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.

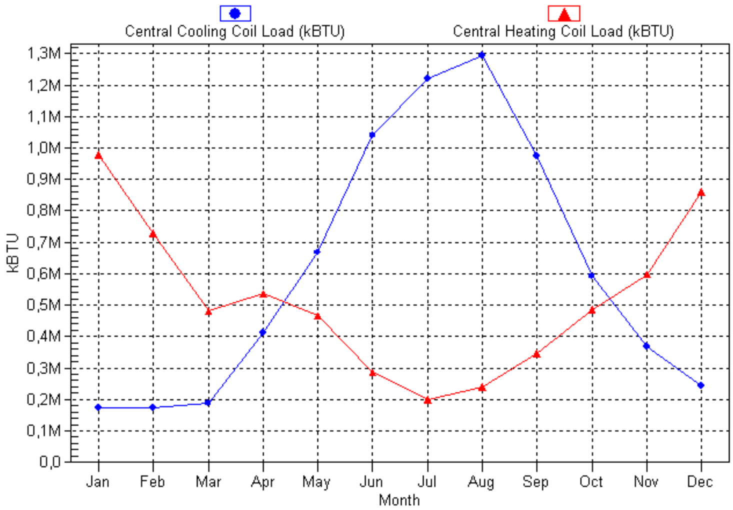

Fig. 1. Heating and cooling loads throughout the year.

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.

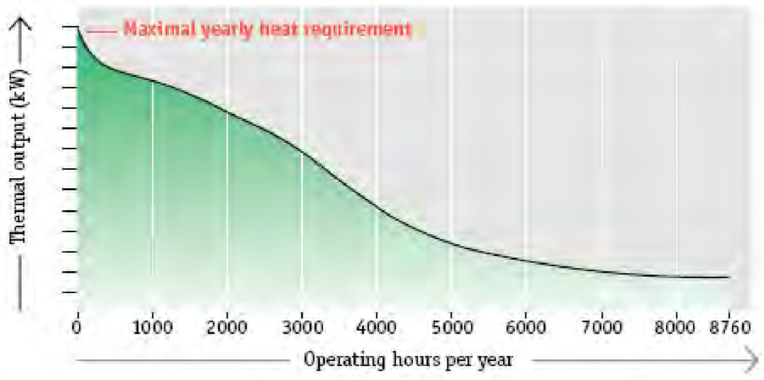

Figure 2. Load duration curve for heating load

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.

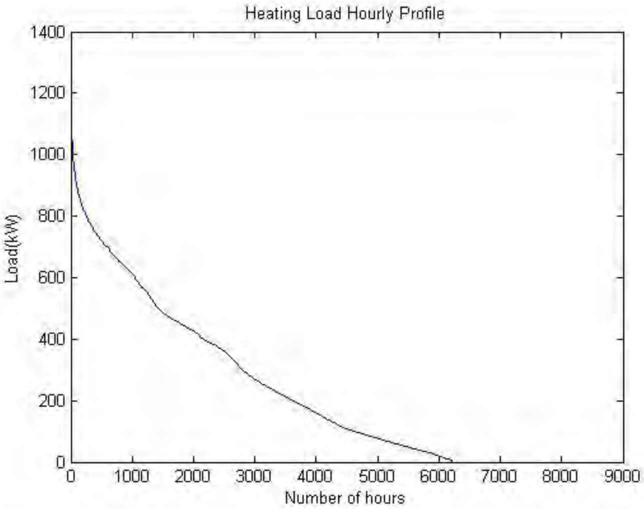

Figure 3. Load-duration curve for heating load

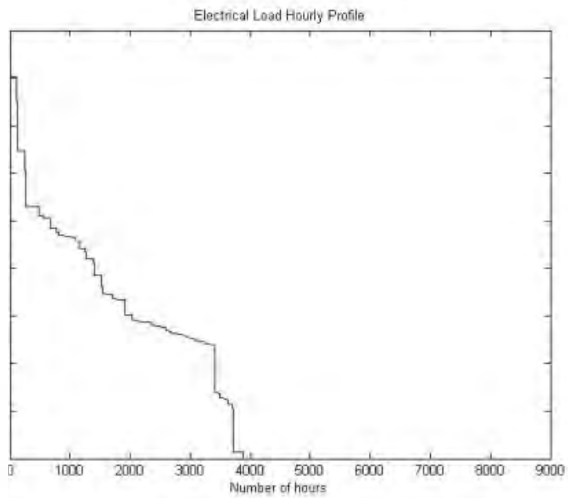

Figure 4. Load-duration curves for electrical load

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.

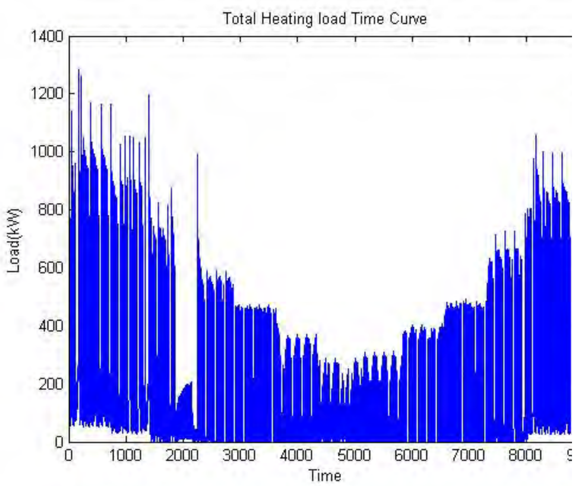

Figure 5. Load-time curve for heating load

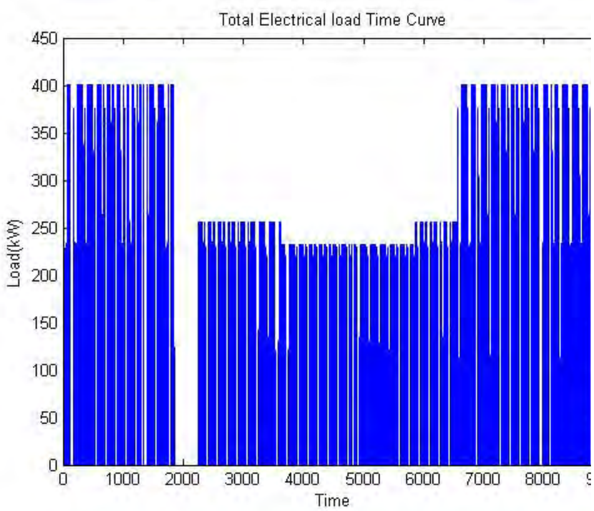

Figure 6. Load-time curve for electrical load

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.

References

[1] X. Q. Kong‹ R. Z. Wong‹ X. H. Huang‹ Energy optimization model for a CCHP system with available gas turbines‹ Applied Thermal Engineering 25 (2005) 377–391.

[2] D. W. Wu‹ R. Z. Wang‹ Combined cooling‹ heating and power: A review‹ Progress in Energy and Combustion Science 32 (2006) 459–495.

[3] P. Arcuri‹ G. Florio‹ P. Fragiacomo‹ 2007‹ A mixed integer programming model for optimal design of trigeneration in a hospital complex‹ Energy 32‹ 1430–1447.

[4] E. Cardona‹ A. Piacentino‹ A new approach to exergoeconomic analysis and design of variable demand energy systems‹ Energy 31 (2006) 490–515.

[5] E. Cardona‹ A. Piacentino‹ Optimal design of CHCP plants in the civil sector by thermoeconomics‹ Applied Energy 84 (2007) 729–748.

[6] Karimi Alavijeh, Saeed. Behbahaninia, Ali. Amidpour, Majid, Modeling and optimization of energy in a CHCP system with gas turbine prime mover, International Conference of Nonlinear Problems (ICNPAA 2008), 24-26 June 2008, Italy.

[7] Feasibility study of private sector's investment in development of local cogeneration systems in Iran, The department of power and energy of Iranian ministry of power, 2008, Tehran, Iran,24-26

[8] Technology characterization, reciprocating engines, Energy and Environmental analysis, Arlington,Virginia, December 2008, 12-16

[9] Mahdi Ali Ahyayi, Sharif University of technology, Tehran, Iran, Design and optimization of cogeneration of power, heating and cooling in different climate conditions of Iran, 2007, 41-45

[10] S.K. Sadr Nezhad, A. Kermanpour, Fuel and Energy, 2001, Tehran, Iran

[11] www.epa.gov/ttnchie1/ap42/ch01/final/c01s04.pdf

[12] S.S Bernow, D.B.Marron "Valuation of Environmental Externalities for Energy planning and Operations", May 1990, Tellus Institute, Boston, Mass., 1990

[13] Dries Haeseldonckx, Leen Peeters, Lieve Helsen, William D'haeseleer, The impact of thermal storage on the operational behaviour of residential CHP facilities and the overall CO2 emissions, 26 September 2005

[14] Adrian Bejan et al, Thermal design and optimization, 1996

[15] A.D. Hawkes a, P. Aguiar b, B. Croxford c, M.A. Leach a, C.S. Adjiman b,d, N.P. Brandon Solid oxide fuel cell micro combined heat and power system operating strategy: Options for provision of residential space and water heating, 28 November 2006