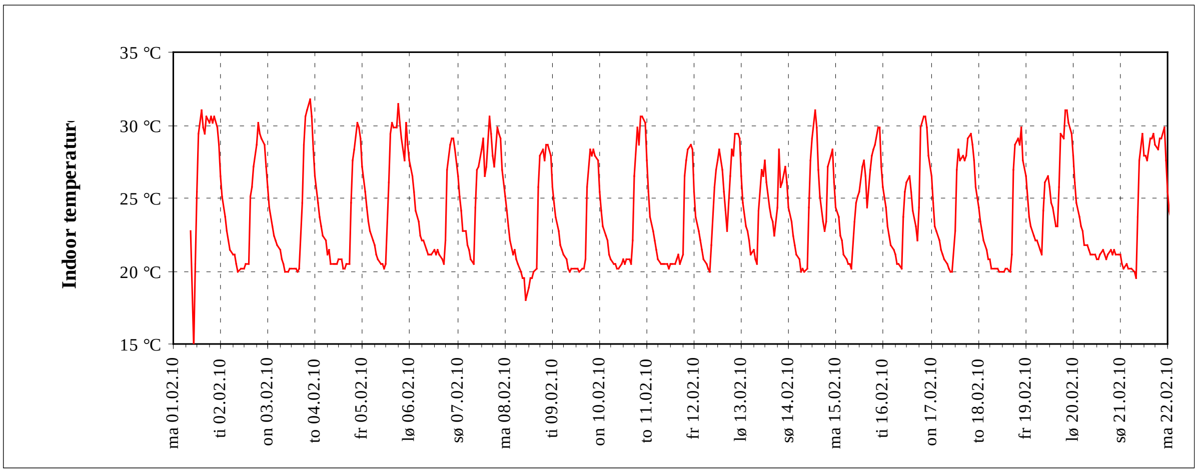

Figure 2. An example of temperature logging in an energy-efficient house carried out over 3 weeks in February 2010. The outdoor temperature in the period was just below 0°C. (Energy Class A).

3.3. Energy performance discussion

Comparing data from the measurements, the interviews and the questionnaires, it became evident that modern wood-burning stoves do function and to a large extent contribute to the heating, also in brand new houses. The advantage of masonry stoves is that they can distribute heat over a long period this way counteracting overheating. Surprisingly, the masonry stoves did not cover the biggest share of the heating, neither in the old house from 1977 (Espergaerde) nor in the new one from 2006 (Ringsted). In the first case the house had large energy consumption and in the second case, the house was equipped with floor heating. Combining stove heating and floor heating was usually less efficient.

4. Indoor emission of particles

Much research has been carried out to detect particle emission rates to the ambient environment. Through laboratory tests, and through measurement on the field is has been possible to set standards of particle emission from wood-burning stoves and to determine the environmental impact to neighbourhoods [6]. A topic neglected is that stoves emit particles to the indoor climate when being operated. Furthermore, among these particles are numerous of ultrafine particles, i.e. particles smaller than 0.1µm. Particles of that scale are suspected of being even more harmful to health than particles smaller than 2.5µm, which are the particles usually being measured. Therefore, the field study set out to look at how operation of a wood-burning stove could cause emission of ultrafine particles and release of gases.

4.1. Particle measurements

Measurements were carried out in two periods, the heating seasons 2009/10 and 2009/10. The measurements started by monitoring the background concentration of particles indoors and outdoors. Then the wood-burning stove was lighted to operate for 1 or 2 hours. [7; 8]. The concentrations of ultrafine particles were monitored by means of two condensation particle counters; one was placed close to the stove, while the second one was used for sampling the outdoor concentration. The two instruments facilitated real-time measurement of particle number concentration. The detection ranges of the instruments ranged between 0.02 and about 1.0 µm. Carbon dioxide, temperature and relative humidity were recorded as well. Finally a passive, multiple tracer gas technique, the so-called PFT technique (PFT: PerFluorocarbon Tracer) was used to measure air-change rates [9]. The duration of the PFT measurements in each house was one week.

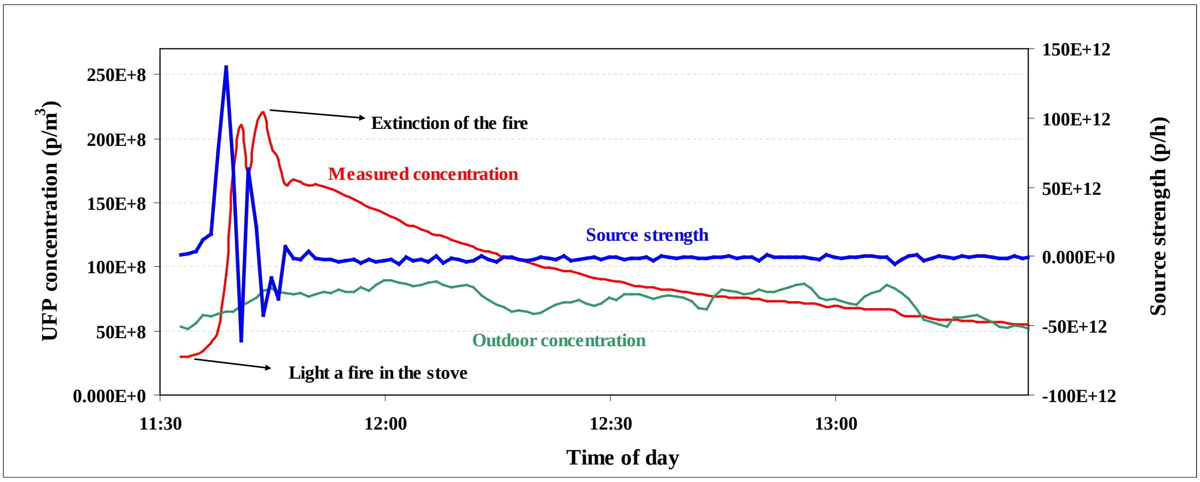

Figure 3. Typical picture of the development of ultrafine particles (UFP). In this case a large emission took place immediately after lighting a fire.

Figure 3 shows that the concentration of ultrafine particles fluctuated for the first 15 minutes after the stove was lighted. A mass balance model, previously applied to analysis of gaseous contaminant concentration, was used. The calculated maximum source strengths and maximum concentration for al measurements of ultrafine particles is shown in Table 5. The concentration of measured ultrafine was fist published in [7; 8].

Table 5. Calculated maximum source strength ($\dot{M}_{max}$), and maximum concentration (C_{max}) for the ultrafine particles studied.

Measured and calculated parameters	C_{max} (p/m^3)		$\dot{M}_{max}$ (p/h)	
	Series 1	Series 2	Series 1	Series 2
Espergaerde	$0.03 \cdot 10^{11}$	$0.24 \cdot 10^{11}$	-	$0.20 \cdot 10^{15}$
Ringsted	-	$1.55 \cdot 10^{11}$	-	$1.96 \cdot 10^{15}$
Hilleroed	$0.05 \cdot 10^{11}$	$0.11 \cdot 10^{11}$	0.00	$9.19 \cdot 10^{7}$
Virum	-	$0.99 \cdot 10^{11}$	-	$1.60 \cdot 10^{15}$
Værloese	$0.22 \cdot 10^{11}$	$0.80 \cdot 10^{11}$	$0.14 \cdot 10^{15}$	$0.44 \cdot 10^{15}$
Esrum I	$2.23 \cdot 10^{11}$	$2.16 \cdot 10^{11}$	$2.14 \cdot 10^{15}$	$1.46 \cdot 10^{15}$
Esrum II	$2.36 \cdot 10^{11}$	-	$0.03 \cdot 10^{15}$	-
Espergaerde	$0.02 - 0.05 \cdot 10^{11}$	$0.02 - 0.05 \cdot 10^{11}$	0.00	-

4.2. Particle emission discussion

During the field study it became clear that in both series, with and without an expert lighting the fire, considerable emission of ultrafine particles to the indoor air might happen, in particular at lighting the fire and adding more wood. But other causes were identified as possibilities for particle pollution, like use of fabric gloves, touching the air valve and suddenly indoor draught. Peak concentration of particles was measured during lighting of a new stove installed in a brand new house (Esrum I and II). One possible explanation for the emission of particulate matter could be a negative indoor-outdoor pressure difference due to the mechanical ventilation system. Moreover, both of the houses mentioned were new, presumably rather airtight and the stoves had chimneys with a height of about 5 meters indoors.

The house in Hilleroed formed an exception in the series of measurements. In this house no elevated concentrations of ultrafine particles were measured except from a slight increase when the side lining of the furnace was dismounted in order to demonstrate the convection principle. The increase was recorded to be a maximum concentration of $0.11 \cdot 10^{11}$, i.e. double background concentration.

5. Conclusion and recommendations

It still seems promising to use a wood-burning stove in new houses. By using small amounts of wood up till one third of the heating demand could be met by this renewable energy resource. However, the field study confirmed that it is still a challenge for the manufactures of wood-burning stoves to meet the decreasing demand of wattage. Still more efficient buildings call for scaling down of the wattage, if overheating is to be prevented in future design. In this perspective masonry stoves were found to be the most adequate to new houses (e.g. the Ringsted house). The challenge to manufacturers of cast-iron stoves is to develop stoves with smaller combustion chambers and a better capability for distributing the heat. Use of heavy materials, like masonry stoves, phase change materials or connection to water reservoirs, if not to floor heating system it self may be a way of meeting the challenge. Scaling down the stoves means scaling down the size of the combustion chamber. This however makes it even more difficult to obtain a clean and efficient combustion process. Furthermore, possible pollution with particles and hazardous substances is more likely to happen. The tendency will be strengthened by the fact that highly developed wood-burning stoves are already today sensitive to airtight building envelopes and mechanical ventilation. In this field study it was found that modern stoves were actually extremely difficult to light and add more wood without causing particle emissions.

To conclude, there is a call for innovation of new smaller, more efficient and more particle-safe wood-burning stoves. Today already there is a need for guidance for salesmen and users of wood-burning stoves explaining not only the right size of the stove and the correct way of lighting it, but also the importance of an optimal interaction between stove and building.

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Energy Led Refurbishment of Non-Domestic Buildings – Who Leads?

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Abstract: Innovative and efficient refurbishment offers significant carbon savings and is a growing activity, driven by Government imposing energy or carbon related standards and policies upon building owners. Many businesses are becoming aware of the wider benefits of these improvements and therefore, their requirements as construction industry clients are changing. Built environment professionals need to recognize this change to remain competitive. This paper considers the question of whether there is a need for a re-alignment of disciplines within the industry to fulfill this growing role. A desk study, supported by structured interviews with users of large, non-domestic buildings and with industry professionals concluded that there is a role within the construction industry for a new built environment professional. A competence specification for this professional was defined and this paper outlines the skill set and knowledge base that this individual would require in order to deliver a truly innovative, comprehensive and compatible intervention set within an energy led refurbishment.

Keywords: *Energy, Refurbishment, Client requirements*

1. Introduction

The pressure placed on the built environment to reduce its CO_2 emissions affects how clients treat their property portfolios. They expect construction professionals to take the lead in energy led refurbishment. The purpose of this paper is to explore the effectiveness of construction professionals, who already deal with a range of design-related issues, in leading such energy-led refurbishment. The main objective of this paper is to identify the competences required of built environment professionals able to lead this work, informed by both a desk study of their governing bodies' requirements and interviews with a small but representative group of professionals.

2. Methodology

A desk study surveyed the competency sets required by professional institutions. Structured interviews with 4 experienced professionals from building surveying, facilities management, project management and quantity surveying, and 3 clients (2 facilities managers and one energy manager) used open-ended questions to encourage discussion. The individuals were very experienced and the interviews were held in their offices, recorded and transcribed afterwards. This process allowed for reflection of the results and key points. .

3. Interview Results

Due to the number of interview questions - twenty-three questions for the construction industry professionals and sixteen for the industry clients – and the limitation on page numbers, the questions will not be presented. However, the questions and corresponding responses have been grouped into themes and it is these themes that are presented within 3.1 and 3.2 of this paper.

3.1. Construction Industry Professionals

3.1.1. Refurbishment Context

The interviewees generally agreed that the refurbishment process can vary widely, with works ranging from cosmetic to changing the function of an entire building.

3.1.2. Education and Training

All the interviewees felt that their original education and training equipped them for their work, but their, possibly over ten years old, qualifications lack emphasis towards energy performance in buildings. Participant 1 stated that sustainability was addressed by their assessment of professional competence with the Royal Institute of Chartered Surveyors (RICS) but at insufficient depth for their day to day work. Those interviewees responsible for building design felt that they were under pressure to be aware of new technologies and materials as well as sustainability policies. Whereas those responsible for managing the design felt under less pressure, but need sufficient awareness to participate in design team discussions. The main pressure was coming from their clients' need for advice on sustainability issues. All were keen to undertake some re-training in the area of low carbon building design and operation, and stated that it would be beneficial if there were more Continuous Professional Development (CPD) events in this subject. The main barrier to undertaking re-training is finding the time to attend due to the pressures of their current role.

3.1.3. Professional Governing Body's Attitude

The participants felt that their professional bodies had recently increased the focus on sustainability and its related issues, evidenced by an increased number of seminars and events on the subject. Participant 2 (engineering background) felt the Chartered Institution of Building Services Engineers (CIBSE) was pushing the 'Low Carbon Consultant' qualification forward, and he wished to pursue this as a credible path to specialising in low carbon design and operation of buildings. The others felt that their professional governing bodies were providing more guidance and seminars in the area but envisaged no change to their core competencies, from what they currently perceive, as an outline overview of sustainability.

3.1.4. Companies' Attitudes

All interviewees were aware of their companies' environmental policies and mission statements. Participant 3 remarked that information on the company's intranet brought the issues to their attention. Participant 4 described his company as forward thinking recognising the great commercial opportunity offered by becoming leaders in the field of sustainability, but did not apply the same practices to their own property portfolio. He believed that true leaders should improve their own properties as well as their clients'. Those needing to advise clients on technical aspects remarked that the message they got from their company was to present improving energy performance as a cost saving for the client, whereas those in a management role felt the company would never tell their clients what to do but rather base everything upon the client's requirements. Participant 4, involved in a range of project types within existing buildings, highlighted that within his company, there are several experts in the low carbon area because they have a keen interest in it or because they are part of the small teams the company creates to work on such projects, but their expertise was not transferred across all disciplines. Although, they felt they could always go to them to discuss issues or ask for advice. Overall the main conclusion drawn from the interviews was that the professionals are supported by their company if they choose to become more interested in sustainability, but are neither incentivised nor penalised if they do not.

3.1.5. Clients' Attitudes

Over the last five years many clients have run projects looking at lighting, cooling, controls etc, but this had slowed down with the recession. Conversely, since the Carbon Reduction Commitment Energy Efficiency Scheme (CRC) – a UK based mandatory emissions trading scheme for large energy users - was launched, clients are being forced to consider energy performance, and so far the professionals have found some clients to be wary of the scheme and try to avoid financial penalties, while others see it as an opportunity to show how energy conscious they are. Participant 3’s comment “got to link it to cost to force change” referred to the need to link energy performance initiatives to financial incentives or penalties. They explained how many public sector clients have to achieve certain environmental performance standards, such as a BREEAM excellent rating, as a minimum in order to gain funding for their project. Other public sector bodies are appointing internal sustainability managers that the client must answer to and this pressure is then being passed onto the design team.

3.1.6. Importance of Energy in Buildings

All of the professionals concurred that energy performance of the building comes third behind health and safety and operational performance. However participant 1 did consider energy performance to form a major part of the operational considerations. In terms of the importance of energy performance of a building within a refurbishment scheme, the participants all agreed that capital cost comes first, although participant 4 stated that they try to communicate the benefits of lower operational costs due to energy saving interventions in the design and it was a matter of convincing clients to look beyond capital cost.

3.1.7. Decision Making in Refurbishment

The level of client involvement on projects depends upon the client type; the professionals explained that some clients are happy to provide basic requirements, e.g. function and seating capacities, while others want to be aware of all decisions made. They found that larger companies with internal design teams already have design guides in place to aid selection of interventions and it depends upon the client how closely the external consultants must follow these guides. The main point made by the professionals was that there is no standard process to refurbishment; the decisions are made based upon the design team’s experience.

3.1.8. Who Leads?

All of the professionals stated that the mechanical and/or electrical engineer could be suited to taking the lead as they have an in depth understanding of the building’s energy consumption but debated whether they would have the leadership competencies to do so, since experience suggests they are very focused upon their area and reluctant to comment more widely. Other professionals identified the building surveyor as a potential candidate due to their broader technical knowledge of buildings combined with their project management competence.

3.2. Construction Industry Clients Interview Results

3.2.1. Company’s Attitude

All participants take a proactive approach to works on their property portfolio. Participant 5’s internal team of designers creates design guides with energy performance requirements which external consultants follow. Some admitted that their buildings weren’t at the leading edge of energy efficiency but they took responsibility for what they consumed and wanted to reduce that as far as possible. All had witnessed a change in their companies’ attitudes, since the late nineties, driven by their clients wanting to see evidence of effective and efficient working practices. Participant 5’s organisation has seen three pressures to become more focused upon sustainability and energy in buildings: firstly, their corporate responsibility reporting, a key driver, secondly, cost reduction to allow money saved on energy to be spent elsewhere, and thirdly, the CRC scheme (see 3.1.5), the introduction of which has driven their organisation to make changes such as accreditation of their building to the Carbon Trust standards. Initially their organisation’s concerns were with the reputational aspect of the CRC Scheme and they were determined to be in the upper quartile of the public CRC league table alongside their industry competitors. However, this puts them at risk of future changes to the scheme.

3.2.2. Company Strategy towards its Stock

Participant 5's company has a proactive strategy towards improvement of their stock, with a continuous upgrade investment programme. Participant 6's company has guidelines for improvement of their portfolio with an energy performance charter, supported by an internal, Europe-wide forum to learn and share best practice. All participants have internal energy performance targets that work in line with their businesses. Participant 5's sustainability framework includes scrutiny of energy performance and puts the highest responsibility on a non-executive director at board level. All agreed that energy performance is high on their agenda. Participant 7's organisation's main driver for building selection is location quality. Energy efficiency comes third and if necessary they will include energy interventions such as fabric upgrades and controls within the fit out, but no major changes to key plant items.

3.2.3. Whom do you consult?

All explained that their organisations use both internal and external construction consultants, depending on the complexity and scale of the project at hand. Participant 5's company use an internal, technical compliance team to prepare and ensure compliance with their own design guides and the energy standards. They have a framework of external consultants who carry out and manage the design in accordance with these internally set standards. All of the participants stated that they have contractual relationships with external consultants and those contracts include energy performance related clauses. The most specific are with the repair and maintenance engineers, and participant 5 explained that the engineer must deliver year on year energy consumption reductions, the progress of which are discussed at monthly contract framework meetings. Participant 7 explained that they need to see evidence of the experience of these external professionals in energy performance improvements and how they have been innovative in past, similar projects. Participant 5 explained that clients are frustrated by the same initiatives and ideas/approaches to improvements in their properties coming from different consultants who are afraid to take risks with newer technologies/ideas. They look for openness and an ability to provide non-standard solutions, achieving the same conditions in their properties but without being restricted to standard, constant volume systems. They expect innovation from the industry experts.

3.2.4. Your Optimum Professional

The majority of the participants agreed that a mechanical and electrical consultant or engineer who has the competencies required to run or lead a project would be the ideal candidate because electricity is their largest outgoing. However they emphasised that they want someone who doesn't cover old ground, who can bring innovative ideas to the table and who can also build strong relationships with similarly innovative contractors and consultants. Participant 5's ideal professional is a controls engineer because focusing on controls does not require replacement of key plant and takes the control of the building to some extent out of the occupier's hands so they can be comfortable but not wasteful. However, they did state that they have not yet worked with a controls engineer who can work with and be intimately knowledgeable of the building, communicate their findings or ideas successfully and then be able to lead a project as well.

4. Discussion

4.1. Potential for a New Professional

Both professionals and clients agreed that a mechanical or electrical engineer is associated most with energy usage in buildings and has the required detailed technical knowledge, and that they would have an in depth understanding of how the building consumes energy and the standards that must be met in non-domestic properties. However, they had never worked on a project where the mechanical or electrical engineer was the lead except where the building required an unusually high level of plant. One professional explained that, in their experience as a project manager, mechanical or electrical engineers tend to focus entirely upon their area of expertise. So the project manager felt that the response to any questions outside that area of expertise was "can't answer that question, we've done our bit". In contrast, the clients wanted a leader to invoke innovative solutions across the property, that were not restricted to the plant room, and they hadn't so far found these leadership qualities in the mechanical or electrical engineers. Half of the professionals stated that the building surveyor may be suited to running an energy-led project due to their broad knowledge of building fabric and mechanical and electrical services as well as their ability to manage projects, and the building surveyor agreed that he would be wish to become more specialised in sustainability and energy in buildings. To lead such a project they would need training to become more familiar with both the legislative and policy side, alongside the technical interventions available. In summary both the professionals and clients interviewed saw the potential for a new service, potentially provided through existing professional routes. The professionals agreed that they all need to learn more in the area but a new or existing discipline needs to branch out into energy in buildings, existing disciplines expanding upon their original technical and management skills.

4.2. Barriers to a New Professional

Developing a new professional would alter the structure of the design team and require a client to accommodate an additional set of fees on projects where an entire design team is required. Participant 3 provided an example of where many of their clients are required, by their organisation, to achieve a minimum BREEAM rating [1], thus forcing them to consult a BREEAM advisor. However, due to the low fees available for this advisor, that individual is not used to their full potential, and is brought in for an initial workshop which often turns into a checkbox exercise, when they could be assessing and contributing to the design. In order to get the client to pay an additional set of fees on larger projects, they would need to be forced to employ that professional to ensure delivery of a particular credit or rating level. Participant 3 also remarked that the new professional would have to be accredited in some form to prove to the client that they are worth employing due to the new nature of the role.

4.3. Drivers behind Energy-Led Refurbishment

One of the major drivers behind energy improvements to client properties is government policies that force them to review and improve their energy performance through reputational and financial penalties. An interesting point to arise from the interviews was the need for careful design of these policies to ensure the desired results are achieved. For example one professional described how a public sector client was forced to meet the local council's renewable energy policy, by ensuring that their properties included a minimum level of energy supply through renewable technologies. There was debate over which heating system to implement and due to such a heavy focus on renewables, the decision was taken to install a cheaper (capital cost) electric heating system instead of a more energy efficient alternative and an air source heat pump was installed to meet the renewables requirement. As a result the building only achieved a C/D rating in its Energy Performance Certificate [2]. If the focus had been on the energy performance of the building as a whole then perhaps a B rating could have been achieved instead, resulting in a more energy efficient property. Following the interviews with owners of large, non-domestic portfolios, it was clear that the drive for refurbishment will also come from their own business needs. Some of those interviewed explained that in the current financial climate they are trying to reduce their property portfolio whilst ensuring growth in the core services they provide. This has resulted in less new build procurement and potentially decreasing the number of properties already in use by moving staff into the same buildings. This adaptation of existing buildings can only provide increased opportunity for energy efficient improvements.

4.4. Construction Industry Views on Energy-Led Refurbishment

One professional pointed out that some other professionals believe that the clients must ask for specific energy requirements during the project briefing and that it is not their job to tell the client what their requirements are. Other professionals disagree and see it as their job as the industry expert to inform the client of opportunities available to them if they consider the energy performance of their property. Some of the professionals explained that they feel it is inappropriate to put forward energy performance requirements to the client as they may not have the budget or may be running a separate energy related project. These barriers to pushing the focus onto energy performance need to be overcome if energy performance is to be taken seriously. In recent years, a sustainable building that does not waste energy is now being seen as a higher quality building. The United Kingdom's Green Building Council's Chairman states that "...good sustainability practice is good business practice – it's about producing better quality products, materials and buildings." [3]. The triangle of cost, time and quality is still prominent in the industry and some professionals do not see efficient energy usage in buildings fitting into that shape. However the clients interviewed have shown that they are eager for the construction industry to take the lead and to show them true innovation.

5. Optimum Built Environment Professional Competency Set

Consideration of the competency sets laid down by the governing bodies of the construction industry professionals, combined with the outcome of the interviews held with built environment professionals and clients, leads to the following set of optimum competencies. This optimum competency set aims to define the core skills that a construction professional must fulfil in order to successfully promote and lead an energy-led refurbishment of a non-domestic property, one that will deliver a truly innovative, comprehensive and compatible intervention set. Table 1 presents the established built environment professions against the optimum competency set and shows which competencies each professional currently fulfils in accordance with their governing bodies' guidance. This is not the first time that the competency sets offered by built environment professionals have been critically examined in response to externally imposed changes. For example the development of project management into a clearly defined, accredited profession within the construction industry, codified a role that was previously considered as an additional competency of other construction professions. Accreditation of architects in building conservation is now established, and offers an alternative route to competence. It is evident that clients want to make their buildings more energy efficient but they are not getting what they need from the industry. They want innovative bespoke solutions that work for their buildings but to offer these the professional needs to be knowledgeable about new technologies and materials and to be able to present their benefits clearly. Current professionals admit that they do not know enough about energy in buildings so either a new profession is needed or the competences of existing professions must be overhauled.

Table 1 Optimum Built Environment Professional Competency Set for Energy-led Refurbishment

OPTIMUM COMPETENCY SET		ESTABLISHED BUILT ENVIRONMENT PROFESSIONS	Quantity Surveyor	Project Manager	Facilities Manager Consultant	Building Surveyor	Building Services Consultant	Architect
OPTIMUM COMPETENCY SET	MANGEMENT	Contract Practice [Awareness of construction contract types and contract law & how to incorporate energy performance criteria into contract clauses]	✓	✓		✓		✓
	MANGEMENT	Energy-Led Project Appraisal [Analysis of client requirements to establish a project brief. Gain thorough understanding of the client's organisation, how they obtain project funding, their sustainability policies/targets/managers]			✓			
	MANGEMENT	Leadership [Core to the role, aware of leadership/motivation techniques, and encourage innovative working environments]		✓	✓			✓
	MANGEMENT	Programme and Planning [Key competency of any project leader]	✓	✓	✓			
	MANGEMENT	Project Administration [Key competency of any project leader]		✓				
	MANGEMENT	Relationships with Suppliers and Specialists [Appoint innovative, experienced design teams & have strong networking capabilities]			✓		✓	✓
	MANGEMENT	Risk Management [Manage risk especially where new technologies are employed]	✓	✓	✓	✓		
	FINANCIAL	Sustainability Knowledge [Full understanding of sustainability in construction be able to communicate and make it relevant to a client]	✓	✓	✓	✓		✓
	FINANCIAL	Design Economics and Cost Planning [Aware of how interventions impact capital cost & operational cost using whole life costing techniques to communicate this]	✓			✓		✓
	FINANCIAL	Procurement and Tendering [Sound knowledge of different procurement routes]	✓	✓				✓
	TECHNICAL	Building Pathology [Thorough knowledge of building fabric, must understand typical defects that may arise due to particular interventions and how they can be addressed. Aware of how the building fabric affects building air movement, moisture movement and temperature variations]				✓		
	TECHNICAL	Conservation and Restoration [Aware of conservation principles as this professional will be specialising in the existing built environment]				✓		
	TECHNICAL	Construction Technology [Understanding of common & emerging technologies]	✓	✓	✓	✓	✓	✓
	TECHNICAL	Energy Performance Policies/Initiatives [Aware of and communicate the significance of energy performance related policies/initiatives and how they can be met within a refurbishment project]				✓		
	TECHNICAL	General Understanding of Building Services [Understanding of building services & how they can be made more efficient, be able to communicate with M&E specialists]	✓		✓	✓	✓	✓
	TECHNICAL	Holistic Approach [Must have a holistic view of the property and understand what interventions are compatible with one another and the building. Consider energy demand before energy supply solutions to reduce energy wastage]						
	TECHNICAL	Inspection [Able to lead a thorough pre-refurbishment inspection & be able to guide the focus towards energy performance improvements]			✓	✓	✓	
	TECHNICAL	Legal and Regulatory Compliance [Specific knowledge of energy requirements]			✓	✓	✓	✓

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6. Conclusion

For the growing field of energy-led refurbishment, industry and clients desire competencies that are not currently offered by any existing professional group practising in the UK. This deficiency can be remedied either by developing a new profession, for which the desired competencies have been presented in this paper, in the same way as Construction Project Management was developed, or by establishing a recognizable specialized branch of an existing profession, in the same way as with architects or building surveyors who specialize in building conservation/preservation. Even though the study was carried out in the UK, the professions of those interviewed are internationally recognized. It would be interesting in a future study to compare the views expressed in other countries.

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Influence of external actors in Swedish homeowners' adoption of energy efficient windows

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Abstract: A questionnaire survey of 1010 homeowners (response rate of 59%) in two counties in central Sweden viz., Jämtland and Västernorrland was conducted to understand the influence of external actors on homeowners' decision to install energy efficient windows. We complemented this survey with interview of 12 window sellers/installers in the Jämtland county. Majority of homeowners (74%) contacted more than one external actor for information when they plan to replace their windows. Window sellers/installers have a strong influence on homeowners' window selection as 97% of homeowners bought the windows that were recommended to them. The sellers/installers recommended windows with a U-value in the range of 1.1 to 1.8 W/m^2K and cited that condensation and high cost are the major drawbacks of windows with a U-value < 1.2 W/m^2K.

Keywords: *Energy efficient windows, homeowners, sellers, installers, Sweden*

1. Introduction

Diffusion of energy efficient windows in Swedish building sector may reduce fossil fuel dependency and mitigate climate change. The thermal performance of windows in Sweden has improved over the years and the energy efficiency standard is higher than that of many other countries. For example, in Sweden a window is considered energy efficient if its U-value is ≤ 1.2 W/m^2K [1], while in Denmark the U-value for such windows is ≤ 1.8 W/m^2K [2].

About 85% of detached houses in Sweden are more than 30 years old [3], and windows in many of these buildings may be in poor condition. Moreover as these buildings were built before energy efficiency was emphasized in the building codes in 1977, a large market is available for energy efficient windows. A survey of owners of detached houses in Sweden revealed that homeowners are more likely to replace/change windows than other building envelope components [4]. Due to their long life span the type of windows installed will influence the energy use of the buildings for a long time. From primary energy saving perspective, it is important that homeowners adopt the most energy efficient windows available in the market.

Homeowners may not adopt energy efficiency measures because of lack of adequate and reliable information, lack of awareness [5, 6], or the inability to interpret the available information. Furthermore, potential adopters may have difficulties in perceiving the performance and advantages of energy efficiency measures if the gains are not directly visible [7], are insignificant or are delayed. In such situations homeowners' final choice of a particular measure is influenced by actors whom they consider as experts in the field. Homeowners' adoption of a particular type of window may depend on the recommendation of the sources important to homeowners. Window sellers/installers are the closest link to customers in the demand chain, and could exert a strong influence on consumer's choice. To the best of our knowledge, no e mpirical studies about influence of external actors on homeowners' adoption of energy efficient windows have been conducted in Sweden. In this paper, we analyse the role of external actors especially window sellers/installers in homeowners' adoption of energy efficient windows.

2. Role of external actors

Homeowners may seek information or advice because of uncertainties regarding information alternatives or due to uncertainties on w hich alternative to choose. For high investments, customers may search for information from various sources [8]. The degree to which customers' search for information depends on their perception of the costs associated with the search [8], or their ability and motivation [9]. Sources of information include mass media, interpersonal sources, sellers/installers and neutral sources like municipal energy advisers. Though mass media could improve consumers' awareness about various products their ability to influence consumers' adoption decision is limited to a small group of innovators and early adopters [10]. To reduce the burden of interpreting vast amount of information and to obtain appropriate information homeowners' may seek advice from expert(s) whom they think are credible. The external advice may help the potential consumer to clear their thoughts about the decision and improve their decision confidence [11]. Individuals give more weightage to advice while performing a difficult task compared to an easy one [12]. Hence the relevance of advice may be more pronounced in the adoption of investment intensive measures like windows.

Trustworthiness of a organization working without profit motive (e.g. state agents or non-governmental organizations) is higher than one working for profit motive (e.g. marketing agents) [10]. However, store sales personnel were found to influence customers' choice [13, 14]. Store visits and salespeople are very important source of information for buyers of durables [15, 16, 17], and individuals who are susceptible to interpersonal influence are more influenced by salespersons [18]. Studies in Sweden have shown that homeowners consider sellers/installers as an important source of information when adopting heating system [19], energy efficient building envelope components [4]. This may be because of homeowners' perception that the sellers/installers are experts in their respective field and/or they usually make house visits to make on t he spot assessment of the requirements of their prospective clients. Moreover homeowners may consider the window sellers/installers in their locality similar to themselves, and the influence of an *expert* salesperson is high in such circumstances [20].

3. Methodology

The research methodology includes both quantitative and qualitative analysis.
Homeowners' perception of external actor's influence in the adoption decision is based on a mail-in questionnaire survey of homeowners who availed investment subsidy to replace their windows with energy efficient windows (U-value ≤ 1.2 W/m^2K). Questionnaire were sent to 1010 homeowners in the two neighbouring counties in central Sweden (315 in Jämtland and 695 in Västernorrland) whose addresses were collected from Boverket (Swedish National Board of Housing, Building and Planning) which administrated the programme during 2007-2008. On an average, the homeowners in our survey received 14% of their investment cost as subsidy. The survey was conducted during November – December 2009. 25 que stionnaires were returned either due to incorrect address or non residence of the addressee. The response rate for the survey after one reminder was 59%. The questionnaire consisted of mainly three parts. Section A included questions about the reasons for replacement of windows, factors influencing respondents choice of windows, influence of external actors, perception towards energy efficiency measures. Questions regarding the influence of policy instruments in respondents' adoption of energy efficiency measures were covered in Section B. Section C included questions related to socio-economic variables.

To understand the supply side actors' perspective on energy efficient windows, we conducted interview of window sellers/installers in Jämtland county. A list of window sellers/installers in the Jämtland county was prepared based on a search on the yellow pages. All the 29 listed window sellers/installers/repairers were contacted for a semi structured interview. However some of them did not participate because they had discontinued their business or merged with other companies or did not have time or were just into window cleaning business, while three sellers/installers were not interested to participate. Accordingly, we interviewed 12 sellers/installers. The interviews were conducted during November 2009 – March 2010. We asked the interviewees mostly open ended questions about their influence on homeowners' choice of windows and their perception towards energy efficient windows.

The interviewed personnel were highly experienced in window business as nine persons had more than 25 years of experience, while two had more than 10 years of experience. Ten of the interviewees were owner or partner of their firm, while two were sales personnel of their organization.

4. Results

4.1. Respondents who availed investment subsidy to install energy efficient windows

79% and 19% of the sample (1010 homeowners) installed windows with U-value 1.2 W/m^{2}K and 1.1 W/m^{2}K, respectively, while the rest 2% installed windows with U-value less than 1.1 W/m^{2}K. The composition of the respondents according to age, education, household income, building age and duration of occupancy in their house is provided in Table 1. Respondents who were old, university educated and who lived in old houses were more likely to replace their windows with energy efficient windows.

Table 1: Composition of the respondents

Age group in years (N=574)	Education (N= 573)	Annual household income ('K SEK) (N= 563)	Building age in years (N=566)	Occupancy period (N=562)
≤ 35 - 9%	Primary - 28%	≤ 150 - 2%	≤ 20 - 1%	≤ 3 year - 15%
36-45 - 18%	Upper - 33% secondary	150 – 300 - 23%	21-30 - 3%	4-10 years - 21%
46-55 - 20%	University - 39%	300 – 450 - 24%	31-40 - 35%	11-20 years - 17%
56-65 - 23%		450 – 600 - 24%	41-50 - 21%	21-30 years - 15%
>65 - 30%		> 600 - 27%	>50 - 40%	31- 40 yeas - 20%
				>40 years - 12%

Note: Percentages are rounded to the nearest unit.

4.2. Information search and role of external actors

For most respondents' window sellers/installers (which include glass working companies) was the most influential actor in their window choice (Table 2). Interpersonal sources such as friends/peers/relatives were reported to be the second most influential external actors. Other external actors were important for only fewer respondents.

Table 2: Importance of external actors' advice in homeowners' choice of windows

Influence of external actor	% of respondents				
	N	Important	Neither nor	Not important	Mean
Window sellers/installers	489	56	22	22	3.51 (0.064)
Friends, relatives and peers	396	33	17	50	2.56 (0.079)
Window manufacturers	388	27	11	62	2.23 (0.080)
Internet forums	373	21	13	66	2.03 (0.075)
Carpenters	377	21	8	71	1.97 (0.077)
Building companies	378	18	8	74	1.83 (0.077)
Municipal energy advisers	363	14	6	80	1.63 (0.066)
Energy companies	345	1	4	95	1.15 (0.029)

N = Number of respondents in respective category. Mean values are based on homeowners' response on a Likert scale of 1 to 5 (1 = not at all important, 5 = very important). Values in parentheses are standard errors.

There was no significant relationship among respondents preference for information sources on windows and their demographic characteristics. However, there was a trend that suggests that respondents with different demographic characteristics accorded varying level of importance to the external actors (Table 3). For example, university educated or aged up to 45 years or female respondents gave higher importance to interpersonal sources.

Table 3: Respondents in different demographic groups who attributed greater importance to an information source compared to other groups of respondents

External actor	Respondents' socio-demographic characteristics			
	Gender	Education	Age	Annual household income (1000 SEK)
Window sellers/installers	Female	Basic	>45 years	
Friends, relatives and peers	Female	University	Upto 45 years	150-300
Window manufacturers			>65 years	
Internet forums		University	Upto 35 years	450-600
Carpenters			46-55 years	150-450
Building companies		Basic	>65 years	
Municipal energy advisers		Basic		

Majority of homeowners (74%) contacted more than one external actor for information when they plan to replace their windows. About 60% of homeowners contacted two or more different type of external actors for information. Majority of homeowners contacted window sellers/installers for information on windows, while energy advisers and energy companies were contacted by least number of homeowners (Table 4).

Table 4: Homeowners' frequency of contact to external actors for information about windows

External actor contacted by homeowners	N	% of respondents contacting a specific external actor		
		Contacted many	Contacted only one	Did not contact any
Window sellers/installers	519	47	37	16
Friends, relatives and peers	431	24	24	52
Window manufacturers	430	17	17	66
Building companies	438	10	18	72
Carpenters	427	5	23	72
Municipal energy advisers	418	2	14	84
Energy companies	410		1	99

N – Number of respondents; 5% of the respondents did not contact any of the above external actors.

26% of respondents bought and installed windows themselves, 21% bought windows themselves and installed it through professionals, and 53% replaced windows on *turnkey* basis wherein a professional did the entire window replacement. The homeowners who bought and installed windows themselves may be more knowledgeable in windows as they were more likely to be aware of better energy efficient windows in the Swedish market ($p \leq 0.01$ as per chi-square test) than those who replaced their windows through professionals. 69%, 18% and 11% of respondents entrusted the *turnkey* job to window sellers/installers, construction companies and carpenters, respectively. The various reasons homeowners' entrust the window replacement task to the professionals is given in Table 5.

Table 5: Reasons for entrusting the window replacement task on a turnkey basis

Reasons for entrusting the work on a *turnkey* basis	N	% of respondents		
		Agree	Neither nor	Disagree
The quality of the work would be high	274	85	4	11
It was time consuming to do it myself	251	84	5	11
It was complex to do it	263	75	9	16
Did not have the skill to install windows myself	281	67	10	23
Did not have the knowledge to select right window	272	43	14	43
It was the cheapest option	253	31	19	50
Friends, relative and peers recommended	241	20	10	70

The most important factors for selecting a particular vendor for window replacement was easiness to contact them and the company's reputation to undertake good quality work and service (Table 6).

Table 6: Reasons for selecting a particular vendor for turnkey replacement of windows

Reason for selecting a particular vendor	N	% of respondents		
		Agree	Neither nor	Disagree
It was easier to contact the company	242	69	16	15
Has the reputation of undertaking good quality work	239	65	23	12
Has the reputation of good service	240	63	25	12
Offered the best price	241	49	24	27
Have good experience of their past work	229	28	12	60
Friends, relative and peers recommended	223	22	13	65
Only one who could offer the manufacturer I wanted	220	18	14	68
Only company available locally	214	8	5	87

53% of the total respondents and 64% of those who entrusted the window replacement task on *turnkey* basis reported that the company from which they bought windows had recommended a specific window. About 97% of respondents had installed the windows that were recommended to them.

4.3. Window sellers/installers perspective

The window sellers/installers believed that they exert a v ery strong influence on their customer's choice of windows. Some of them stated that their suggestions/information had a very strong impact as often the customers were not aware about the choices.

"Normally they [homeowners] decide about the type of windows when I visit them".

"They [homeowners] have many questions, …generally the advice we give weighs heavily".

Window sellers/installers recommend/prefer windows with U-value from 1.1 to 1.8 W/m^{2}K (Table 7).

Table 7: U-value window sellers/installers prefer/recommend

U- value (W/m^{2}K)	Number of interviewees
1.1 -1.2	2
1.2	6
1.3	2
1.5	1
< 1.8	1

Majority of the sellers/installers do not recommend U-value less than 1.2 W/m^{2}K mostly due to condensation problem and high cost of such windows. Some of the interviewees on condensation stated:

" Below 1.2 [U-value] you can get problems with condensation…. There is a wild chase to reduce U-values…. But in reality it does'nt work…"

"Customers think it is too damn that they bought new windows and it gets condensation in the outside"

"…if you get down to 1.2,…, the risk of condensation is large and I think the requirement is too hard"

"If you get highly annoyed if you see a white window when you come down to eat breakfast in the kitchen, it was not nice of you to bought a low U-value window"

According to a couple of sellers/installers, it is difficult to *sell* the window manufacture's argument that the external condensation in windows indicates its high energy efficiency. As per four sellers/installers, condensation in external surface of energy efficient windows occurs only during a very few occasion in Jämtland. As per many sellers/installers if the homeowners were informed about the potential condensation problem then the homeowners will not be "surprised" by condensation and thereby would not be dissatisfied by it. Window sellers/installers usually inform their customers about condensation issue associated with energy efficient windows.

The price of windows with U-value < 1.2 W/m^{2}K was a concern for many of the interviewees. Eight sellers/installers reported that it was expensive to buy windows with U-value 1.0 W/m^{2}K, and energy efficiency benefits of such windows compared to windows with U-value of 1.2 W/m^{2}K was only marginal. Hence, according to window sellers/installers it is not worth to buy such windows.

5. Discussion and conclusion

Prior to window purchases, majority of homeowners approached multiple external actors for information. Hence, Swedish homeowners may undertake active pre-purchase information search before buying windows. This study shows that majority of homeowners' considered window sellers/installers as the most influential actor in their window choice. We found that the influence of window sellers/installers on homeowners was so strong that if window sellers/installers recommended a particular window, homeowners' usually would install it. Other external actors were not that influential. This indicates that window sellers/installers have a determinant role in the diffusion of energy efficient windows in Swedish detached houses Majority of homeowners in our sample (79%) who availed the investment subsidy for window replacement had installed windows that had a U-value of 1.2 W/m^{2}K. Their choice of windows with U-value of 1.2 W/m^{2}K may be due to the favourable advice they received from window sellers/installers on such windows and that a U-value of 1.2 was required to receive the subsidy.

Window sellers/installers preferred a window that was "reasonably" energy efficient, and majority did not recommend windows with U-value <1.2 W/m^{2}K. They believed that the investment required for windows of U-value <1.2 W/m^{2}K is not economically justifiable and also such windows cause condensation problem. To convince homeowners about the cost benefits and condensation issues, the sources they rely most (viz., window sellers/installers) need to be confident on those issues. The adoption rate of higher energy efficient windows could be increased by addressing the concerns of window sellers/installers towards condensation issues and higher prices of such windows.

For a significant percentage of homeowners professionals did the entire window replacement. This is mainly because of respondents' perception that the quality of the work would be good or due to time constraints to install windows themselves. Window sellers/installers were the most preferred actor for installing windows on *turnkey* basis. The most common reasons reported for selecting a particular vendor was easiness to contact them and reputation to undertake good quality work and service. The price offered was reported by relatively less number of homeowners in selecting the vendor. This may be because owing to the competition there could be only small price difference similar windows sold by vendors.

Only 14% of respondents considered energy advisers as an important source of information on windows, and only 16% contacted an energy adviser. Our result is similar to earlier findings on homeowners contact with energy advisers [21]. The reasons could include low awareness about the energy advice service and a perception that energy advisers may not be experts in windows.

Our discussions on homeowners' adoption decision are based on a mail-in questionnaire survey, and this has some disadvantages. For example, about 41% of the homeowners did not respond, and therefore, non-response bias might be a concern which we did not investigate. Furthermore, the respondents may not have entirely understood the questions, as in all questionnaire surveys, and we were not able to clarify the questions, which in turn might have influenced the responses. Similarly, as local climate may influence external condensation on windows, the perception of window sellers/installers on condensation in energy efficient windows and their subsequent recommendations may vary across Sweden.

Acknowledgments

The authors gratefully acknowledge the financial support from Swedish Energy Agency and from the European Union. We like to thank Kerstin Hemström for conducting the interviews.

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The 'time' dimension of electricity, options for the householder, and implications for policy

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Abstract: Electricity has always had a 'time' dimension for suppliers, and the advent of variable renewable generation may make this dimension more obvious to consumers than it has been in the past. Variable generation increases the need for an 'active demand-side', in order to balance load and achieve security of supply, and various forms of smart grid are under consideration and trial, possible prototypes for the grids of the future. However, it is often not clear what the implications of an active demand side are for small-scale end-users, although their participation (or cooperation, at a minimum) is seen as essential. As utilities increasingly require the cooperation of their customers in managing distribution networks, so they need to persuade them to adopt new tariffs, technologies and customer-utility relationships. Four options are outlined and discussed, with the aim of developing a better understanding of the social and behavioural dimensions of distributed generation. The options are based on work carried out as part of the SUPERGEN HiDEF (Highly Distributed Energy Future) project in the UK. The focus is on householders, who have been used to a passive relationship with their energy retailers, along with simple tariffs. Policy questions revolve around how to encourage the cooperation of end-users – an 'active demand side' - and questions of control, equity and data privacy are significant factors in the embryonic public debate over smart grids.

Keywords: *household, electricity, dynamic demand, tariffs*

1. Introduction

Electricity has always had a 'time' dimension from the viewpoint of suppliers: it must be generated, transmitted and distributed in order to meet demand with as little wastage as possible. This has entailed careful planning so that generating plant is available when needed and, increasingly, a degree of planning so that demand from larger consumers is predictable and manageable. However, most residential and small business customers in most parts of the world have been used to a flow of electricity at any time, and at constant prices per unit.

With growing demand, especially growing peak demand, the time dimension has become more and more important to planners – hence the attention paid to demand-side management over the past few decades in parts of the world with sharp peaks, most commonly associated with high demand for air-conditioning on hot afternoons. In regions with a high proportion of nuclear generation, too, there have been adaptations to shift electricity demand in order to use the baseload available at night, such as storage heaters. Now, an increasing proportion of renewable generation increases the need to move from the old 'predict and provide' utility paradigm to one with a more 'active' demand side – where demand can be decreased *or* increased in order to match supply with demand.

Various forms of 'smart grid' are proposed in order to make this accurate matching possible. The term is used to mean many things, just as the term 'smart meter' has meant many things to many people [1]. In essence, though, a smart grid involves the merging of communication networks (fast-evolving technologies) with electricity grids and networks (not much changed in their basic structure since the time of Edison). The European Technology Platform defines the Smart Grid as:

– *an electricity network that can intelligently integrate the actions of all users connected to it -generators, consumers and those that do both –in order to efficiently deliver sustainable, economic and secure electricity supplies.* [2]

The intention is that smart grids will enable and/or require customer 'participation' , allowing for better control of generation, distribution and usage at all levels. But early pilot grids (such as those in Boulder, Colorado, and Amsterdam) are raising as many questions as they are answering. There are still fundamental questions to be asked about approaches to the smart grid. For example, should it be incremental and carefully costed and tested at each stage, or implemented comprehensively through massive infrastructure investments, in confidence that enough applications will emerge to justify those investments? If the latter, how are customers to be persuaded to fund the SG through their taxes and electricity charges? If the former, how much will consumer priorities influence SG development, and how much will the SG influence consumer practices?

While much attention has been paid to technical specifications for these grids, it not always clear what the implications are for small-scale end-users. While the grid itself is seen as an intelligent agent, it is often not clear how electricity customers may also be agents. They tend to be seen as passive elements in the system, communicating only through the billing system and the complaints system. The UK government has probably gone as far as any in its stated ambition for consumer/prosumer participation, in setting out a specification for smart meters that includes provision for microgeneration, customer feedback displays, ability to change supplier and tariff readily, and ability to control devices in the home; and in its statements on the nature of a smart grid. For example:

> A focus on the consumer's perspective must be at the heart of decision making at each stage under the programme; as well as the views of industry participants who will take on responsibility for delivery following changes to the regulatory framework [3].
>
> Consumers will need to be involved in the process of developing the electricity system… plans need to be developed in consultation with consumer interests… Clear rules and arrangements for the protection of consumer privacy will need to be a priority. First step: building increased smartness into homes, giving a clearer picture of energy use, greater choice and control [4].

If there is a sufficiently powerful combination of factors in implementing an active demand side, then the distribution of activity could change significantly. These factors would need to include:

(a) suppliers' and distributors' strong need to cultivate an 'active demand side' in order to manage the system;

(b) the ability and willingness of consumers to become prosumers, contributing to supply and storage as well as using it;

(c) regulatory support for distributed generation and equitable participation; and

(d) reliable and trusted technology.

It may be useful to break down the idea of 'activity' into aspects of control, investment decisions (e.g. network operators investing in substation equipment, or customers investing in efficient freezers or frequency-response-enabled appliances). It is unrealistic to imagine that all consumers will change from their relatively passive positions in the system to active , interested engagement, but there is potential for some change in most consumers [5].

As utilities increasingly need some cooperation from their customers in managing distribution networks, so they may need to 'teach' customers about the time dimension of electricity flows, in order to persuade them to adopt new tariffs and technologies more readily. An early example of this sort of practical education, conducted in the course of a trial of real-time pricing, is given in [6]. Technological and commercial drivers are moving in the direction of more sophisticated control and pricing arrangements, including real-time pricing, remote control of appliances by the utility, demand aggregation, and 'dynamic demand' through smart appliances. The purpose of this paper is to examine some of these options in order to move towards a better understanding of the social and behavioural dimensions of both 'active demand' and distributed generation.

2. Method

The material for this paper comes mostly from a literature review carried out as part of the SUPERGEN HiDEF (Highly Distributed Energy Future) project in the UK. The project is developing approaches, technologies and policies for an electricity system that provides sustainability, security and low carbon emissions through widespread deployment of distributed energy resources. It analyses possibilities for decentralising five features of electricity systems: resources, control, network infrastructure, participation (markets and commercial arrangements), and policy.

A number of possible types of customer-utility relationship arise from these possibilities. In this paper, four are selected and discussed with an eye to their policy implications. This of course means that other options are ignored – for example, demand aggregation and community energy services companies – but the aim is to open up the debate on active demand, not to give an exhaustive account of all that it might involve.

3. Themes in the active demand literature

The research literature on demand management does not always acknowledge or reflect the variety in electricity systems. This variety can be assessed on a number of scales, but three immediately come to mind: composition and timing of demand, type and scale of generation, and degree of regulation. For example, what are the current patterns of demand, and how much are they likely to alter in future, in what directions? Does the system have large-scale biddable centralized generation, a high proportion of nuclear (inflexible) generation, or a significant proportion of distributed and variable generation? How heavily regulated is the market?

The answers to these questions will affect what is seen as possible and desirable for the future. So will the technologies that are available, and the extent to which they are marketed around the world. Grid management that is suitable for a summer-peaking region with highly regulated utilities may not be applicable to a temperate region with liberalized markets, yet there will be an inevitable push to increase the market for technologies that have been designed for one set of circumstances into areas with other conditions. But as yet, there is not a great deal of experience in implementing demand response in parts of the world other than North America. A recent review of experience in the EU concludes that progress has been slow because of limited knowledge of demand response-related energy-saving capacities. The high estimated cost of necessary technologies and infrastructure, and the policy focus on market liberalisation [7]. Nor is there much on the relationship between demand response and demand reduction, in spite of its clear importance in terms of reducing the environmental impact of electricity more generally [8, 9]. And neither is there a great deal of research on what demand response means to consumers. Most of what there is comes from research carried out with customers who have opted into a programme, typically a very small proportion of the population to which they belong.

Therefore it is still useful to do some basic thinking about how we might best research demand response as seen from the standpoint of the end-user. As an exercise in this, four possible ways of encouraging an active demand side have been selected, to take an initial look at what they might mean to small-scale consumers or prosumers. They are outlined below.

3.1. Demand reduction via efficiency, rethinking energy services and lowering discretionary demand

Demand reduction is not always included in discussions of active demand, but I would argue that it is a central consideration. Managing a high-demand system is very different (and, mostly, more problematic) than managing a low-demand system. Climate change and energy security considerations mean that demand reduction is still normally a governmental policy objective, even if not necessarily a central objective for de-regulated utilities.

For demand reduction, the supplier-consumer relationship is normally voluntary/persuasive, sometimes assisted by technology. Although improved customer feedback from the supplier is useful, highly detailed data are not essential [10]. Some benefits are realised through changes in daily routines and practices, some through investment in improved technology, retrofits or efficiency measures, and some through rethinking the customer's approach to energy services – for example, car-sharing, turning down heating in unoccupied rooms, or line-drying laundry rather than using a mechanical tumble drier.

This would seem to be the simplest form of active demand, one that affects overall *and* peak demand. Truly 'active' customers minimise demand as a conscious exercise, often becoming more energy literate in the process. At the extremes, they may live in passive-standard homes and go off-grid. Much of this is likely to be beyond the control of suppliers, although there are structured and monitored forms of demand reduction in which suppliers are incentivised to invest in efficiency. An example is the Carbon Emissions Reduction Target in the UK, one of a number of initiatives introduced in the EU in response to concerns that market liberalisation would lead to increased consumption through lower prices. Under schemes such as this, although suppliers have no obvious reason to minimise demand in a competitive market, they do have an obligation to act in concert with their customers by funding efficiency measures and feedback/advice programmes (and, for CERT, some microgeneration), in order to be able to continue their business. Reference [11] gives an account of lessons learned in three EU countries from demand reduction obligations.

In demand reduction initiatives, control of usage normally rests with the customer. There may be equity considerations: who benefits most from subsidies, grants or demand reduction incentivizing tariffs? CERT has rules which address equity issues by defining priority groups and requiring suppliers to give minimum levels of assistance to them. Data privacy is rarely a problem, as benefits are likely to be estimated rather than measured, but even if they are measured, there is no need for high-resolution data. Evaluation of this type of active demand initiative can be a problem, though, when benefits are estimated.

3.2. ‘Static’ time-of-use pricing to minimise peak demand, through reduced discretionary demand and load-shifting

Static time-of-use (TOU) tariffs – static in that they stay the same over relatively long time periods of time, are often cited as the main reason for introducing smart metering. The customer-supplier relationship here is normally voluntary, with customers choosing to opt into TOU pricing, although there are moves in some parts of the world (e.g. Ontario) towards making it the default mode, especially for business customers. The tariffs rely on interval metering and an upgraded billing system, each of which is expensive and time-consuming to implement.

From the customer standpoint, adopting TOU tariffs need not mean any change in activity at all. Some will benefit in any case if they move away from a flat rate, depending on how the TOU tariff is structured and what their normal daily routines are. The TOU prices are dependable, and provided the customer has accurate information about when it is best to avoid high consumption, new habits of demand reduction and load-shifting can be formed.

The supplier continues to carry any risk associated with volatile electricity prices in the short term, even if that is likely to be passed to the customer in the longer term. There is a degree of supplier-customer engagement, and TOU pricing could be seen as a means of educating customers about the ‘time’ dimension of electricity, opening their eyes to the concepts of peak and trough demand. There is also scope for some automation, with a simple example being the programmable thermostat or washing machine, so that customers can cut down or cut out consumption at certain times of day; and scope for direct load control by the utility, to use consumer heat stores at certain times of day and reduce load at others.

Most of the control of consumption (and generation) still normally rests with the customer, although a range of options exist. Still, the customer can normally choose how much control to hand over to a supplier or network operator, and whether to adopt any form of ‘enabling technology’. Typically, customer participation in TOU programmes is very low, around 1%, if they are expected to opt into the programme. There is resistance to *compulsory* smart metering in several regions at the time of writing, on grounds of cost, invasion of privacy, and even the claimed damaging impact of radio waves from smart meters on health. Data privacy may be an issue for some customers, as individual load curves are being recorded and used for billing, and direct load control is certainly an extension of supplier power into the home, likely to be seen as a loss of privacy. Equity issues become more complex than they are for demand reduction: for example, why should a low consumer subsidise the installation of load-control technologies in the homes of high consumers? And the system can be somewhat inflexible, not offering any incentives for extra demand reduction at the times of greatest stress [12]. Evaluation of TOU pricing, though, can be fairly straightforward: what was the peak demand reduction in different weather conditions? Did consumer response persist? How many people participated? And who were the main gainers and losers from the new tariffs? (More difficult, this, but still possible to establish).

3.3. Dynamic (real time) pricing

One of the main features of real time pricing is the way in which it transfers some of the risk of price volatility to customers, by charging them the current spot price for electricity. It is mediated by smart metering and billing systems, and is likely to be of particular interest for microgenerators and/or for anyone interested in energy storage. There are few examples of real-time pricing (RTP) for small-scale end-users, beyond the trial stage. To date, the relationship between supplier and consumer/producer is normally voluntary, though contractual.

RTP requires a constant flow of information between supplier, consumer (and microgeneration technologies), so is heavily reliant on functioning ICT. Because of the unpredictable nature of local load balance at any point, response is best not left to the voluntary choice of the customer, but requires some automation. For example, the customer could set the upper boundary beyond which s/he will not pay for any more supply and the system must cap supply to the home; or the lower boundary beyond which s/he will not export any own-generation to the grid.

There is little experience with RTP for residential customers, and there is a great deal to be discovered about their response in terms of price elasticity and wider impacts on behavior patterns. A couple of early trials show some encouraging results when a relatively simple, robust scheme is put in place with well-informed customers [13, 14]. But we still know very little about how RTP might fit with microgeneration, storage generally, and new technologies such as heat pumps and electric vehicles. There are clearly both equity and data protection considerations, considering the potential complexity of RTP systems.

3.4. Dynamic demand – automated network balancing

Dynamic demand comes at the least 'active' end of the active demand spectrum. The relationship between network operator and customer is essentially one in which they co-manage the load in a locality through frequency response in smart appliances. The appliance responds to minute changes in frequency by cycling on or off according to the load on the network at any instant. Customers make the investment; it is not yet clear whether or how this type of arrangement might be formalised through contracts in which the customer payments are reduced in recognition for their contribution of ancillary services to the network operator. There is no householder intervention, other than choosing to buy the appliance, and even that may become a non-choice in time.

The four options are summarised in Table 1 overleaf.

4. Conclusions

The purpose of this paper was to examine some 'active demand' options for householders, in order to move towards a better understanding of social and behavioural dimensions of both 'active demand' and distributed generation. Involvement in active demand involves recognition of a dimension in electricity supply and usage – time – that is new to many consumers. However, 'active' can have many meanings, and an active demand side does not always mean that the people making the demand are consciously thinking about it. Indeed, they typically think about it very little and, for the more fine-tuned types of active demand, thinking is unnecessary: the function has to be automated.

Overall demand reduction – where conscious activity counts for most – tends to be relegated to the fringes of the debate on active demand. The debates on demand reduction and better load management are sometimes confused: achieving the latter does not necessarily mean that any progress is made on the former, although the former is, in the long term, the most important issue. Questions of control, equity and data privacy emerge as significant factors in the debates that are already taking place in California, Ontario, Victoria, and the Netherlands (to give a few examples) – debates that will spread to other regions before long.

Table 1: Summary of four 'active demand' options, from the end-user standpoint

Options for householders in a 'new dimension' world	**Main objectives**	**Householder activity**	**Comments**
Demand reduction	Better-informed energy management; retrofits and investment in energy efficiency.	Question routines and practices, change practices, invest in efficiency measures, develop energy literacy.	The most conscious and obviously 'active' option. Enabling technology or measures can be very simple or non-existent.
Static time-of-use tariffs	System management to reduce peak load and need for expensive 'peaking plant'	Choice of tariff and possible direct load control by utility; possible changes in routines / investment in enabling technology.	Must have interval metering. Raises some equity and data management issues. May have application for microgenerators, to optimise generation in home over time.
Real-time pricing	Load management to reduce peaks *and* utilize variable generation efficiently	Choice of tariff/ contract, and technologies.	More complexity and risk than TOUP, but more flexibility – necessary for less predictable supply. Relatively untried, but central to the idea of the smart grid.
Dynamic demand, smart appliances	Network management to maintain grid frequency	Choice of appliances and possible contract with network operator.	Least problematic of all options, and compatible with any of them. But requires highly reliable, robust technology.

There are likely to be tensions between approaches that aim to inform and involve householders (leaving them with considerable control), and those that encourage them to adopt technologies that will lessen their control and/or transfer it to the utility. Consumers and prosumers vary in their willingness to pay attention to their energy use, let alone to manage it. There is scope for a suite of approaches, in order to involve as many of the population as necessary in system management; however, there is a strong case for incentivising active consumer involvement in the first instance.

Acknowledgements

The author was funded for this work by the Engineering and Physical Sciences Research Council, under the SUPERGEN Highly Distributed Energy Future research programme. The author is also grateful to the reviewers of the paper.

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Impacts of end-use energy efficiency measures on life cycle primary energy use in an existing Swedish multi-story apartment building

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Abstract: In this study we analyze the effects of energy efficiency measures on the life cycle primary energy use of a case-study (reference) 4-story wood-frame apartment building using electric resistance heating, bedrock heat pump, or cogeneration-based district heating. The reference building has an annual final heat energy demand of 110 kWh/m^2. The energy efficiency measures analyzed are improved windows and doors, increased insulation in attic and exterior walls, installation of improved water taps, and installation of a heat recovery unit in the ventilation system. We follow the buildings' life cycles and calculate the primary energy use during the production, retrofitting, operation and end-of-life phases, and the energy reduction achieved by the measures. The results show that the measures give significantly greater life cycle primary energy savings when using resistance heating than when using district heating. However, a resistance heated building with the efficiency measures still has greater life cycle primary energy use than a district heated building without the measures. Ventilation heat recovery is the most effective measure when using resistance heating while improved windows and doors is the most effective when using district heating. This study shows the importance of considering the interactions between individual measures and the type of heat supply system when selecting energy efficiency measures.

Keywords: *Life cycle, Primary energy, End-use energy efficiency measures, Retrofitting, Low energy buildings*

1. Introduction

The building sector offers significant potential to reduce primary energy use and thereby reduce CO_2 emission [1]. Several strategies can be used to realize this potential, e.g. reduced heating demands and increased efficiency in energy supply chains. The construction of new low energy buildings is important in the long term, but has small effect on the building sector's overall energy use in the short term, as the rate of addition of new buildings to the building stock is low [2]. Large potential exists to reduce primary energy use in existing buildings in the short term, through energy efficiency measures. Energy efficiency measures may be implemented at any time in a building's service life, but some measures are more cost-effective during major renovation works [3].

The life cycle of a building encompasses production, retrofitting, operation and end-of-life phases, which all are interlinked. The final operation energy use in existing buildings can be reduced considerably by implementing energy efficiency measures, e.g. improved insulation, efficient windows, heat recovery from exhaust ventilation air and efficient appliances. These building retrofitting measures also increase material use and the production energy use. Together that reduce the dominance of the operating phase and other life cycle phases becomes relatively more important [4]. The primary energy use depends on the energy supply systems. The energy supply of a building can be provided by different types of supply systems resulting in a large variation in primary energy use for a given final energy use [5]. Hence, the primary energy savings of energy efficiency measures depend on the energy supply systems. Commonly, the difference in final operation energy use before and after implementing energy efficiency measures is used to estimate the savings from such measures. This is inadequate because the energy implications of implementing energy efficiency measures extend beyond the operation phase. Instead, a comprehensive approach to analyze the savings of energy efficiency measures requires a system-wide perspective, including all life cycle phases of a building and the entire energy chains, from natural resources to final energy services.

In this study we analyze the potential final energy savings in an existing Swedish apartment building by energy efficiency measures, and explore the life cycle primary energy implications of implementing the measures. We consider space heating systems using electric resistance heating, heat pump or district heating.

2. Method

We calculate the primary energy use for all life cycle phases of a reference building before and after implementing the energy efficiency measures, taking into account the production, retrofitting, operation and end-of-life phases.

2.1. Case-study building

The case-study building is a 4-storey wood frame apartment building constructed around 1995 in Växjö, Sweden. It has 4 floors and 16 apartments, and a total heated floor area of 1190 m^2. The roof consists of two layers of asphalt-impregnated felt, wood panels, 40 cm mineral wool between wooden roof trusses, polythene foils and gypsum boards, giving an overall U-value of 0.13 W/m^2 K. The windows are double glazed and have a U-value of 1.9 W/m^2 K. The external doors have a U-value of 1.19 W/m^2 K and consist of framing with double glazed window panels. The external walls have a U-value of 0.20 W/m^2 K and consist of three layers: 5 cm plaster-compatible mineral wool panels, 12 cm thick timber studs with mineral wool between the studs, and a wiring and plumbing installation layer consisting of 7 cm thick timber studs and mineral wool. Two-thirds of the facade is plastered with stucco, while the facades of the stairwells and the window surrounds consist of wood paneling. The ground floor consists of 1.5 cm oak boarding on 16 cm concrete slab laid on 7 cm expanded polystyrene and 15 cm macadam, resulting in a U-value of 0.23 W/m^2 K. The construction and thermal characteristics of the building, including the U-values of the components are given by Persson [6].

2.2. Energy efficiency measures considered

We model energy efficiency measures to the case-study building to achieve a passive house standard. The energy efficiency measures are shows in Table 1. We calculate the U-values resulting from implementing these measures using the method recommended by Swedisol [7].

Table 1. End-use energy efficiency measures applied

Description	*Effect of improvement*
Improved taps	Reduced hot water used
15 cm additional mineral wool insulation to the roof	U-value from 0.13 to 0.08
Windows replaced by triple glazed units (krypton filled)	U-value from 1.9 to 0.90
Doors replaced by triple glazed units (krypton filled)	U-value from 1.19 to 0.90
25 cm additional mineral wool insulation to external walls	U-value from 0.20 to 0.10
Incorporation of heat recovery unit in the ventilation system	Reduced ventilation heat loss

We use simplified assumptions when modeling the measures for the building. For the exterior walls, we assume that the additional 25 cm mineral wool insulation is added to the exterior façade of the building, and covered by new stucco and plasterboard cladding supported by wooden studs spaced at 0.6 m apart. We assume that the original roof overhang is sufficient to cover the wider walls. For the roof, we assume that the additional 15 cm mineral wool insulation can be installed in the existing attic space. We assume that the ventilation heat recovery unit with 85% efficiency is installed and that the ventilation ducts for incoming air can be fitted in the buildings [8]. Based on data from the Swedish Energy Agency [9], we assume that final energy for tap water heating is reduced by 40% by changing from conventional to efficient water taps.

2.3. Production and retrofitting phases

During the production and retrofitting phases we account for all the materials used in the building, including the initial construction and the energy efficient retrofitting. We calculate the primary energy used to extract, process, transport and assemble the materials, and also the available bioenergy recovered from biomass residues in the wood product chain [10]. The specific end-use energy for building material production is based on two Swedish studies [11, 12]. The on-site construction energy used to assemble the building material is estimated using data from Adalberth [13]. We assume that the on-site energy used for the retrofitting work is proportionally equal to the on-site energy used for the initial building construction, weighted by the relative amounts of energy used to produce the building materials used in the reference building and in the improved building. For calculations of biofuel recoverable from biomass residues we use data from Lehtonen et al. [14] and Sathre [10]. To convert end-use energy for material production to primary energy, we use fuel cycle loss values of 10% for coal, 5% for oil and 5% for natural gas, and we assume electricity comes from coal-fired plants [15].

2.4. Operation phase

During the operation phase, we consider the primary energy used for space heating, ventilation, domestic hot water, and household electricity. We model the operating energy of the building before and after applying each of the energy efficiency measures, to determine the final energy savings from the measures. The reference building was built in 1995, and we model the pre-retrofitting operating energy use for 15 years. We assume the retrofitting takes place in 2010, and we assume a building lifespan of 50 year after retrofitting. The final energy for space heating, ventilation, domestic hot water and household electricity are modeled using ENORM software [16]. We assume an indoor temperature of 22^{o}C and use climate data for Växjo, in southern Sweden. The average annual maximum and minimum temperatures of Växjo are 28 and -18 ^{o}C, respectively.

To quantify the primary energy required to meet the final operation energy use we use the ENSYST software [17], which calculates primary energy use considering the entire energy chains from natural resource extraction to final energy supply. We analyze cases where heat is delivered by electric resistance heating, heat pump or district heating. For the electric resistance heating and heat pump, 95% of the electricity is assumed to be supplied from stand-alone biomass steam turbine (BST) plants and the remaining from light-oil gas turbine plants. For district heating, 90% of the district heat production is assumed to be supplied from combined heat and power (CHP) BST plant, with oil boilers accounting for the remainder. We credit the cogenerated electricity to the district heat plant assuming that it replaces electricity produced from a stand-alone plant with similar technology and fuel [18].

2.5. End-of-life phase

We assume that the building is demolished after its service life, with the concrete, steel and wood materials recovered. We calculate the net end-of-life primary energy use as the primary energy used to disassemble and transport the building materials, minus the primary energy benefits from the recovered concrete, steel and wood. We follow the methodology developed by Dodoo et al. [4], and use data from Adalberth [13] and Björklund and Tillman [12].

3. Results

Table 2 shows the final and primary energy use for heating and ventilating of the reference building and after applying each of the energy efficiency measures to the building. The measures cumulatively decrease the primary energy use by 61%, 52% and 39% for the resistance heating, heat pump and district heating scenarios, respectively. Heat recovery of ventilation air gives the biggest single decrease in primary energy use when using resistance heaters and heat pump, while efficient windows and doors give the highest primary energy savings when using district heating. The use of heat recovery ventilation system also increases the electricity use, reducing the primary energy savings of ventilation heat recovery. For district heating system mainly based on CHP production, a reduced heat use also reduces the potential production of electricity.

Table 2. Annual final and primary energy use (kWh/m^2) for operation after implementation of different measures. Each successive measure includes the effects of all previous measures.

Applied end-use energy efficiency measures	*Final energy use for different energy services*				*Total Primary energy use for space and tap water heating, and ventilation*		
	Space heating	Tap water heating	Venti-lation electricity	Total	Resistance heating	Heat pump	District heating
Reference	70	40	4	114	340	109	72
+Improved taps	70	24	4	98	293	95	63
+ Additional roof insulation	69	24	4	97	290	94	63
+ Improved windows/doors	51	24	4	79	236	78	53
+ Additional external walls insulation	43	24	4	71	212	71	49
+ Ventilation heat recovery	13	24	8	45	134	57	44

Table 3 shows the net primary energy used for the production of the building in the reference and the improved cases. The primary energy balance for the improved building comprises the initial construction primary energy plus the additional primary energy due to the energy efficient retrofitting. Material production primary energy use increases by about 17% when the measures are cumulatively applied.

Table 3. Production primary energy balances for the reference building and the improved building with all the energy efficiency measures applied.

Description	*Primary energy used (kWh/m^2)*	
	Reference	Improved
Production of building materials	579	680
On-site construction work	50	59
Recovered biomass residues	-345	-355
Total	**284**	**384**

Fig. 1 shows the primary energy use during 50 years of operation of the reference building and the improved building with all the measures implemented when using BST supply technology. In the improved building the primary energy for space and water heating decreases, but that for ventilation increases, as additional electricity is used to run the heat recovery ventilation system. The cumulatively applied measures results in greater decrease in operation primary energy in the cases where the building is heated with electricity. However, the reference building with district heating has lower operating primary energy than the improved building with resistance heating. Thus, the type of heat supply has greater impact on primary energy use than do the energy efficiency measures.

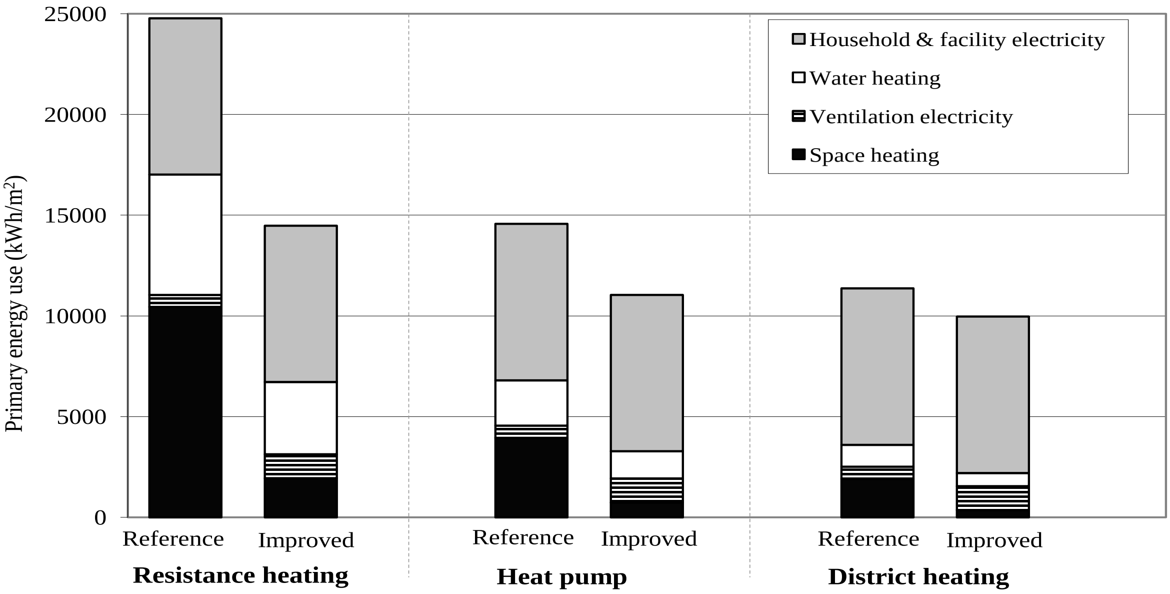

Fig 1. Primary energy use for building operation for 50 years, for the reference building and the improved building with all the measures cumulatively applied.

Table 4 shows the primary energy balances of the end-of-life phase of the buildings. Recovery of wood for use as biofuel gives the greatest end-of-life primary energy benefit, followed by recycling steels to replace ore-based steel. Recycling of concrete as crushed aggregate gives a minor end-of-life primary energy benefit.

Table 4. End-of-life primary energy balances for the reference building and the improved building with all the energy efficiency measures applied.

Description	*Primary energy used (kWh/m²)*	
	Reference	Improved
Disassembly	5	5
Concrete recovery for crushed aggregate	-3	-3
Steel recovery for feedstock	-60	-60
Wood recovery for fuel	-305	-311
Total	**363**	**369**

Fig. 2 shows the development over time of the primary energy use of the building with and without the energy efficient retrofitting for space and tap water heating and ventilation. The construction of the building in 1995 uses 579 kWh/m^2 of primary energy, while 345 kWh/m^2 of bioenergy can be recovered from biomass residues. From 1995 to 2010, energy is used for space and tap water heating and ventilation of the reference building, and is greater for the resistance heated building than for the building with district heating or heat pump. In 2010, additional energy is used to retrofit the buildings. The primary operation energy from 2010 to 2060 is significantly lower if the building is improved. The energy "pay-back period" for the energy used for retrofitting is short. The net life cycle energy benefit of the improvement is the difference between the unmarked and the corresponding marked lines at the year 2060. The benefit is positive in all cases and is greatest when the building uses electric resistance heating.

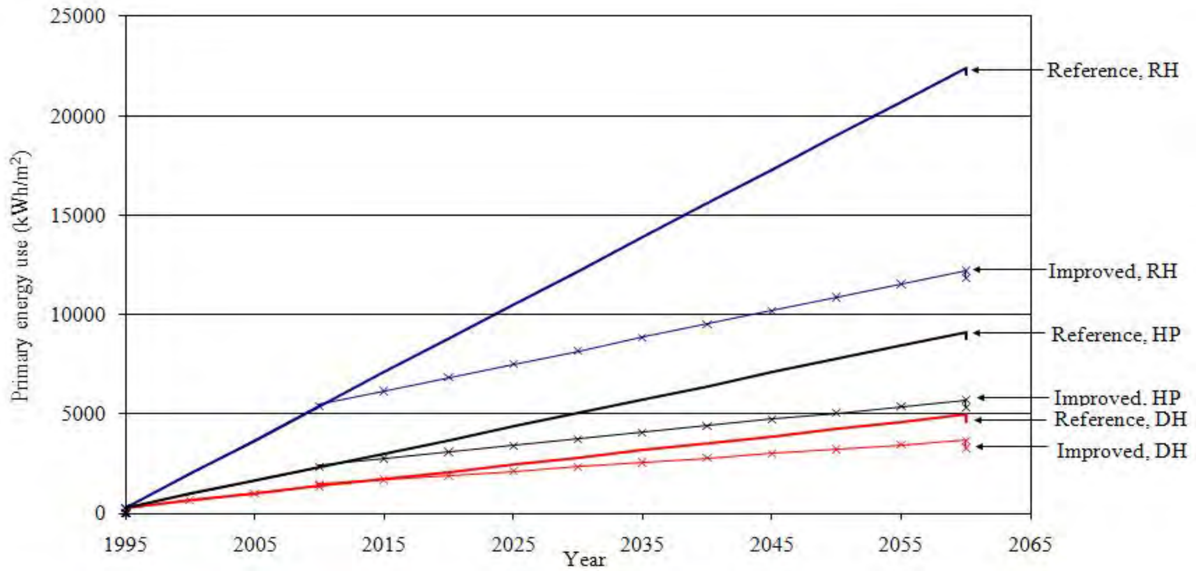

Fig 2. Cumulative primary energy use for space and tap water heating, and ventilation for the buildings with (marked lines) and without (unmarked lines) improvement, with resistance heating (RH), heat pump (HP) or district heating (DH).

Fig. 3 shows the total cumulative primary energy use of the building with and without the energy efficiency measures but including the primary energy for household electricity. The energy benefits of improvements to the building are still apparent, but are proportionally less significant as the total primary energy use is considered.

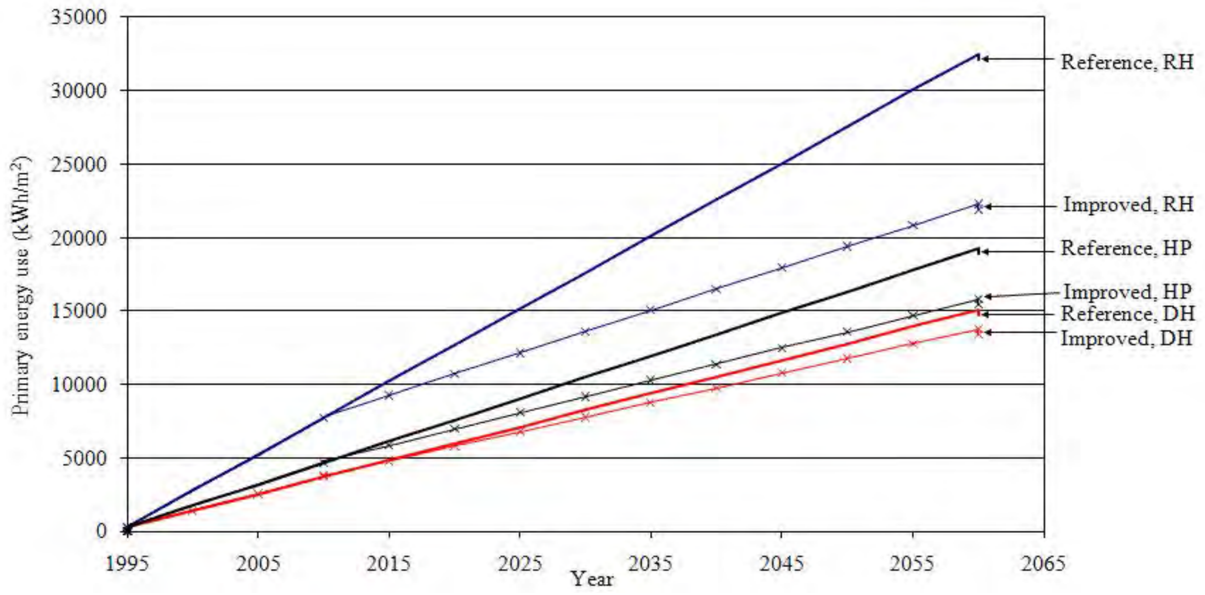

Fig 3. Cumulative primary energy use, for the buildings with and without improvement, including space heating and ventilation as well as energy for household electricity.

Table 5 shows the primary energy use during the life cycle phases of the buildings. The primary energy use during the operation phase dominates, but the relative importance of other life cycle phases increase when the energy efficiency measures are implemented. The primary energy balance during the production phase is relatively small because the primary energy used for material production is largely offset by energy gained from the biomass residues.

Table 5. Net primary energy use of the life cycle phases of the reference and improved buildings, including the production, operation and end-of-life phases.

Life cycle phases	*Primary energy use (kWh/m²)*					
	Resistance heating		Heat pump		District heating	
	Reference	Improved	Reference	Improved	Reference	Improved
Production/retrofitting	284	384	284	384	284	384
Operation (50 years)	24781	14481	14569	11046	11365	9968
End-of-life	-363	-369	-363	-369	-363	-369
Total	**24702**	**14496**	**14490**	**11061**	**11286**	**9983**

4. Discussion and conclusions

The primary energy savings of different energy efficiency measures depend in part on used heat supply system. Heat recovery from ventilation air is most effective where heat supply is from electricity-based systems. The increase in ventilation electricity, however, erodes part of the primary energy reduction. For heat supply from cogeneration-based district heating, efficient windows and doors are the most effective.

The production primary energy becomes increasingly important as buildings become more energy efficient. Primary energy used for production increases significantly by retrofitting a building, but the resulting reduction in space heating primary energy is much higher, resulting in an overall life cycle primary energy reduction.

The results show that the choice of heat supply system has greater impact on primary energy use than the end-use energy efficiency measures, confirming the results of Gustavsson and Joelsson [5]. Hence, to further minimize primary energy use when buildings are refurbished, priority should be given to energy efficient supply systems such as district heating where possible. When selecting energy efficiency measures, attention should be given to the interaction between individual measures and the type of heat supply system, in particular the electricity use for ventilation heat recovery together with cogeneration-based district heating.

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Mechanical ventilation and heat recovery for low carbon retrofitting in dwellings

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Abstract: The ventilation heat loss in a typical unimproved UK dwelling is approximately equal to the conduction loss; therefore draught-proofing measures should form part of any energy refurbishment package. This will improve the building's air permeability but risks incurring additional energy costs associated with the need to provide controlled ventilation to maintain indoor air quality. This paper aims to determine the point at which the air permeability of the building improves the energy performance by enough to justify the increase in energy associated with the installation of mechanical ventilation with heat recovery (MVHR). A 1930's style semi-detached house, representative of a large proportion of solid wall dwellings in the UK, has been improved by a package of measures including MVHR. The building air tightness plays a critical role in reducing the building energy consumption and CO_2 emissions.

Keywords: *Retrofitting, Building Simulation, Mechanical Ventilation, Heat Recovery*

1. Introduction

The UK has the oldest housing stock in the developed world with over 8.5 million properties over 60 years old1. The consequence of this is that building energy performance was not a concern at time of construction, therefore space heating dominates as a result of poor heat transfer characteristics associated with the building envelope and high infiltration rates. Of the 25 million dwellings in the UK, 34% are solid-wall dwellings and responsible for 50% of the total UK domestic sector CO_2 emissions[2]. CALEBRE (**C**onsumer-**A**ppealing **L**ow **E**nergy technologies for **B**uilding **Re**trofitting) is a £2 million research project, funded jointly by Research Councils UK Energy Programme and E.On. The project aims to establish a validated, comprehensive refurbishment package for reducing UK domestic CO_2 emissions, whilst being acceptable and appealing to householders. As part of this project, a newly-constructed occupied test house (the E.On house), specially built to 1930s standards and located on the campus of the University of Nottingham, is being used to evaluate retrofit solutions specifically targeted at solid-wall properties (classified as 'hard-to-treat'). Currently a number of improvements to the thermal properties of the construction and glazing fittings have been applied, in addition to a series of draught-proofing measures to improve the building air-tightness. An air permeability test is carried out after the application of each measure, and the ongoing energy performance of the building is recorded using a comprehensive monitoring system.

As the air tightness of the building improves it will become necessary to introduce a controlled ventilation system to maintain the indoor air quality (IAQ). As part of this research project a mechanical ventilation system with heat recovery (MVHR) has been installed and the impact on the building performance with regards to energy performance and IAQ is being monitored. The combined effects of improving the air tightness and installing MVHR reduces the building's space heating demand by decreasing infiltration and recovering thermal energy from the exhaust air to preheat the supply air. These savings come at the expense of the energy associated with the system's continuous operation; therefore there is a delicate balance between energy conservation and energy consumption associated with the system.

This paper reports a preliminary study to understand the relationship between energy savings attributable to the MVHR system and whole house air tightness, and to determine the critical value of air permeability above which MVHR is ineffective as a means of energy saving in the dwelling.

2. Building Air Tightness

Findings generally support the notion that dwellings in more severe climates, such as Sweden, Norway and Canada are built more airtight, where the primary aim is to conserve energy and improve thermal comfort[3]. This level of air tightness necessitates a method of controlled ventilation and MVHR is generally installed as standard. The UK experiences a milder climate and dwellings are predominantly less airtight[4], relying on infiltration combined with natural ventilation to provide the necessary air change rate to maintain indoor air quality. Boost extract is employed to remove high levels of pollutants at the point of production, but this strategy cannot guarantee a sufficient level of ventilation throughout the year. The consequences of this could be a build-up of pollutants, and conditions which permit the development of allergens[5], whereas the installation of a mechanical ventilation system can help to mitigate this risk.

In modern society, people spend up to 90% of their time in an artificial environment[6], whether it is a dwelling, workplace or transport vehicle. The ventilation of these spaces plays a critical role in maintaining indoor air quality and ensuring the well being and comfort of the occupant. An insufficient supply of fresh air can be a contributor to ‘sick building syndrome’, where occupants may be susceptible to a range of symptoms such as lethargy, headaches and respiratory problems. Improvements to building air tightness over the last two decades are thought to have contributed to a degradation in indoor air quality where ventilation has been reduced or poorly addressed. An effective ventilation strategy plays an essential role in introducing outdoor air, to dilute contaminants, and promote air movement within the occupied space.

Moisture, although in itself innocuous, is considered a pollutant within the built environment as it is continuously emitted by occupants and the processes they carry out in their day to day activities. As the moisture levels increase, so too does the risk of condensation forming on areas with cool surface temperatures, which can lead to the degradation of the building fabric, as well as other problems such as spores of mould and fungi. This can pose a health hazard causing allergies and illness such as asthma, rhinitis and conjunctivitis[5]. A ventilation strategy plays a key role in controlling humidity levels which can be the driving force behind the specified flow rate.

3. Methodology

A model of the E.On house was built using dynamic thermal modelling software IES Virtual Environment. The Test Reference Year (TRY) weather data for Nottingham was applied and used to predict the annual building energy consumption. Templates were created for each room type, specifying values for internal gains and corresponding diversity profiles. This was based on information detailed for domestic buildings in the NCM database[7], which also provided room heating set-points and domestic hot water consumption. This information was consistent for all analyses.

A series of studies were carried out to determine the critical performance parameters of the MVHR system and whole house air tightness to ensure a net reduction in building energy:

- An initial study considers the energy performance of the E.On house in its original state, and the performance associated with the application of each retrofit measure
- Subsequent studies consider the energy performance associated with an MVHR unit specified to minimum building standards at varying levels of air tightness, and compares this with system components specified to best practice performance standards.

The 'leakiness' of the building is determined by carrying out an air permeability test, or 'fan-blower door test'[8] which creates a differential pressure between the indoor and external environment. Numerous researchers have tried to link this empirically tested value to a background infiltration rate. Kronvall[9] developed a rule of thumb method, dividing the tested air change rate by 20, whereas Dubrul[10] increased the divisor range to between 10 and 30, depending on the exposure of the site. Sherman[11] produced a complex model which incorporated a number of influencing parameters including climate zone, wind shielding, height of the house and size of cracks, whereas Jukisalo[12] further developed this to include leakage distribution and balance of ventilation strategy.

Energy modelling is a detailed and time consuming process if the set-up is to accurately represent the building design and operation, therefore a degree of simplification has been applied to the modelling to provide an initial indication of the impact the variables have on the building performance and energy savings achieved. After assessing the site exposure, Kronvall's rule of thumb has been applied to the analyses to determine the background infiltration rate based on the measured air permeability values. This information will be used to select a number of investigations to consider in more detail, based on information obtained from the extensive measuring and monitoring which is continuing on the house. This preliminary report focuses on modeled output and measured data will be reported later.

4. Results and Discussion

4.1. Application of retrofit measures to the E.On House

The following investigation considers the annual building performance of the E.On House. Table 1 summarises the series of improvements, and the air permeability values tested at 50Pa. These are detailed in units of $m^3/m^2.h$, and corresponding values in ach^{-1}. Notice the poor workmanship which resulted in only a small change in air permeability between stage 1 and 2, and the extensive detailed interventions necessary to achieve low air permeability in this house.

Figure 1 shows the heat losses occurring when the peak space heating load occurs in the E.On house. The improved thermal properties applied in stage 1 halve the external conduction losses, but there is little change in the infiltration losses due to only a marginal improvement in the building air tightness. Infiltration now forms a greater proportion of the overall heat loss, and the introduction of the MVHR system has increased the building air change rate, adding to the load placed on the space heating system. As more draught proofing measures are applied for stage 2, the tested air permeability is significantly reduced contributing to a considerable decrease in infiltration losses. The stage 3 draught-proofing measures provide yet further reductions.

Table 1. E.On House Series of retrofit measures

Stage	Description of work carried out	Air Permeability ($m^3/m^2.h$)	Air Permeability (ach^{-1})
Base Case	Single glazed windows, uninsulated walls, floor and roof space, no draught-proofing	15.57	14.85
1	Double Glazing, wall and loft insulation, draught proofing applied to most windows and doors. Installation of MVHR system	14.31	13.65
2	Draught proofing throughout house re-done as inadequate installation previously, and extended to remaining windows and vents.	9.84	9.39
3	Service risers sealed. Covers fitted to door locks, pipe work envelope penetrations sealed (radiators, water pipes etc), Kitchen fan removed and bricked-up. Sealing around boiler flue.	8.6	8.21

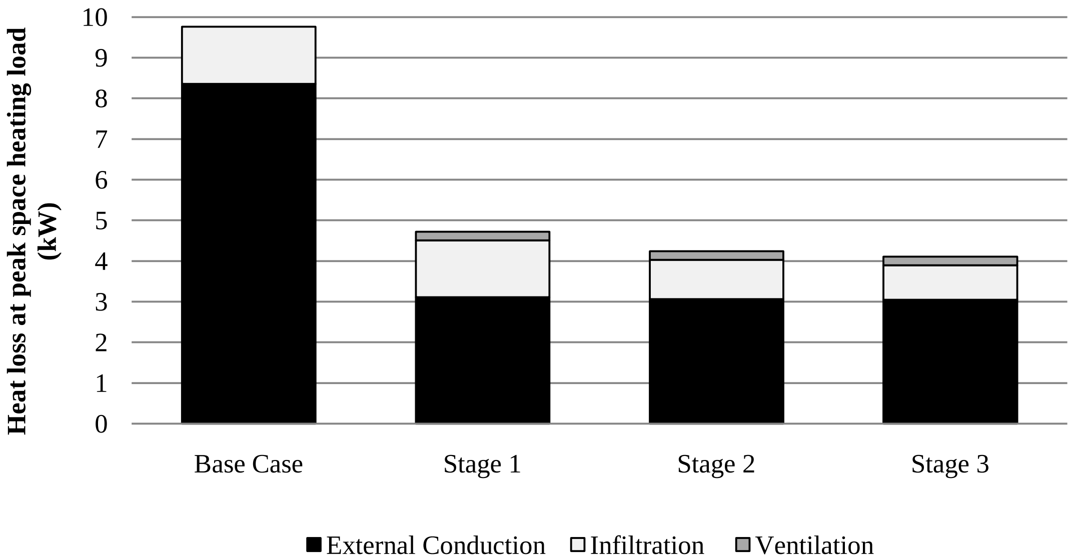

Fig. 1. E.On house heat loss at peak space heating load

Figure 2 details the distribution of the annual building's energy consumption, and the percentage reduction achieved after applying the series of retrofit measures. The MVHR system installed in stage 1 contributes to an increase in auxiliary energy, but the impact is minimal in this instance because of the considerable reduction in space heating due to the thermal upgrades. Stage 2 and stage 3 improvements demonstrate further reductions in annual energy performance, totalling 64% as a result of the improvements to the building air tightness and heat recovery efficiency.

Although stage 3 displays lower building energy consumption compared to the previous analyses, the comparison is not a fair one as there is debate about the point at which a controlled ventilation strategy becomes necessary. BRE Digest 398[12] advises that a whole house ventilation strategy should maintain an air change rate of $0.5ach^{-1}$, less the background infiltration rate. Applying Kronvall's rule, a tested air change rate of $13.65ach^{-1}$ corresponds to a background infiltration rate of $0.68ach^{-1}$ for the E.On house, indicating that a forced ventilation system is unnecessary. If the MVHR system was not included in stage 1 and stage

2 analyses, the building energy consumption would be lower as the auxiliary energy would decrease, and the lack of ventilation losses would mean less demand on the space heating. Stage 3 therefore does not necessarily demonstrate an improved energy performance compared to less airtight buildings when they are considered without a forced ventilation strategy.

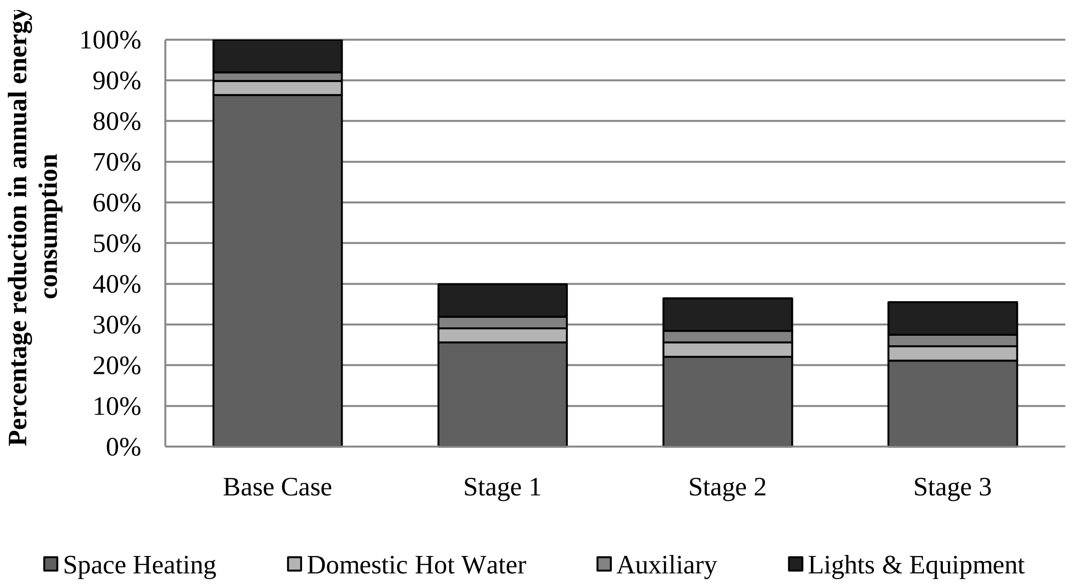

Fig. 2. E.On house percentage reduction in annual building energy consumption

4.2. Impact of building air permeability on the thermally improved E.On House

The second investigation assesses the impact on the performance of the E.On house if future draught-proofing measures were able to achieve lower air permeability values. A ventilation strategy was applied based on the guidance outlined in Approved Document F[13], detailed in table 2. The results are compared against a naturally ventilated E.On house, at an air permeability of $10m^3/m^2.h$ at 50Pa.

Table 2. Building Regulation Criteria

Standard	Criterion	Infiltration Reduction	E.On House Ventilation Flow Rate (l/s)
Approved Document F (Air permeability > 5 $m^3/m^2.h$)	0.3 $l/s/m^2$*	0.04 x gross internal volume	21 l/s
Approved Document F (Air permeability < 5 $m^3/m^2.h$)	0.3 $l/s/m^2$*	n/a	30 l/s

* 21 l/s flow rate is stated for a three bedroom house, but the ventilation should not be less than 0.3 $l/s.m^2$, therefore the greater of the two values should be applied.

The introduction of the ventilation flow rate initially increases the E.On house heat losses at the time of the peak space heating load (Figure 3), however the combined effects of the MVHR system and improvements to the building air tightness to achieve $7m^3/m^2.h$ at 50Pa decrease the infiltration by enough to reduce the overall heat loss to less than the naturally ventilated case.

The ventilation losses are greater for the last two analyses, but it should be noted that the peak space heating load occurs at a different time for these from the first three analyses. The ventilation losses are dependent on the temperature difference between the supply air and the room temperature, which vary over the course of the day depending on the room use. This means the peak ventilation loss does not necessarily coincide with the peak space heating load. As a result, figure 3 shows that improving the building air permeability to 5m^3/m^2.h or less reduces the infiltration losses by enough to move the peak space heating load to a different time, when the ventilation losses form a greater proportion of the total heat loss.

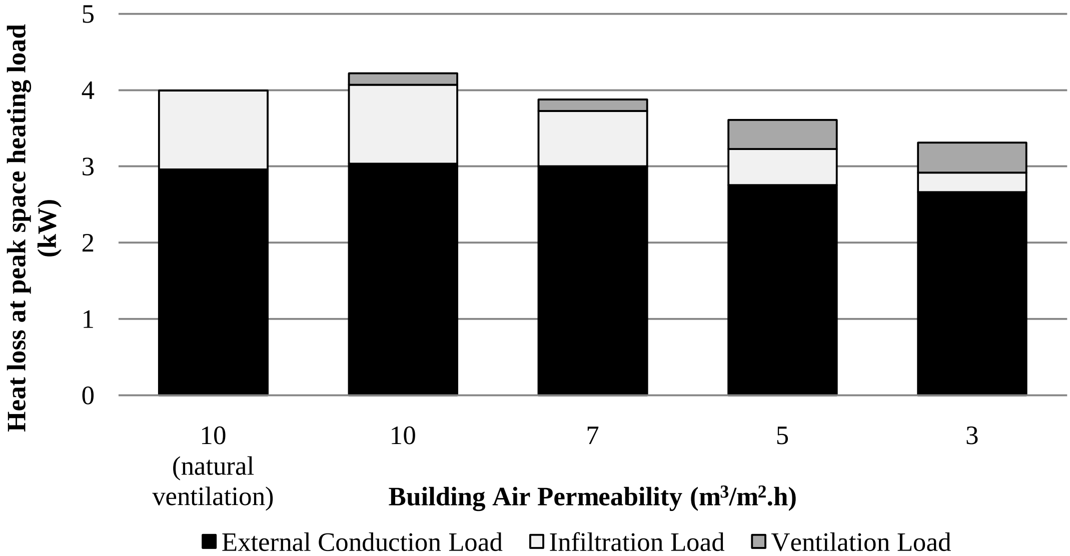

Fig. 3. Heat loss at peak space heating load for improving building air permeability

The annual energy consumption associated with the operation of the building is attributable to the space heating, auxiliary energy (e.g. pumps and fans), domestic hot water, lighting and equipment. The last three parameters are related to occupancy behavior, and predefined by the room templates. Based on the assumption that there is no change in occupancy behavior, table 4 reports the annual energy consumption associated with the space heating and auxiliary systems for the E.On house at different air permeability values. Table 4 details values associated with the E.On house for a natural ventilation strategy with an air permeability of 10m^3/m^2.h at 50Pa, an MVHR system specified to minimum building standards and an MVHR system specified to best practice standards. Table 3 gives the performance parameters of system components associated with these strategies.

Table 3. Performance parameters of system components

Component	Minimum Building Standards[14]	Best Practice[15]
Specific Fan Power (Exhaust Only)	0.5 W/l/s	n/a
Specific Fan Power (Whole House Ventilation)	1.5 W/l/s	1 W/l/s
Heat Recovery Effectiveness	70%	85%

The introduction of the MVHR system increases auxiliary energy consumption, and initially increases the space heating energy as a result of forcing an increased building air change rate which places an additional load on the boiler. The combined effects of improved building air tightness and effective heat recovery need to reduce the space heating energy by enough to negate the increase in auxiliary energy.

For an MVHR system specified to minimum building standards, a reduction in annual energy is achieved when the building air permeability has been improved to $3m^3/m^2.h$ at 50Pa, compared to the naturally ventilated case.

In contrast, an MVHR system operating at best practice standards achieves the break-even point at an air permeability of $7m^3/m^2.h$ at 50Pa. Further improvements contribute to overall energy savings, with an air permeability of $3m^3/m^2.h$ at 50Pa achieving a 10% reduction in the combined annual space heating and auxiliary energy from the naturally ventilated case.

However, an energy reduction does not directly equate to a CO_2 reduction because of the higher carbon intensities associated with electricity compared to gas. The combined effects of reduced air permeability and MVHR must reduce the space heating energy by nearly three times the increase in auxiliary energy to ensure a net reduction in CO_2 emissions. Improving the building air permeability to $3m^3/m^2.h$ at 50 Pa successfully realises a total reduction in CO_2 emissions for the E.On house when the MVHR equipment is specified to both minimum and best practice standards, though the saving is more significant for the latter.

Table 4. Annual space heating and auxiliary energy consumption for improving air permeability

Building Air Permeability at 50Pa ($m^3/m^2.h$)		**10**	**7**	**5**	**3**
Naturally Ventilated Building	Space Heating (kWh/m^2)	85.19	-	-	-
	Auxiliary (kWh/m^2)	9.55	-	-	-
	Combined (kWh/m^2)	**94.74**	**-**	**-**	**-**
Minimum Building Standards MVHR equipment	Space Heating (kWh/m^2)	96.67	85.83	83.42	76.32
	Auxiliary (kWh/m^2)	11.83	11.83	12.72	12.72
	Combined (kWh/m^2)	**108.50**	**97.66**	**96.13**	**89.04**
Best Practice Standards MVHR equipment	Space Heating (kWh/m^2)	94.67	83.92	80.72	73.73
	Auxiliary (kWh/m^2)	10.81	10.81	11.40	11.40
	Combined (kWh/m^2)	**105.48**	**94.73**	**92.12**	**85.13**

5. Conclusion

The modelling indicates that the application of all the retrofit measures detailed in table 1 have successfully reduced the energy consumption associated with the E.On house by 64% compared to the initial 1930's base case scenario.

An MVHR system operating at minimum building standards achieves an overall reduction in building energy consumption compared to the naturally ventilated case only when the air permeability has been reduced to $3m^3/m^2.h$ at 50 Pa, based on the E.On house which has been thermally upgraded.

On the other hand, an MVHR system operating at best practice standards can equal the energy performance of the naturally ventilated case when an air permeability of $7m^3/m^2.h$ at 50 Pa is achieved. Further improvements to the building air tightness to achieve $5m^3/m^2.h$ at 50 Pa or less will contribute to net energy savings.

The results from the modelling show that the building airtightness plays a critical role in achieving a reduction in building energy consumption, and more significantly CO_2 emissions. The difficulties experienced by the E.On house in improving the building air tightness suggest that the challenge of achieving the necessary air permeability should not be under-estimated, and the practicalities should be carefully considered when addressing existing dwellings in the UK.

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Barriers to implement energy efficiency investment measures in Swedish co-operative apartment buildings

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Abstract: We sent a questionnaire to chairmen of 3000 co-operative hosing association across Sweden to analyse their perception about energy efficiency aspects during June-October 2010, and 24% responded. About 80-95% of the respondents had no intention to retrofit their building envelope components during the next ten years measures. A greater proportion of respondents perceived that energy efficient windows were more advantageous than improved attic, basement and external wall insulation. Respondents gave high priority to economic factors in deciding on an energy efficiency investment measure. For 54% of the respondents, lack of expertise of the executive board to assess the benefits of energy efficiency measures was a barrier to energy efficiency investments. Majority of respondents considered economic policy instruments, like investment subsidies and tax deductions, as the most effective method to improve energy efficiency.

Keywords: *Co-operative apartment buildings, energy efficiency, Sweden*

1. Introduction

In Sweden, the residential and service sector's final energy use in 2008 was about 141 TWh, or 36% of the national final energy use [1]. Building envelope components offer a large potential to reduce energy use in existing buildings as they are important source of heat loss. For example, approximately 15 TWh of heat is lost annually through windows of Swedish residential buildings [2], and this loss could be reduced significantly by upgrading the window stock [3]. Sweden has around 2.44 million dwellings in multi-storey buildings [4], which constitute about 55% of the total dwelling units. These buildings provide considerable opportunities for energy efficiency measures and many of them were built in the *million house* programme[1], and require renovation.

The ownership pattern of multi-storey apartment buildings can be categorised into municipal, private and tenant-ownership (henceforth co-operative). Approximately 40% of apartments in multi-storey buildings belong to municipal housing companies, while the rest is equally shared by private companies and co-operative housing associations. The municipal housing and private companies give their apartments for rent, while the co-operative sector resembles a condominium sector [5]. In this paper we discuss co-operative housing associations plan to replace/change their building envelope components, and the barriers to implement investment intensive energy efficiency measures.

There are about 26500 co-operative housing associations in Sweden. These housing associations usually do not have individual measurements for heating and hot water consumption. Typically, the billing for heating and hot water use is included in a monthly rent and is based on the apartment size. The household electricity bill is usually metered separately, and charged to individual apartment owners. The decisions pertaining to the buildings are usually made by the executive board which is headed by a chairman. The executive board members and the chairman are elected by the members of the association and

[1] The decision to built one million dwelling was made in 1965 to address the housing shortage and to stimulate the construction industry.

they occupy the post for a specific time period. The chairmen are in a good position to share information about the implementation of energy efficiency measures in their association's buildings. The paper is based on the response of the chairmen of co-operative housing associations to our questionnaire.

2. Theoretical Background

Potential adopters consider adopting an innovation if they feel a *need* for it [6]. Need is a state of dissatisfaction or frustration that occurs when there is a difference between the desire and perceived actual state [7], i.e., when a problem is recognised [8]. Potential adopters may gather information on various alternatives and process the information to make the decision that best fulfil their prioritised need [8]. In doing so, they usually compare various alternatives based on their perception of the alternatives' attributes, e.g. investment cost, environmental performance, ease of installation. A measure that has greater *perceived* advantages compared to others is likely to be adopted.

In building envelope component replacement decisions, need may arise because of the condition of the existing component(s). The conditions generally depend on the age of installation. In addition, the perceived high cost of energy or a positive attitude to reduce energy use may induce the implementation of such measures. Furthermore, the awareness level [7] of such measures influence the adoption.

However, there may be barriers to implement energy efficiency measures. Building owners or housing associations may not adopt such measures due to lack of awareness or lack of adequate and reliable information [9, 10], or the inability to interpret the available information. Furthermore, potential adopters may have difficulties in perceiving the performance and advantages of energy efficiency measures if the gains are not directly visible [11], insignificant, or delayed. Financial constraints such as difficulty to access capital also hinder investments in energy efficiency [12]. Even if owner/organizations have access to capital, still they may not invest in energy efficiency measures due to the perceived risk of such investment. The perceived risk may be due to their inability to understand the performance and benefits of the installation or due to the uncertainty in future energy price. For example, the return on investment for an energy efficiency measure will be less attractive if the energy price falls [12]. In such situation a risk-averse investor may avoid, or postpone or expect higher returns from energy efficiency investments [12]. A potential adopter may be able to collect information about energy efficiency measures from various sources. But, time, money or both is needed to acquire relevant information [13]. Such hidden costs could act as a barrier to invest in energy efficiency. Moreover, organizations might consider other matters for example cleaning and maintenance of the buildings more important than spending resources in energy efficiency.

3. Methodology

To investigate the adoption of energy efficiency measures in co-operative apartment buildings we sent a questionnaire to the chairman of about 3000 co-operative housing associations across Sweden. Major building management-decisions in co-operative housing associations are made by an executive board, which is headed by a chairman. The chairmen are in a good position to share information about the implementation of energy efficiency measures in their association's buildings. As the number of such association varies significantly across different regions in Sweden, we sent the questionnaire to about 10-11% of associations in each of the 21 counties in Sweden to avoid regional bias. The addresses of the associations were collected from Bolagsverket which drew the address randomly. The questionnaires were sent during

June-October 2010. Some of the associations replied that they could not respond to the questionnaire for various reasons, including their association is very small or their apartments were not currently occupied. Some questionnaires were returned unanswered due to a change in the recipients' addresses. In total, we received approximately 675 completed questionnaires, which corresponded to a response rate of 24%.

4. Results

Approximately 50%, 19% and 14% of the respondents reported that their associations' apartments were heated by district heating, combination with a heat pump and electrical heating, respectively. Approximately 15% of the respondents thought that their annual heating cost was high, while only 6% respondents considered their annual electricity cost as high. Still, for 55% and 38% of respondents, it was important to reduce heating and electricity use, respectively.

About 80-95% of the respondents had no intention to retrofit their building envelope components during the next ten years (Table 1). One of the reasons was that they were satisfied with the condition of the existing installations. The majority of the respondents felt that their windows (76%), attic insulation (59%), basement insulation (64%) and insulation of external walls (80%) were in good condition (Table 2).

Table 1: Plan to improve/change the majority of the building envelope components

Building envelope components	% of respondents		
	No	Yes, with in 3 years	Yes, 3-10 years
Windows (N=578)	79	8	13
Attic insulation (N=555)	84	8	8
Basement insulation (N=534)	94	2	4
External wall insulation (N=548)	94	3	3

"Do not know" responses were considered as missing value

Table 2: Perceived condition of the building envelope components

Building envelope components	% of respondents			
	Good	Medium	Bad	Do not know
Windows (N=662)	76	19	4	1
Attic insulation (N=654)	59	25	10	6
Basement insulation (N=636)	64	19	5	12
Facade (N=658)	80	16	3	1

Potential adopters typically compare various energy efficiency measures based on a number of factors. The factors that are given high priority guide the decisions. A ranking of the priority of various factors is presented in Table 3. The results showed that annual energy cost saving and investment cost were the most important factors. Environmental factors were given low priority. 41% of the respondents reported that their associations consider life cycle cost while making investment intensive measures, while 26% and 32% of respondents reported that will not consider life cycle cost and sometime consider such cost, respectively (not shown in the table).

Table 3: Importance of various factors in respondents' energy efficiency investment decisions

Factors	N	% of respondents Important	Medium	Less important
Reduce annual energy cost	597	88	10	2
Investment cost	593	88	9	3
Functional reliability	532	70	25	5
Improve indoor environment	540	60	35	5
Payback period	547	59	30	11
Environmental benefit	523	42	45	13
Improve market value	525	43	34	23
Technical limitation of buildings (for example no space to add more insulation)	510	37	41	22
Reduce greenhouse gas emission	514	32	47	21
Small/no disturbance to residents	523	33	43	24

N = Number of respondents

We compared the respondents' preference of various energy efficiency measures in building envelope to the ten factors mentioned in Table 3. Table 4 shows that significant percentage of respondents did not know about which building envelope components fares better among the various factors. However, those respondents who were aware about performance of building envelope components preferred energy efficient windows followed by improved attic insulation. More respondents were found to be aware or very much aware about energy efficient windows (59%) than about attic (53%) or basement (42%) or external wall insulation (50%) improvements (not shown in the table).

Table 4: Preferred building envelope measure against the various factors

	% of respondents (N=673)				
	Energy efficient window	Attic insulation improvement	Basement insulation improvement	External wall insulation improvement	Do not know
Annual energy cost reduction	26	24	7	12	27
Investment cost	27	21	6	10	25
Functional reliability	14	9	3	5	43
Improve indoor environment	19	7	4	7	37
Payback period	9	8	3	6	48
Environmental benefit	11	9	5	6	47
Improve market value of the property	17	7	3	6	44
Technical limitation of the buildings	4	6	4	4	54
Reduce GHG emission	7	7	3	5	50
Small/no problem for residents	8	9	3	5	45

Respondents' views on issues that may influence implementation of investment intensive energy efficiency measures (like building envelope components, improvement in ventilation system) are presented in Table 5. For 54% of the respondents, lack of expertise of the executive board to assess the benefits of energy efficiency measures was a barrier to such investments. About 35-40% of respondents thought lack of appropriate and easily available information was a barrier, while economic constraints were reported to be a barrier by 34% of the respondents. Approximately 77% of respondents considered the financial position of their association as good and 61% considered it would be easy to finance renovation of their buildings. Similarly, about 40% of the respondents reported that their associations were interested to invest in energy efficiency measures if they receive attractive financing (not shown in the table). Respondents' did not think that residents would oppose energy efficiency investment measures. However, in response to another question, a large number of respondents (45%) believed that if the investment in energy efficiency measure will increase the monthly payment then the residents will resist investments in such measures.

Table 5: Issues regarding investment intensive energy efficiency measures in apartment buildings

Statements	% of respondents		
	Agree	Neither nor	Disagree
The board does not have own expertise to assess the benefits of energy efficiency measures (N=629)	54	22	24
Uncertainty about future energy prices makes it difficult to invest in energy efficiency measures (N=608)	40	31	29
It is difficult to obtain reliable information about costs and benefits of energy efficiency measures (N=611)	37	33	30
Time and effort required to collect necessary information is too high (N=612)	35	31	34
Financial constraints makes it difficult to invest in energy efficiency measures (N=611)	34	29	37
If the association reduce heat energy, district heating companies will increase energy price, thus making the effort worthless (N=550)	26	26	48
Changing behaviour like switching off lights is more beneficial than investments in energy efficiency measures	22	40	38
Investments in energy efficiency measures are low priority compared to other measures (N=622)	21	38	41
Members of association does not support investments in energy efficiency measures (N=609)	8	34	58
Association has a complex chain of decision making process which makes it difficult to invest in energy efficiency	7	15	78

N = Number of respondents

Sweden uses an array of policy instruments to promote energy efficiency in building sector. However, the effectiveness of policy instruments may vary. Majority of respondents considered economic policy instruments, like investment subsidies and tax deductions, as the most effective method to improve energy efficiency (Table 6). More frequent meter reading and energy billing was favoured by less number of respondents.

Table 6: Chairmen's responses to the question, "Irrespective of how much you know about the following measures – How effective do you think the following measures are to encourage you to implement measures to reduce energy use in your apartment buildings"

	% of respondents		
	Effective	Moderately effective	Less effective
Investment subsidy (N=568)	73	18	9
Tax deduction (N=563)	64	20	16
Individual metering of tap water (N=555)	41	27	32
Individual metering of space heating (N=555)	41	27	32
Building regulations (N=546)	34	38	28
Energy tax (N=574)	39	32	29
Energy declaration (N=564)	29	31	40
Energy labelling (N=531)	22	41	37
Carbon dioxide tax (N=561)	27	33	40
More frequent reading of energy (N=550)	28	29	43
Electricity certificate (N= 551)	20	38	42
Voluntary program (N=528)	14	40	46
More frequent billing of energy (N=549)	22	26	52

N = Number of respondents

5. Discussion and Conclusions

Approximately 55% of the chairmen of co-operative housing associations' have a positive attitude to reduce heat use. The lower concern towards electricity use by the respondents could be because the household electricity bill is usually metered separately and the collective burden of electricity cost is less. However, majority of co-operative housing association did not intend to replace/change majority of their building envelope components during the next ten years. One of the reasons is that the associations were satisfied with the condition of existing building envelop components. In this situation, it is important to increase the awareness of energy efficient alternatives. A large percentage of respondents were not aware about the various energy efficient possibilities in building envelope. Moreover, about 35-40% of respondents thought lack of appropriate and easily available information was a barrier to implement energy efficiency investment measures. Information stressing the cost benefits of the energy efficient alternatives should be effectively communicated. The source of information is also very important in the adoption of investment measures. Hence, it is necessary to use the sources such associations consider important in adoption of energy efficiency measures.

As annual energy cost reduction is a very important guiding factor in associations' adoption of energy efficiency measures, information campaigns announcing the cost advantages of energy efficiency measures may be helpful in adoption decisions. However, majority (54%) of respondents reported that they did not have the expertise to assess the benefits of energy efficiency measures, while 34% of respondents reported financial constraints as the barrier. Innovative energy efficiency renovation package which include consulting, financing, contract work and follow up may be able to tap this segment.

Since respondents gave higher priority to reduce the annual cost of energy than to environmental benefits, increasing energy prices using economic instruments to internalise the environmental costs could encourage people to implement energy efficiency measures. In Sweden, external cost of energy use is internalized through taxes on emission of CO_2, sulphur and NO_x. However the price elasticity of energy demand in Sweden is low [14], and in such situations imposition of taxes to reduce energy use may be less effective [15].

Respondents gave high priority to investment cost in their energy efficiency decisions. Respondents also favour economic policy instruments compared to other policy instruments as the most effective method to improve energy efficiency. Subsidies may encourage the adoption of investment intensive energy efficiency measures by reducing the investment cost. The cost effectiveness of the subsidies could be improved by restricting its beneficiaries, for example subsidies may be granted based on the age of the components/buildings.

More respondents were unsatisfied with their attic insulation compared to other building envelope components. However, the respondents were more likely to replace windows than attic insulation. This could be because windows have a higher degree of *observability* as compared to attic insulation. If we encounter a problem frequently, we give priority to that problem more so than to others that are less observable [16]. Also more respondents had a favourable attitude towards energy efficient windows compared to other building envelope measures on various factors that influence the adoption decision.

A large percentage of respondents were unaware about various aspects of different energy efficient building envelope measures. The situation calls for measures to improve awareness about such measures among co-operative housing associations. As many respondents were not satisfied by the attic insulation of their buildings, it may be relatively easier to influence them to implement energy efficiency improvements in the attic insulation.

Acknowledgments

The authors gratefully acknowledge the financial support from the Swedish Energy Agency and from the European Union.

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Performance of a cold storage air-conditioning system using tetrabutylammonium bromide clathrate hydrate slurry

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Abstract: A cold storage air-conditioning system was built to investigate the energy saving effect of using tetrabutylammonium bromide (TBAB) clathrate hydrate slurry (CHS) as cold storage medium, the corresponding *COP* during TBAB CHS generation and the pumping power during the cold release were measured. As the increase of the TBAB CHS mass fraction during the generation, the system *COP* generally decreased from about 1.92−2.95 to about 1.05−1.49, depending on TBAB CHS flow rate. To clarify the performance of this system, several cold storage strategy cases are studied, the corresponding electric power consumption and the cost saving, compared with water as the cold transportation medium, are shown in this work as well.

Keywords: *Clathrate hydrate slurry, Secondary loop air-conditioning system, evaluation.*

1. Introduction

As a new kind of phase change slurry material, tetrabutylammonium bromide ($[CH_3(CH_2)_3]_4NBr$, TBAB in abbreviate) clathrate hydrate slurry (CHS) was studied by many researchers in recent years. Due to the adjustable phase change temperature over the range of 5−12 ^oC, the good cold-carry capacity which is about 2−4 times of that of chilled water and the good fluidity, TBAB CHS is considered promising in an air-conditioning system, where this slurry can be used both as cold storage and transportation medium.

Researchers in Japan firstly reported this new material for air-conditioning using, and measured the basic thermo-physical properties, including the phase diagram, latent heat, density, heat capacity, thermal conductivity etc. [1, 2], and they also applied it to a real application [3]. Hayashi et al. [1], Darbouret et al. [4], Xiao et al. [5] and Ma et al. [6] all investigated the flow characteristics of TBAB CHS in straight tubes, nevertheless, the results reported were divergent. Moreover, Ma et al. [6] reported the forced convective heat transfer characteristics. However, the application of TBAB CHS is still limited by the deficient studies, and the performance in an air-conditioning system is rarely reported.

In the present study, a cold storage air-conditioning system using TBAB CHS was built and the corresponding performance was presented. System *COP* during TBAB CHS generation and the pumping power during cold release were both measured, based on which the system energy consumption was numerically estimated in different cases. In addition, the cost saving of using TBAB CHS compared with that of using chilled water as the cold transportation medium was evaluated.

2. Methodology

2.1. Basic thermo-physical properties of TBAB CHS

The TBAB CHS is a kind of solid-liquid suspension with white color, as shown in Fig. 1, which can be easily generated at atmosphere condition by cooling down the TBAB aqueous solution to supercooling state. The melting temperature, mass fraction, latent heat and other properties (such as density, heat capacity and thermal conductivity) of TBAB CHS are introduced in this section.

Fig. 1. Photo of the TBAB CHS.

The melting temperature could be determined with the aid of the phase diagram, which describes the relation between it and the corresponding solution concentration. Differential Scanning Calorimeter (DSC, TA, Q2000) was applied to record the heating processes of TBAB CHS at a heating rate of 0.5 ^{o}C/min, and then the phase diagram could be plotted based on the test results, which is shown in Fig. 2 as well as the comparison with that obtained by other researchers.

The volume and mass fraction of CHS can be determined by Eq. (1) and (2), with several requisite parameters provided by the phase diagram.

$$\omega_{p} = \frac{\omega_{0} - \omega_{liq}}{\omega_{H} - \omega_{liq}} \quad (1)$$

$$\varphi = \frac{\omega_{p} / \rho_{p}}{\omega_{p} / \rho_{p} + (1 - \omega_{p}) / \rho_{liq}} \quad (2)$$

where ω_{p} is the crystal mass fraction of TBAB CHS, ω_{0} is the initial solution concentration, ω_{H} is the TBAB mass fraction in the hydrate crystal, ω_{liq} is the concentration of the liquid phase in the slurry, φ is the TBAB CHS volume fraction, ρ_{p} and ρ_{liq} are densities of the crystal and the liquid phase, respectively. Two different hydrates with different hydration numbers were observed, and the corresponding thermo-physical properties have been summarized by Ma et al. [6], as shown in Table 1, the two values of some properties in the table were the result of different researches referenced.

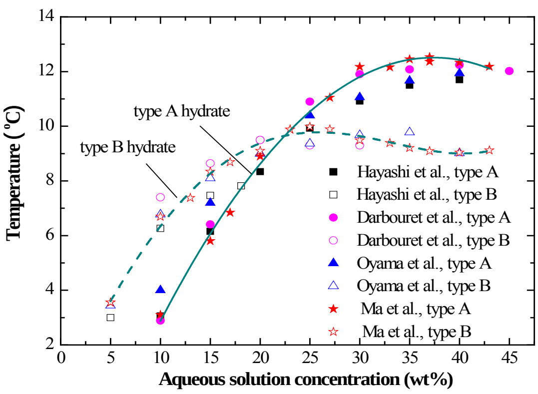


Fig. 2. Phase diagram of TBAB CHS. [6]

Table 1. Thermo-physical properties of TBAB hydrate crystals [6].

	Hydration number -	Melting temperature (°C)	Density (kg/m^3)	Latent heat (kJ/kg)	Heat capacity (kJ/(kg·K))	Thermal conductivity (W/(m·K))
type A	26	11.8/12.0	1080	193.18±8.52	2.22/1.86–2.61	0.42
type B	36/38	9.90	1030	199.59±5.28	2.00–2.54	–

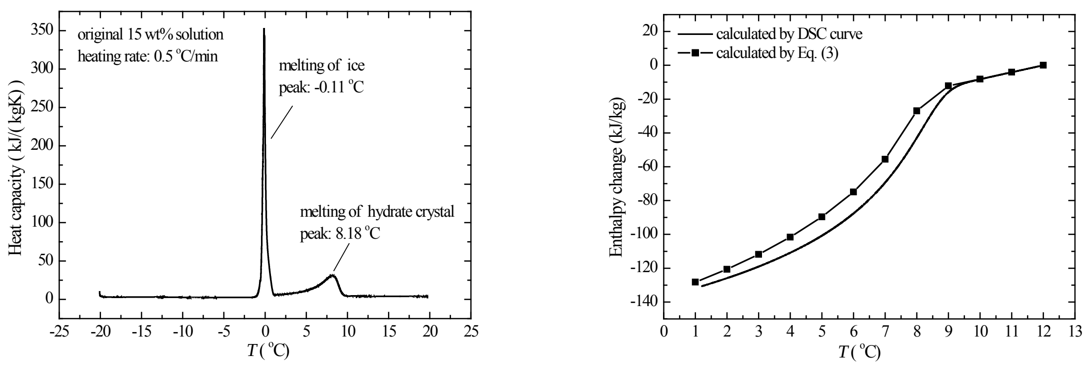
Density of TBAB aqueous solution was measured using a balance (FS: 2200g, accuracy: 0.01 g) and a graduated flask (FS: 50 mL, accuracy: 1 mL), while the heat capacity was measured based on the heat balance with water in a plate heat exchanger. Thereafter, these properties of TBAB CHS can be calculated by the corresponding values of TBAB solution we measured and that of TBAB hydrate crystal given in Table 1. Meanwhile, thermal conductivity of TBAB aqueous solution as well as TBAB CHS was measured by a transient hot-wire unit (the measuring error was less than ±3% while water was applied). All the properties of TBAB CHS (type B hydrate, original 15 wt% solution) are presented in Table 2.

Table 2. Thermo-physical properties of TBAB CHS (type B hydrate crystal, original 15 wt% solution).

Mass fraction (wt%)	Density (kg/m^3)	Heat capacity (kJ/(kg·K))	Thermal conductivity (W/(m·K))
5	1015.690	4.001	0.469
10	1015.656	3.933	0.473
15	1015.635	3.865	0.476
20	1015.608	3.798	0.480
25	1015.585	3.732	0.483
30	1015.560	3.667	0.485

The enthalpy change (*Q*) of TBAB CHS in a certain temperature range, 5–12 °C for example, is an important parameter which indicates how much cold energy is stored or released. Basically, there are two methods to calculate the enthalpy change of this slurry. One is introducing the slurry fraction change ($\Delta\omega$), the latent heat (ΔH) and the sensible heat ($Cp\Delta T$) into Eq. (3):

$$Q = \Delta\omega\Delta H / 100 + Cp\Delta T \tag{3}$$



(a) (b)

Fig. 3. (a) DSC curve; (b) enthalpy change of TBAB CHS.

The other method is integrating the DSC heating curve against temperature shown in Fig. 3(a). The comparison between these two methods is shown in Fig. 3(b). The enthalpy change within the temperature range of 5 to 12 ^{o}C calculated by Eq. (3) is about 10.9% smaller than that calculated by DSC curve, and the latter method was applied in the present work.

2.2. Experimental set-up and CHS generation method

Fig. 4 shows the schematic diagram of the constructed cold storage air-conditioning system using TBAB CHS. Two thermal insulated tanks (1.2 m^3) were used for solution and slurry, respectively. Three Pt100 sensors（accuracy: ±0.15 ^{o}C) were employed to record the temperature variations at the bottom, middle and top of the each tank. A double-tube heat exchanger (ShenShi, GT-U0480) with corrugated flow passage was applied to undertake the heat exchange between solution and the evaporating refrigerant. The refrigerator used was an outdoor unit of a commercial air-conditioner, which can switch from cooling to heating by a four-way valve. The used slurry pump was a speed adjustable rotational pump and a stabilizing tank located at the downstream of the pump was used to stabilize the flow. A simple agitator was mounted on the slurry tank, which was operated to avoid the deposition of crystals. A plate heat exchanger (Swep, B8×30) was selected as the load side heat exchanger since its high heat transfer rate, and hot water acted as the cooling load. The hot water was stored at an insulated water tank before experiment and was drained after used. Moreover, pressure sensors (accuracy: 0.1%) were located at different positions of the fluid flow to measure the pressure drop, and the electric power consumed by the refrigerator and the pump were measured as well.

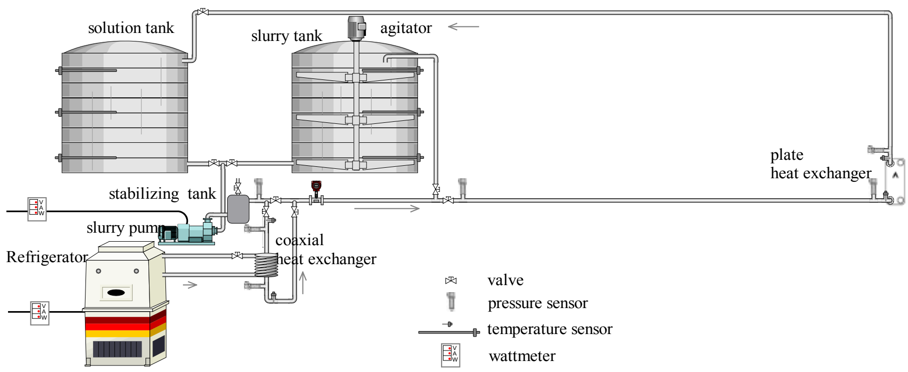


Fig. 4. Schematic diagram of the experimental set-up.

The test was divided into three steps based on the state of the TBAB CHS: (1) The aqueous solution was cooled to supercooling state. However, the supercooling state cannot be achieved by only one cycle from the solution tank to the slurry tank due to the limited cooling power of the refrigerator. As a consequence, the solution must be continuously pumped through the double-tube heat exchanger from and back to the slurry tank. (2) Hydrate crystals appeared. Accompanied with mechanical shocks between the returned fluid and the stored fluid, TBAB hydrate crystals can be generated in the supercooled solution, and the fluid temperature increased because of the released latent heat. Moreover, sometimes the agitator should be operated to accelerate the hydrate crystal generation. (3) TBAB CHS was kept cooled to reach the desired crystal fraction. (4) TBAB CHS was pumped to the load side to release the stored cold energy, and afterwards became aqueous solution again and flowed back to the solution tank.

The crucial disadvantage during the entire test occurred in step 3. Before the desired hydrate fraction was achieved, TBAB CHS was continuously cooled and hydrate crystals grown inside the heat exchanger. The generated crystals would adhere to the heat transfer surface where the temperature was extraordinary low. The adhered crystals layer deteriorated the heat transfer between refrigerant and TBAB CHS. The worse thing was that the refrigerant temperature dropped a lot to maintain the heat exchange, which resulted in forming more hydrate crystals and creating thicker crystal layer on the heat transfer surface. A malignant cycle occurred, the hydrate crystals were difficult to be continuously produced and the system efficiency became low.

Three methods are mainly proposed to solve the aforementioned low-efficiency problem: (1) Maintaining the refrigerant temperature at a certain temperature range by adjusting the refrigerant flow rate. (2) Increasing the flow velocity of the TBAB CHS to be high enough to flush and break off the crystal formed on the flow passage wall so that to ensure a good heat transfer. (3) Operate the refrigerator reversely from cooling to heating for a while to melt the adhered hydrate crystals. In this work, a manual needle throttle valve was applied to implement the first method, and it was found that more accurate control of the throttle valve was needed. Thus, the method (2) and (3) were applied to ensure the continuous generation of hydrate crystals and high system efficiency, as shown in Fig. 5. With high flow rate (about 16–18 kg/min in Fig. 5) and reverse operation, we obtained 31 wt% TBAB CHS successfully.

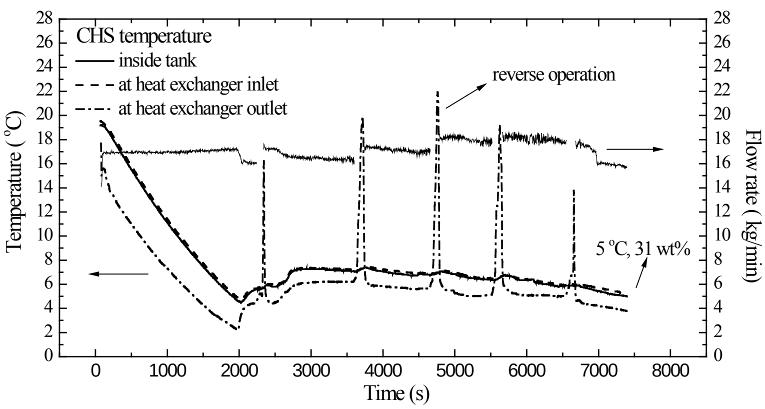


Fig. 5. Typical generation process of TBAB CHS.

3. Results and discussions

The system *COP* during the CHS generation was calculated by Eq. (4):

$$COP = \frac{\text{cold energy stored by TBAB CHS}}{\text{refrigerator power} + \text{pumping power}} \quad (4)$$

It should be claimed that the stored cold energy was all calculated from 15 ^{o}C solution to the stored TBAB CHS. Fig. 6 shows *COP* as function of the mass fraction as well as the flow rate. The *COP* of 0 wt% TBAB CHS shown in the figure was the average system *COP* before the hydrate appearance. The hydrate crystals were generated instantaneously, thereafter about 14–16 wt% mass fraction was soon reached, hence *COP* from the beginning to this moment was higher than that before the generation. However, as increase of the mass fraction, *COP* reduced from about 1.92–2.95 to about 1.05–1.49 due to the aforementioned crystals adherence to the heat transfer surface. Meanwhile, the reverse operation of refrigerator consumed additional energy, which was another attributor to the *COP* reduction. As mentioned, high flow velocity was beneficial to the heat transfer between TBAB CHS and refrigerant, since the adhered crystals would be flushed down by the strong shear force, which was validated by *COP* profile shown in the figure—higher flow rate generally led to a higher *COP*. However, this phenomenon depended on the performance of the pump.

The pumping power during the cold release will be reduced if TBAB CHS is applied as the secondary refrigerant instead of chilled water due to its higher cold-carry capacity and thus the flow rate is lower. Fig. 7 presents the pumping power of water, 20 wt% CHS, 25 wt% CHS and 30 wt% CHS as the function of the cooling load during the cold release. As seen in the figure, more energy saving on pumping power was achieved by using TBAB CHS with higher mass fraction.

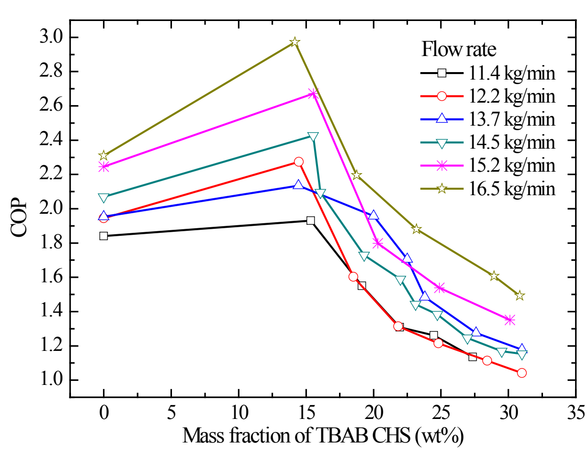


Fig. 6. System COP during the CHS generation.

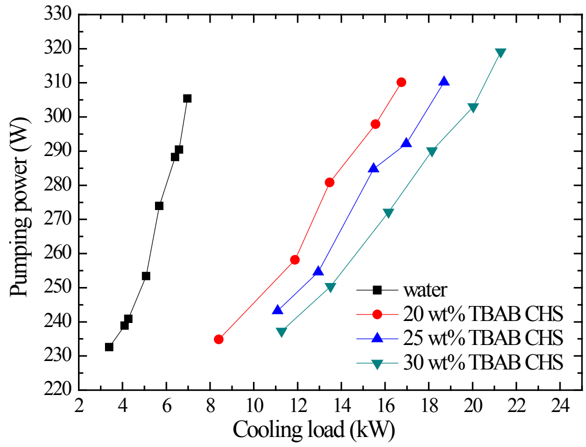


Fig. 7. Pumping power during the cold release.

A study case is assumed for better exhibiting the performance of TBAB CHS. The assumed cooling load is in eight hours in daytime, during which the average cooling load is 21 kW and the maximum value is 33 kW, therefore the totally cooling duty is 604800 kJ. Fig. 8 shows four types of system operation strategies. For each case, 20 wt%, 25 wt% and 30 wt% CHS are applied, the system *COP* during the TBAB CHS generation is about 2.10, 1.79 and 1.54, respectively based on the results in Fig.6 (flow rate: 16.5 kg/min). The storage ratio (which is the ratio of the storage cold energy to the total required cold energy) of case 1 and case 2 is 40% while that of case 3 and case 4 is 60%, the other cooling load is satisfied by the refrigerator (average system *COP* is about 2.32) while considering water as the secondary refrigerant. Moreover, assume the application of water as case 5 for the comparison, and consider water as the secondary refrigerant for all the cold release and no cold storage is conducted.

Fig. 9(a) shows the electric power consumption with all the study cases based on the present system. It can be seen from the figures, the power consumption increases as the increase of the mass fraction, which is obviously caused by the lower system *COP*. All the power consumptions in cases 1-4 are higher than that of case 5, which means there is no energy saving of the application of TBAB CHS compared with water. However, the operation cost does decrease as the increase of TBAB CHS mass fraction and the cost saving is shown in Fig. 9(b) (the price of the electricity is taken as 0.3 RMB/kWh during night time while 0.6 during daytime), about 8–27% cost saving can be achieved. However, since the the present system is limited by the room space, the piping from the storage tank to the load side is very short and thus the pumping power shown in Fig.7 is not coincident to the practical system with the assumed cooling load. Therefore, we re-calculate all the cases with amplifying the pumping power to 3 times as large as the present measured values during the cold release, the original case 1–5 become to case 1'–5'. Fig. 10(a) and (b) show the corresponding electric power consumption and the cost saving. It is noticed that about 1.4–3.5% energy saving is achieved, calculated by 20 wt% TBAB CHS with all the operation strategies, while the cost saving increases to about 10–29%.

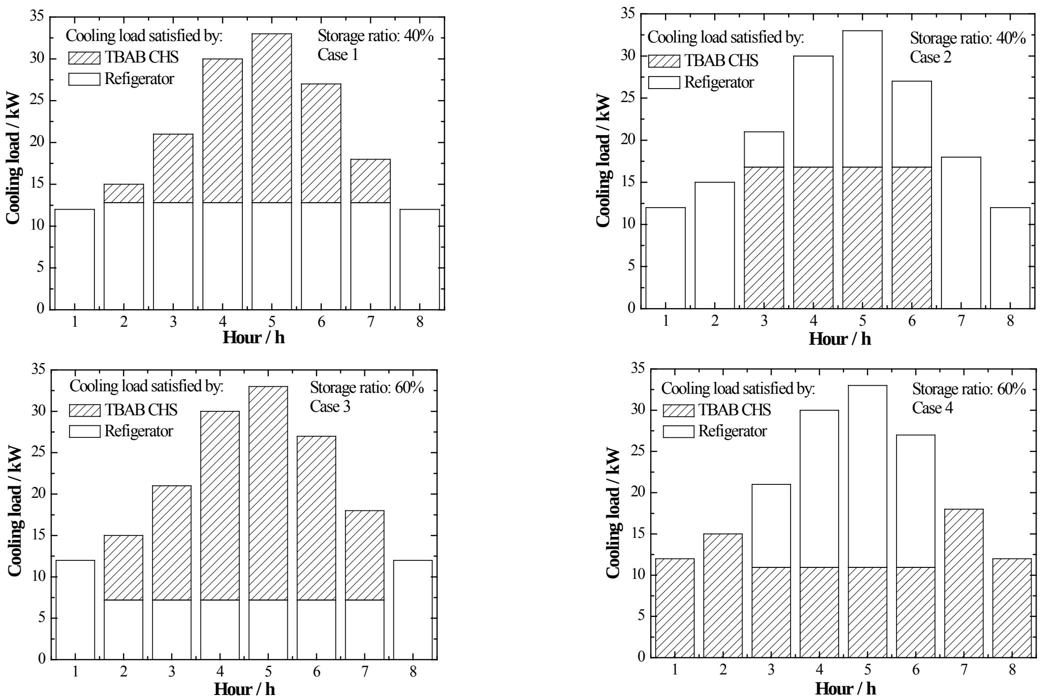


Fig. 8. System operation strategies.

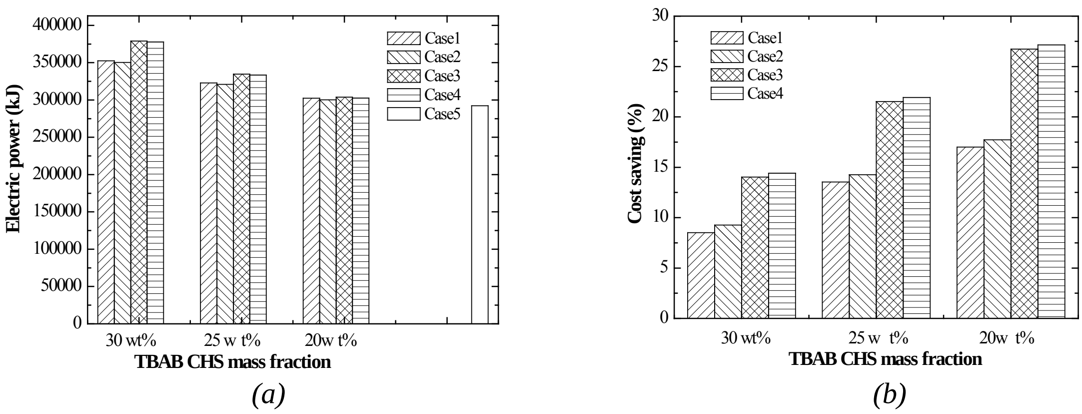
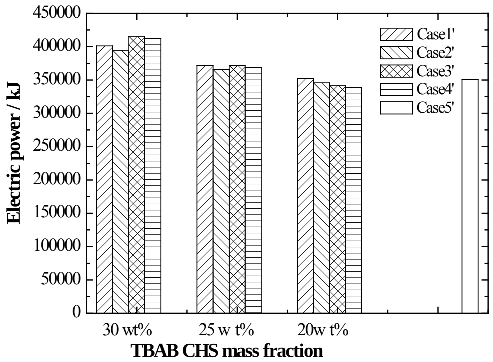


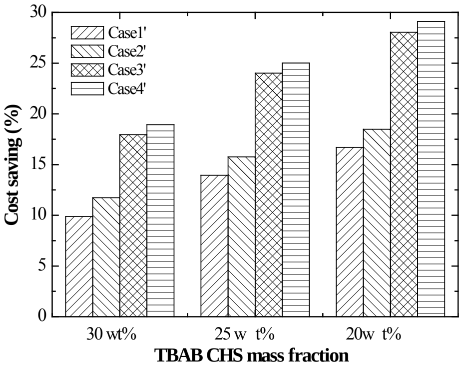
Fig. 9. Electric power consumption and cost saving.

4. Conclusion

The present work mainly constructed and tested a cold storage air-conditioning system using TBAB CHS and estimates the energy consumption. The system *COP* decreased from about 1.92–2.95 to about 1.05–1.49 during CHS generation. The energy saving by using TBAB CHS instead of water was not achieved as expected since the piping was short and the pumping power was low in the present system, while 8–27% cost saving was achieved. However, about 1.4–3.5% energy saving could be achieved if the pumping power was amplified to 3 times as large as the original values, meanwhile the cost saving was about 10–29%.



(a)



(b)

Fig. 10. Electric power consumption and cost saving with amplified pumping power.

Acknowledgements

The authors are grateful to the "Shu Guang" project supported by Shanghai Municipal Education Commission and Shanghai Education Development Foundation under the Contract No. 09SG11 and the Science and Technology Commission of Shanghai Municipality under the Contract No. 10160710700. This research is also partially supported by the Specialized Research Fund for the Doctoral Program of Higher Education under the Contract No. 20100073110039.

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Understanding occupant heating practices in UK dwellings

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Abstract: The 2008 Climate Change Act has committed the UK government to reduce CO_2 emissions by 80% of 1990 levels by 2050. To meet this target a significant reduction in energy consumption will be required from domestic dwellings and in particular space heating which accounts for more than 50% of the energy used in the UK housing stock. The UK government has initiated a number of policies to reduce energy use from UK dwellings. Energy savings that result from energy efficiency improvements to dwellings have sometime been lower than expected as a result for the rebound effect. Discussion of the rebound effect has questioned whether these polices will result in the CO_2 reductions required to meet the national targets. Large-scale survey research has shown that energy use is related to climate, built form of properties, efficiency of heating systems, socio-economic indicators and occupant behaviour. Temperature monitoring studies have been undertaken to gain insight into how occupants heat their homes. If the variation in indoor temperatures can be explained by; (1) social determinants such as age, income and the number of household occupants and; (2) technical determinants such as house type, house age and level of insulation then this would enable energy efficiency initiatives (e.g. cavity wall installation or education programmes) to be targeted where they will be most effective. This paper presents preliminary results from a large-scale city-wide survey of over 500 homes in the city of Leicester, UK. temperature measurements were recorded at hourly intervals over a nine month period for the living room and main bedroom spaces in over 300 homes. Household data, including socio-demographic information, was collected for each household. This dataset is used to investigate indoor temperatures across house types. The results confirm that house type is related to differences in indoor temperatures. Flats have the highest average temperatures while detached homes have the lowest. To gain insight into heated periods households with average evening temperatures were identified. It was found 45% of mid terrace properties had evening temperatures below 18°C and more than a third of detached and semi detached home also had cold evening temperatures. There are a number of reasons for low indoor temperatures in dwellings during occupied periods including inefficiency of buildings and heating systems, the inability of occupants to afford heating and personal choice. It is concluded that to meet Government CO_2 reduction targets the rebound effect should be taken into account when calculating the energy savings expected from energy efficiency programmes. Further analysis is ongoing to identify how other social and technical factors relate to indoor temperatures. Multiple regression analysis will be used to identify how internal temperatures are correlated against a number of determinants including building characteristics (built form type, age, heating system type, heating controls) and household characteristics (age of occupants, income).

Keywords: *Indoor temperature, Heating practices, Household behaviour, Space heating, Energy efficiency.*

1. Introduction

The 2008 Climate Change Act committed the UK government to reduce CO_2 emissions by 80% of 1990 levels by 2050 [1]. To meet this target a significant reduction in emissions will be required from all energy sectors. In 2008 energy use from domestic buildings accounted for 27.5% of total UK energy consumption [2]. CO_2 emissions associated with domestic buildings are predominantly related to electricity generation and energy used for space and water heating. Space heating accounts for 57% of all energy used in UK domestic buildings [3]. Reducing the energy used for space heating is a challenge as it is related to the technical performance of the building and its heating systems, as well as the behaviour of occupants [4, 5]. The UK government has introduced a number of policies that are designed to reduce the energy use related to space heating. One of these is the 'Green Deal' which was announced by the UK government in 2010. Householders will be given a loan to make energy efficiency improvements to their properties and are expected to make repayments using money saved due to lower energy bills [6]. Technical improvements to dwellings such as cavity wall or loft insulation or the installation of energy efficient boilers do not always result in the expected energy savings [7]. This was evidenced by the Warm Front study, energy use was measured before and after energy efficiency improvements and theoretical energy use compared to actual energy use. It was found that actual energy improvements were approximately 30% less than expected [7]. This phenomenon is called the ‘rebound effect’ and brings into question the ability of households to make payments based on energy savings [8]. Literature on the ‘Green Deal’ does not discuss how payments will be made if energy efficiency improvements do not result in financial savings. The rebound effect has been used to argue against making efficiency improvements in the existing housing stock [9]. As a consequence, Government emissions targets based on expected energy savings are unlikely to be met. This criticism, however, does not account for the improvements in health and wellbeing of occupants that are related to the increase in indoor temperatures that can be the result of energy efficiency measures [10]. The challenge for policy makers is to address energy and CO_2 reduction while accounting for the ‘rebound’ effect. One example of this is the households in fuel poverty. A household is said to be in fuel poverty if they require more than 10% of their income to heat their home to a comfortable temperature [11]. In 2007 3.5 million households in the UK were in fuel poverty [11], if energy efficiency improvements were made in these dwellings it is assumed that energy savings would be minimal, as indoor temperatures would increase in many of the households.

The health and wellbeing of the occupants has been addressed for new builds since the publication of the Code for Sustainable Homes in April 2007 [12]. Health and wellbeing have, however, not been addressed in discussions about energy efficiency improvements in older properties which make up the majority of the housing stock or in the energy saving advice that is provided by local and national government. Generic energy saving advice such as ‘turn your thermostat down 1°C will save you 10% of your heating bills’ may be appropriate for some households but not occupants that are already living in cold homes [13]. These issues raise two concerns; (1) how can energy efficiency policies ensure both energy savings and improved health and comfort of occupants and; (2) what energy savings should be expected as a result of energy policies after the indoor temperatures in some households have increased. The mitigation of the effects of climate change is a strong driver for energy reduction but should not be addressed outside of the context of other health and comfort issues. For energy policy to effectively reduce CO_2 emissions and improve the health and comfort of building occupants more information about the housing stock and the drivers of indoor temperatures is required. The accidental benefits of energy improvements such as improved health of occupants should not be ignored. Joined up solutions designed to reduce energy consumption in the housing stock while improving the thermal comfort of vulnerable household occupants are required to address a fully sustainable approach to emissions reduction programmes. The benefits of the rebound effect should, therefore, be recognised despite the reduction in CO_2 emissions savings that may result in a portion of the housing stock. For policy makers to accurately predict the result of energy efficiency improvements at the national scale the proportion of dwellings where reduced savings are expected should be considered.

To promote the health and wellbeing of building occupants the World Health Organisation (WHO) has suggested dwellings are heated to indoor temperatures of 21°C in the living room and 18°C in bedroom spaces [14]. Previous temperature monitoring studies provide insight into the temperatures to which UK dwellings are heated. To understand whether dwellings are heated to the recommended temperatures it is important to ascertain what the indoor temperatures are in living spaces during occupied periods. Shipworth et al. (2010) measured temperature in a large sample across the UK [15]. Daily peak temperature was estimated to be

21.1°C. This finding, however, can be easily influenced by periods of high internal or solar heat gain. Other studies have reported temperatures averaged over the whole day. Oreszczyn et al. (2006) monitored temperature in over 1600 low income dwellings. Average living room temperature, adjusted for outdoor temperature, was reported to be 19.1°C [10]. Summerfield et al. (2006) monitored indoor temperatures in 14 UK dwellings built to high thermal standards and found that the average living room temperature was 19.1°C [16]. Yohanis and Mondol (2010) reported an average living room temperature of 19.4°C measured in 25 dwellings in Northern Ireland [17]. All of the average temperatures reported in the UK studies are lower than the recommended temperature of 21°C.

The temperatures reported in these papers have not been analysed to ascertain which dwellings have low indoor temperatures. In order to inform how policy can be targeted a sample which includes all house types and people groups is required. These studies have gained valuable insights into indoor temperatures in UK dwellings but have not reported indoor temperatures during occupied periods. Isaacs et al. (2010) monitored temperature in New Zealand homes and calculated average temperatures for different parts of the day [18]. Average temperatures suggested that many dwellings were not heated to the 21°C recommended by the WHO [18]. Dwellings heated by solid fuel were found to have warmer living room temperatures on average than those heated in other ways. This finding led to a policy change by the New Zealand government to subsidise the installation of wood burners as well as gas and electric fires. Empirical evidence is required to see if any changes to UK CO_2 reduction policy are necessary.

This paper presents initial analysis of temperature data collected in over 300 houses across Leicester, UK between July 2009 and March 2010. This data set is novel as it is the first large scale study to focus on a single UK city. This work seeks to identify where energy efficiency initiatives should be targeted. This information is key for the accurate prediction of CO_2 savings so that Government can ensure that targets are met. Dwellings with low indoor temperatures during heated periods will be identified as it is assumed that these dwellings would benefit from efficiency improvements without the expectation of energy savings. Findings will be valuable for policy makers to ensure that energy efficiency policy will deliver estimated CO_2 emissions reductions and additional benefits for the health and comfort of vulnerable portions of society.

2. Methodology

Data were collected during a large-scale city-wide housing survey carried out in Leicester, UK in 2009-2010 [19]. The Living in Leicester (LIL) Survey was designed by the 4M project - Measurement, Modelling, Mapping and Management (4M): An Evidence-Based Methodology for Understanding and Shrinking the Urban Carbon Footprint - a collaboration between four Universities funded through the Engineering and Physical Sciences Research Council (ESPRC). 4M is studying CO_2 emission sources and sinks in urban areas and has collected data from households within Leicester including indoor air temperatures in domestic buildings. Households were randomly selected after stratifying by percentage of detached homes and percentage of households with no dependent children in each of the 36 middle layer super output areas. 575 households were involved in face to face interviews which were conducted by the National Centre for Social Research (NatCen).

Hobo data loggers (Figure 1) were used to monitor air temperature every hour between July 2009 and March 2010 in a subset of these households. The sensors were calibrated by Tempcon Ltd and were found to be accurate to ±0.4°C [20]. NatCen interviewers asked the occupants to place the Hobos in the living room and main bedroom. Guidance on the placement of sensors was provided and stated that the Hobos should be placed away from heat sources and not in direct sunlight. A distinct advantage of this data set compared to previous national studies is that outdoor temperature and climate can be assumed to be the same across the whole sample. At the end of the monitoring period the Hobos were returned in pre-paid envelopes. 620 Hobos were returned from 321 households. Only households with temperature data for living room spaces were suitable for this analysis. 31 households were excluded from the analysis for a number of reasons including; loggers failing to download; data not being available for the whole monitoring period; and average temperatures being below 10°C (when it was assumed that sensors were in unheated spaces, misplaced or faulty).

Figure. 1 Hobo data logger used to measure indoor air temperature in 290 dwellings in Leicester City.

Temperature data for the month of February 2010 were analysed to provide understanding of heating patterns during a typical winter heating period. The average daily temperature profile was calculated for each house. Although average temperatures were calculated for both living room and bedroom spaces only living room temperature considers the ability for households to heat their living spaces to adequate temperatures. Consequently, this analysis concentrates on living room temperatures. Average temperatures for morning (7:00-9:00), day (9:00-17:00), evening (17:00-23:00) and night (23:00-7:00) were calculated to aid understanding heated and unheated periods. Temperature data were combined with data on the built form of the properties for analysis.

3. Results

3.1. Analysis of indoor temperature data

Average temperatures were compared to those measured in New Zealand homes, which is a comparable study reporting average evening temperatures [18] (Table 1).

Table 1. Average temperatures reported. Temperatures in Leicester for the 4M project are reported for February 2010. New Zealand (HEEP) temperatures are for the whole winter.

Room		Average evening temperature (°C)			
		Morning (7:00-9:00)	Day (9:00-7:00)	Evening (17:00-23:00)	Night (23:00-7:00)
Living room	4M (n=290)	17.4	17.8	18.7	18.9
	HEEP (n=348)	13.5	15.8	17.8	14.8
Outdoor	Leicester	1.5	3.6	2.6	1.6
	New Zealand	7.8	12.0	9.4	7.6

Indoor temperatures measured in Leicester were found to be higher than those measured in New Zealand; average evening temperatures were 18.7°C and 17.8°C respectively. Temperatures in UK dwellings are also more uniform throughout the day; New Zealand morning temperatures were 13.5°C compared to 17.4°C in Leicester. There are numerous reasons why this might be that case, these include that homes in Leicester may have longer heating periods, better thermal insulation, more efficient heating systems or occupants that prefer warmer indoor temperatures. Average temperature profiles were used to identify the variation of indoor temperatures relating to different house types (Figure 2). None of the property types had average temperatures that reached the temperatures recommended by the WHO. It was observed that flats were warmer for the majority of the day, on average, compared with other house types. It is hypothesised that this is due to flats being more thermally efficient than other property types as they have less exposed surface area. Detached dwellings reach the lowest temperatures. Although mid terrace properties have less exposed wall area than end terraces and are assumed be more thermally efficient, lower temperatures on average were observed. Further data analysis is required to comment on the reasons or validity of this observation.

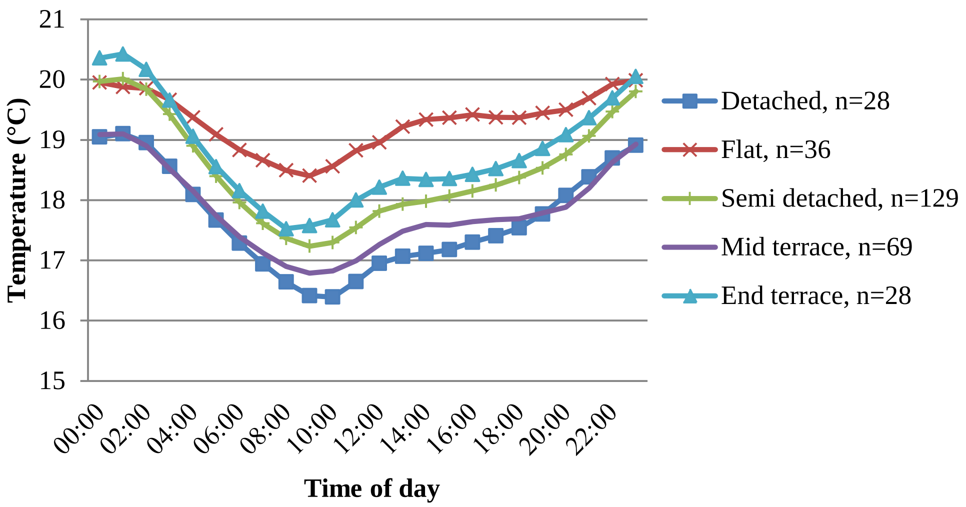

Figure 2. Daily living room temperature profile averaged for each hour in February 2010 for indoor temperatures measured in 290 homes in Leicester.

3.1 Recognising rebound in UK policy making

Analysis was carried out to identify the proportion dwellings where energy efficiency improvement may not result in the expected energy savings. To do this it was assumed that the heating was operational in all dwellings during evening periods. A histogram of average evening (17:00 – 23:00) temperatures illustrates the variation in indoor temperatures during heated periods (Figure 3). Mean evening indoor temperature was 19.9°C with a standard deviation of 2.1°C. 7% of dwellings can be observed to have evening temperatures over 22°C (Table 2). In these homes it is assumed that energy efficiency improvements are expected to result in energy savings as higher indoor temperatures are unlikely to be desired. 36% of dwellings had evening temperatures below 18°C and therefore it is assumed that energy efficiency improvements may not deliver energy savings but contribute to increased indoor

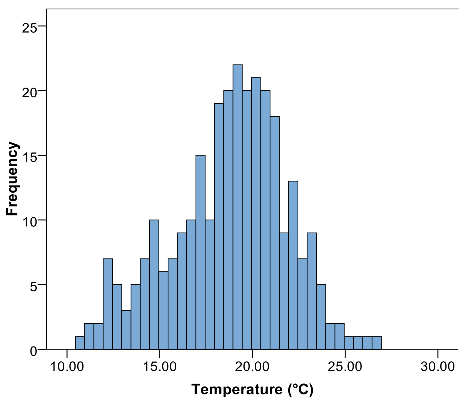

Figure 3. Histogram of average evening living room temperature measured in 290 households in Leicester during February 2010.

temperatures. These data were divided into house types to see whether certain house types could be targeted by policy makers. 45% of mid terrace properties were found to have low evening temperatures and more than a third of detached and semi detached homes also had low evening temperatures. Further analysis of these data is required to identify which other social and technical variables also relate to indoor temperatures and to test the statistical significance of these results.

Table 2. Average evening temperatures under18°C measured in dwellings in Leicester in February 2010

	% with average evening temperature under 18°C	% with average evening temperature above 22°C
All dwellings (n=290)	36	7
Detached (n=28)	39	4
End terrace (n=28)	29	7
Flat (n=36)	25	14
Mid terrace (n=69)	45	6
Semi detached (n=129)	35	6

3.2 Discussion

A challenge in this analysis is the number of influences on indoor temperatures. Thermal comfort is defined as a product of indoor temperature, mean radiant temperature, air speed and occupant activity. Indoor temperature is related to the outdoor climate, the efficiency of the built form and heating systems in dwellings as well as occupant behaviour. Gathering and analysis of data to inform policy makers is therefore complex and it is important not to make assumptions. For example, if improvements were made to a buildings' air tightness this would reduce the energy lost via infiltration and reduce drafts (air speed). This could increase occupant thermal comfort while indoor temperatures could remain the same or even be lowered. This measure would reduce energy use from the dwelling but this could not be observed by using only indoor temperature data. It should also be noted that although it is assumed here that there is a portion of the housing stock where occupants are unable to maintain their preferred temperature due to the inefficiency of building fabric or heating systems or the inability to afford heating, there are some occupants that prefer lower indoor temperatures. Further analysis and data collection are therefore required to continue to develop the understanding of the drivers of indoor temperatures in domestic dwellings and how these can be analysed to inform policy makers. This will include using analysis of covariance to identify the variables which influence households to have high or low temperatures during occupied periods. This analysis will address whether other social and technical factors can explain more of the variation in indoor temperatures. This dataset will be used to explore relationships between indoor temperature and income, house price, built form, controllability of heating systems, age of property and number of occupants. Outdoor air temperature, average temperatures during heated periods and estimations of daily heating period and demand temperature based upon analysis of daily temperature profiles will also be considered.

4. Conclusion

This paper presents initial analysis of indoor temperature data measured during February 2010 in 290 households in Leicester, UK. Average temperatures were calculated to identify variations in indoor temperature in dwellings. The data were used to address how house type relates to indoor temperatures. Temperature profiles showed that on average flats had higher indoor temperatures than other house types. It is suggested that this was due to flats being more thermally efficiency due to their limited exposed wall. Average temperatures for evening periods were calculated to identify the proportion of Leicester properties which have high and low evening temperatures. It was found that 36% of the households had average evening temperatures below 18°C which is below the 21°C recommended by the WHO. Nearly half of all mid terrace properties and over a third of detached and semi detached properties were found to have evening temperatures below 18°C. Further analysis is required of this data set to fully address the reasons why these properties have low temperatures during occupied periods. There are many drivers of indoor temperatures in domestic dwellings which require understanding if energy reduction policy is to be fully effective. It is concluded that to meet Government CO_2 reduction targets the rebound effect should be taken into account when calculating the savings expected as a result of energy efficiency programmes.

Acknowledgements

4M is a consortium of four UK universities, funded by the Engineering and Physical Sciences Research Council under the Sustainable Urban Environments programme (grant reference EP/F007604/1). The university partners are assisted by an advisory panel drawn from UK central and local government, and UK and overseas industry and academia. For further information please see www.4Mfootprint.org. The Living in Leicester survey was carried out by the National Centre for Social Research. We are grateful for the participating households without whom this work would not be possible.

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