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The effect of long lead times for planning of energy efficiency and biorefinery technologies at a pulp mill

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Abstract: The pulp and paper industry has many promising opportunities in the biorefinery field. To reach this potential, investments are required in new, emerging technologies and systems solutions which cannot be quickly implemented. In this paper, an approach to model the necessarily long planning times for this kind of investments is presented. The methodology used is based on stochastic programming, and all investments are optimized under uncertain energy market conditions. The uncertain cost development of the emerging technologies is also considered. It is analyzed using scenario analysis where both the cost levels and the timing for market introduction are considered. The effect of long lead times is studied by assuming that no investments can be decided on now and implemented already today, and only investments planned for today can be implemented in, for example, five years. An example is presented to illustrate the usefulness of the proposed approach. The example includes the possibility of future investment in lignin separation, and shows how the investment planning of industrial energy efficiency investments can be guided by using the proposed systematic approach. The example also illustrates the value of keeping flexibility in the investment planning.

Keywords: *Investment planning, Optimization under uncertainty, Process integration, Lignin separation, Pulp and paper industry*

1. Introduction

As a result of the increased climate concern in society, energy market conditions are bound to change, and energy and products based on renewable feedstock will gradually be valued higher. The pulp and paper industry, which already today is a large user and producer of biomass-based energy and materials, therefore has a large opportunity to increase and diversify its revenues through different biorefinery concepts, see e.g. [1–7]. For mills to become successful in this biorefinery arena, process integration investments are required to ensure energy efficiency of the combined pulp and paper production and biorefinery process. This also calls for investments in new, unproven technologies, with highly uncertain investment costs – for example, carbon capture, black liquor gasification, or lignin extraction.

Investments in these emerging technologies are not quickly implemented. Time is needed for analyzing different options, planning of construction including any shutdowns of the plant, contracting, and so on. This results in long lead times from the first decision to start planning for a certain technology path until the plant is finally run continuously at full load. This is true also for traditional options being evaluated in competition with emerging technologies.

Considering that new decisions cannot be immediately implemented if they have not previously been planned for, decision-makers need guidance – not only regarding what investments to make – but also, and more importantly, to what future investments should be planned for. Better tools to aid decision-makers in this field will hopefully lead to that more of these energy-efficiency and emission-reducing measures are carried out. The purpose of this work is therefore to further develop a methodology for process integration investment planning under uncertainty to consider these aspects of long-term decision-making. Here, we will also use the proposed approach to illustrate the effect of a five-year planning lead time in an example of a pulp mill that considers a future possibility of investing in lignin separation.

2. Methodology

The methodology used in this paper is based on a methodology for optimization of process integration investments under energy market uncertainty [8, 9]. In this work, we have used an approach which in addition allows the influence of the investment cost development for new, emerging technologies to be studied [10]. While investments are optimized under uncertainty in energy market parameters with a stochastic programming approach, the effect of different cost developments on the optimal solution is studied through sensitivity analysis. The solution to the optimization model will be an optimal investment plan with respect to the expected net present value (NPV) based on the information we have about the future today.

We model the investment optimization problem using AMPL [11] and solve it using CPLEX [12]. A strategic view of the analyzed investments is assumed, and the discount rate is therefore set to 9.3% over a 30-year-long planning horizon.

2.1. Long lead times for investment planning

Here, we use the expression 'lead time' to denote the time between the decision to invest and the actual implementation or installation of the technology invested in. This is simply modeled based on the assumption that it takes a few years to analyze, plan and prepare for these extensive process changes. When studying the effect of long lead times it is therefore assumed that it is too late now to decide about investments that should be implemented today, and the first investments will instead be implemented in five years.

Since there are costs associated with evaluation and planning of investments – mainly related to the time committed by engineers, consultants, etc. – a basic assumption is that it is not possible to plan for all investments that might be of interest. In this way, although the planning costs are not explicitly accounted for, they are implicitly considered in the proposed modeling approach. The idea of the proposed approach is then that investments planned for today will constrain what will be possible to implement in five years.

To find different planning alternatives, the approach is to start by optimizing the investment in each cost development scenario assuming that the first investment will be in five years. This will, however, lead to solutions where different investments should be made in five years depending on the cost and price development. Based on the solutions obtained, a matrix can be constructed that shows which investments will be possible to implement depending on what has been planned for. A general illustration of such a matrix is shown in Fig. 1.

The matrix could also contain other investment solutions based on experience from working with the model and the mill. The model will then be run for each of the planning alternatives, with possibilities for implementation as constraints. Thereby the results of different investment plans considering an initial lead time of five years can be analyzed, and the best one possibly identified.

Long lead times should also be modeled for later points in time, but this makes the model and especially the solution of the optimization problem hard. As a first step towards an improved understanding of the effects of lead times we therefore settle for the initial lead time. Experience shows, however, that for a majority of investment plans, very few investments are made at later points in time. Therefore, the modeling of later lead times should not be as important. Furthermore, the optimal solution will obviously result in a plan also for later investments, even though it is not considered that decisions have to be made years before the actual implementation and hence possibly before future energy prices and cost reductions have been revealed.

		Possible to implement 2015				
		Technology 1	Technology 2	Technology 3	Technology 4	Technology 5
Plan 2010	Investment package 1	X	X			
	Investment package 2		X	X		
	Investment package 3		X		X	
	Investment package 4					X

Fig. 1. Generic matrix for investment planning.

3. Input data and assumptions

3.1. The pulp mill

We have applied the proposed approach to a pulp mill example that has previously been presented by the authors [10]. This mill is a computer model representing an average Swedish market pulp mill, producing 1000 tonnes per day of bleached Kraft pulp (see also [1, 13]).

Through process integration and more efficient technology, there is a potential to achieve a steam surplus at the mill of about 25%. The steam could, for example, be used to produce more electricity in a low-pressure turbine, or to produce district heating for a nearby community, or for cogeneration of both heat and electricity. District heating could also be produced from lower-quality excess heat at the mill. Except for these traditional ways of making use of the steam surplus, there are new, emerging technologies that might become promising alternatives. We will here look at the example of lignin extraction.

For energy conversion data and investment costs, the reader is referred to [10]. The cost development scenarios for the lignin separation process are presented in Section 3.3.

3.2. Energy market uncertainty model

The energy market model used in this study is the same as the one used in the previous study on the effect of uncertain investment cost developments for emerging technologies [10]. This uncertainty model was developed using the ENPAC tool [14]. The model consists of 28 scenarios for market electricity and fuel prices, see Fig. 2. The same probability has been assumed for each scenario.

3.3. The investment cost scenarios

For the cost development of the emerging lignin separation technology, six scenarios have been used. For this technology, we have assumed that market introduction might happen in 2015 or 2020. It is assumed that market introduction might happen at the base level (L), corresponding to the estimated cost of the N^{th} plant assumed in previous studies (see [10]), or at a higher cost level (H), here assumed to be 50% higher than the base cost level.

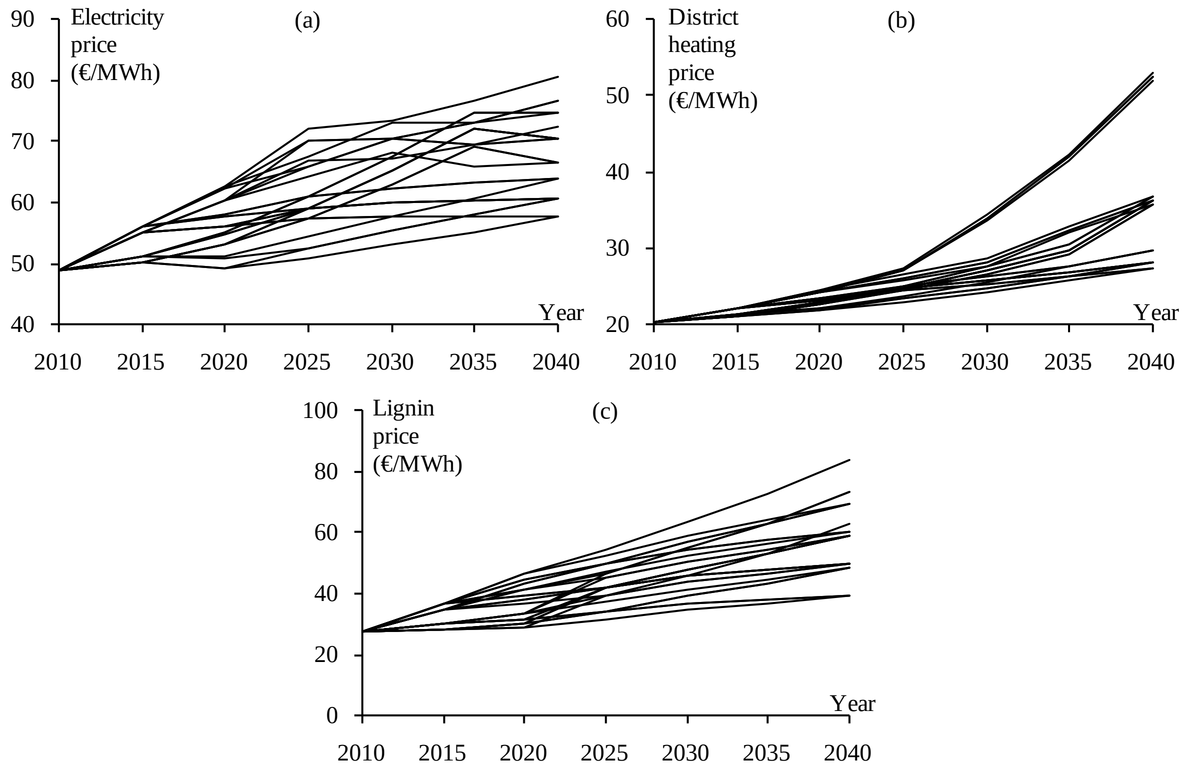

Fig. 2. a) Electricity price scenarios. b) District heating price scenarios. c) Lignin price scenarios.

Table 1 presents the different scenarios for the investment cost of the lignin separation plant. If the market introduction happens at the base cost level, the cost stays permanently at that level (Scenarios A and B). If, instead, market introduction happens at the higher cost level, the cost might stay at the higher level (Scenarios C and D), or it might drop later as a consequence of technological learning (Scenario E) if, for example, not very many plants are sold. There is also a possibility that the technology is never introduced to the market (Scenario F).

Table 1. Investment cost scenarios for the lignin separation plant.

Scenario & Market introduction (year)		2010	2015	2020	2025	2030	2035
A	2015 at base cost level	–	L	L	L	L	L
B	2020 at base cost level	–	–	L	L	L	L
C	2015 at higher cost level where cost is stabilized	–	H	H	H	H	H
D	2020 at higher cost level where cost is stabilized	–	–	H	H	H	H
E	2015 at higher cost level with drop to base cost level 2020	–	H	L	L	L	L
F	Never	–	–	–	–	–	–

–: Unavailability
L: Low cost / base cost level = Estimated cost of Nth plant
H: High cost / Higher cost level = 1.5L

4. Results

As described previously, the effect of long lead times is studied by assuming that no investments can be made already today, and that the first investments in five years must be planned for. Furthermore, we assume that the costs and personnel resources associated with planning of investment and implementation make it impossible to plan for every interesting investment opportunity. To find a number of reasonable investment packages to plan for, the model was solved for one cost development scenario at a time with the constraint that the first investments could be made in five years. The solutions obtained are presented in Table 2.

Table 2. Optimal investments 2015 in different cost development scenarios.

Scenario	Optimal investment	
A, C, E	Lignin:	64 MW lignin
	Heat pump:	32 MW delivered heat
B, D	Cogeneration:	5MW elec. and 26 MW delivered heat
F	Cogeneration:	5MW elec. and 26 MW delivered heat
	Heat pump:	19 MW delivered heat

These three packages obviously differ regarding the lignin extraction investment, but also regarding the amount and means of district heating deliveries. The reason for this difference in district heating production is that the preferred way of generating district heating is by cogeneration from low-pressure steam, but when lignin is extracted as for Scenarios A, C and E, no low-pressure steam is available. In these scenarios, district heating is therefore generated by a heat pump instead. Also in the case of cogeneration, a heat pump might be interesting to further increase district heating deliveries as in Scenario F. By this solution, the mill is, however, locked into a district heating contract of substantial deliveries for which the production based on low-pressure steam is needed to fulfill the delivery requirement. In Scenarios B and D, later opportunities for lignin extraction might make it interesting to use the low-pressure steam for lignin extraction at a later point in time. Therefore, district heating deliveries are more limited, making it possible to replace the production from cogeneration with production from the heat pump.

In some mills, the power boiler and back-pressure turbine might be oversized. Under such conditions, it would probably be more beneficial to increase district heating deliveries by increasing the fuel input to the power boiler than to invest in a new heat pump. Here, however, the boiler is already assumed to be run at maximum capacity.

Fig. 3 is a matrix showing which investments can be made in 2015 depending on what investment package has been planned for. In addition to the alternatives from Table 3, we also added the alternative to plan for a condensing turbine and a heat pump. The alternative not to plan for any investment should obviously never be better than to plan for something, since there is always an option to avoid making an investment that has been planned for. However, the ‘no investment’ planning alternative was included for comparison. It might be interesting if costs and resources for planning are considered explicitly, which they are not here.

The X’s in the matrix represent that an investment is possible, though not required. That means, for example, that if a heat pump has been planned for, this possibility exists in 2015 but there is also always an option to withdraw from the investment. This option to abandon a planned investment is especially important for lignin extraction since this technology might not even be available on the market in 2015. Based on the matrix, the optimization model was solved for different planning alternatives. The expected net present value for the alternatives in the different cost development scenarios is shown in Fig. 4.

		Possible to implement 2015				
		Lignin	Heat pump	District heating from 145 and 100°C heat	Turbine (145-100°C)	Turbine (100-35°C)
Plan 2010	Lignin and heat pump	X	X			
	Cogeneration only			X	X	
	Cogeneration and heat pump		X	X	X	
	Condensing turbine and heat pump		X		X	X
	No investment					

Fig. 3. Matrix of possible technology implementations depending on what has been planned for.

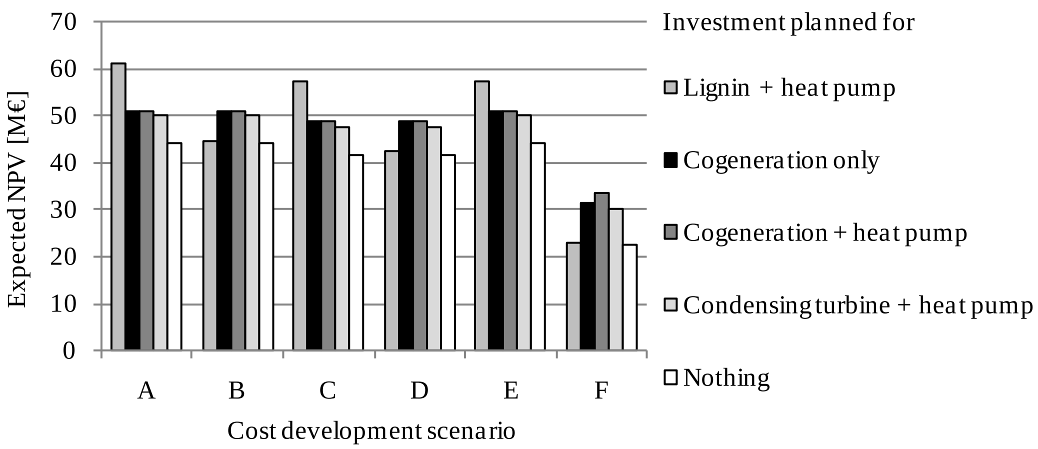

Fig. 4. Expected net present value for different planned investments in 2015.

As can be seen, depending on the cost development scenario, lignin extraction could either be by far the best or by far the worst alternative (at least except planning for nothing). This is explained by the large potential associated with this technology if it becomes a reality, which disappears if the technology has not yet become available for the pulp mill.

The good runner-up is instead cogeneration, which is either the best or the next best alternative in all scenarios. The difference is very small if you include the heat pump or not. Obviously, it is better to include the heat pump in the plan since there is no requirement of going through with the investment. In Scenario F where lignin extraction never becomes available on the market, the heat pump is slightly advantageous. As anticipated, the ‘nothing’ alternative is the worst one in all scenarios.

5. Discussion

In theory, the optimal planning alternative would include all different technology options, but this would obviously be difficult in practice. Principally, planning for everything means the same as staying flexible and that should be striven for. However, the underlying assumption in this study was that this is too costly to achieve in reality. Nevertheless, the lack of flexibility obviously has a cost. The results show that if lignin extraction is not planned for, but cogeneration instead, the loss is 19% in expected NPV in Scenario A (17% and 12% in Scenarios C and E respectively). On the other hand, if the plan is for lignin extraction and a heat pump but the lignin separation technology does not become a possibility, the loss is 15%, 15% and even 46% in Scenarios B, D and F respectively. Considering that the use of expected NPV as investment evaluation measure partly hides differences in cash flows because of discounting and weighting of scenarios, these losses in expected NPV are quite important (see for example [10, 15] where differences in expected NPV are related to corresponding differences in annual net profits). These high values of staying flexible by planning for many different investment opportunities imply that, strategically, it should be worth committing more organizational resources to planning of these kinds of investments.

Nevertheless, if we assume that it is not possible to invest in anything else than what has been planned for, and if we further assume that it is not possible to plan for more than a few different new technologies, results like the ones presented in Fig. 4 can be used to evaluate different investment plans. In the example presented here, investment in lignin extraction involves both the highest potential and the highest risk, while cogeneration seems to be a more robust option. The best decision depends on the decision-maker's beliefs about the probabilities of the different cost development scenarios.

5.1. Limitations

The work presented in this paper provides a good starting point for an investment planning methodology where consideration is given to the long lead times that are often involved in these kinds of decisions. There are, however, some limitations which might make it difficult to use the methodology for some applications where these aspects are of importance. Further work with model development should focus on these issues. For example, the costs associated with evaluation, planning and detailed analyses of different investments and their implementation are not explicitly considered in this model. It should also be possible to differentiate these costs and the length of the planning lead time between different kinds of investment alternatives. Further work is needed, too, if not only the initial lead time but also the lead time for subsequent investment stages should be accounted for.

6. Conclusions

The proposed approach for modeling of long lead times for planning of industrial energy efficiency investments gives a more realistic representation of this kind of decision-making. An example illustrates how the planning of future investments can be guided by using this systematic approach considering uncertainties in future energy market conditions as well as in cost development of new technologies. The results clearly show the importance of considering the long lead times involved in the investment planning, since significant values are at stake by making the right or the wrong decision about which investments to plan for.

We have also shown how the proposed approach can be used to value flexibility in the planning of industrial energy efficiency measures. The example demonstrates that the value of this flexibility can be quite high. There is, however, a trade-off between the value of this flexibility and the associated planning costs required to obtain it. It is therefore important to continue the work regarding long lead times to incorporate these planning costs.

Acknowledgements

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Energy use project and conversion efficiency analysis on biogas produced in breweries

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Abstract: Electric power, steam and chilled water were consumed in beer brewing process. The process is intensive in energy conversion and utilization. The brewery wastewater can generate biogas of high methane content through anaerobic sludge fermentation. This high concentrated biogas could be an excellent choice employed in energy conversion and utilization. The reclaimed water, after proper treatment, could be employed to scrub CO_2 and H_2S in biogas. Through compression, the purified biogas could be stored as fuel for mechanical operation and further incorporated into the municipal LNG pipe network. According to biogas yield and energy requirements in breweries, energy usage efficiency and configuration of device for biogas Integrated Energy System (IES) were investigated. This paper introduced an Otto cycle internal combustion engine using biogas for power generation. With the biogas yield of 34.84m^3/h (standard state), the power efficiency of 28.45% could be generated with electricity of 70.0kW. Efficiency of combined heating and power (CHP) can reach 61.80% employing the excess heat of the engine exhaust. There are successful examples of combined cooling and power (CCP), combined cooling and heating (CCH) that has efficiency of over 60%.

Keywords: *Biogas produce, Purification process, IES conversion Using efficiency*

1. Introduction

In China, Biogas is not only new energy source, but also an important aspect of sustainable development for the renewable energy. The biogas is generated by industrial wastewater or municipal solid waste through degradation process of anaerobic digestion. Consequently, heat and electricity is generated through the biogas [1]. Adopting the technology of combined cooling, heating, and power (CCHP), this is also known as trigeneration, or integrated energy system (IES). CCHP is the simultaneous production of mechanical power (often converted to electricity), heating and/or cooling from one primary fuel, and is an extension of CHP (combined heat and power, also defined as cogeneration) by coupling with thermally activated cooling technologies that take the waste heat from CHP for producing cooling [2].

Moving parts of internal combustion engines and gas turbine contacts directly with burning gas, there need cleaner fuels, biogas as a biomass energy source by the removal of CO_2 and H_2S and combined with high conversion efficiency, low emission rates, suitable for CHP, CCH and CCP technology. Medium and small-scale units high exhaust temperature, heat recovery of flue gas is conducive to heat (cold) output, and improve unit efficiency.

Because the biogas contains a large share of the inert gas, emissions of oxides of nitrogen (NOx) were reduced relative to natural gas, while unburned hydrocarbons (CH) were increased, and exhibit penalties of performance compared with spark ignition engine of natural gas or gasoline [3].

Kautz et al. [4] studied a 100kW gas turbine recuperative cycle of exhaust to heat air and the influence of low calorific biogas on the combustion air ratio. Kim et al. [5] studied regenerative Brayton cycle using gas turbine recycling exhaust heat. Nwafor [6] examined the impact of advanced injection timing on the emission characteristics of dual-fuel engine.

Ahead of injection timing was intended to compensate for longer ignition delay and slower burning rate of fuelled natural gas engine, and there was a s lightly increase in the oil consumption accompanied with reduced emission of CO and CO_2.

Smith et al. [7] introduced an innovative domestic scale combined heat and power (CHP) plant incorporating a heat pump (HP). HP incorporating enhanced economy efficiency of domestic use of CHP equipment and satisfied flexibility of the family energy requirements.

Biogas was compressed to gather energy density and reduce storage capacity, the best method is biogas purified, then to compress [8]. For example, in New Zealand, both gas compressor and gas scrubber used in conjunction with, in Belgium, biogas produced from the livestock manure is being dried, scrubbed, compressed and stored in a steel tank with pressure of 4 bar in 0.2 m^3, so that is alternative fuels for CNG(compressed natural gas), gasoline, diesel and LPG (liquefied petroleum gas) [9].

2. Biogas process and energy demand in breweries

2.1. Biogas process

Brewery wastewater comes from various procedures, such as the cleaning process of the malt production, brewing, bottling, and the wastewater from cleaning the recycled beer bottle and the packaging sterilization, as well as the overflow, disqualified product, and filter back wash water. This wastewater is rich in carbohydrates, pectin, mineral salts, cellulose etc. Therefore, it is an organic wastewater with high BOD_5 and COD.

Aeration pond m ethod is the application of biological treatment earlier; because of aerobic bacteria have an allergic reaction to load fluctuations, not to deal with high carbohydrate and volatile components of beer wastewater. Use of the up-flow anaerobic sludge blanket (UASB) has a feature that of high organic loading, short hydraulic retention time, no filler in reactor, no sludge return and stirring device, low operation cost, can be inoculated directly with the sludge particles to produce biogas etc., and that is a wastewater treatment technology for sustainable development. It can not meet emission standards used alone. In most cases, the first need to treat beer wastewater by anaerobic digestion, the most of high concentration organic wastewater in UASB was degraded, and then, under the aerobic environment oxidize and decompose low concentration of pollutants in wastewater.

Fig.1 shows the brewery wastewater processing units and biogas generation set. The brewery wastewater discharged from workshop flows to the sump. Most of suspensions in waste water filter through the sieve grid. The pretreatment pool is necessary for wastewater with unqualified temperature and other physical/chemical conditions. Subsequently, the wastewater flows through the balance pool with the pH values adjusted by acid, alkali or $FeCl_3$. The adjusted water is pumped to UASB reactor in the reaction pool to decompose the organic first into acids, then to methane and CO_2. The three phase separator on top of the reactor could separate the biogas, mud and wastewater efficiently. Meanwhile, the methane bacteria could be effectively retained. The biogas is collected in gas tank after adsorption of H_2S through activated carbon. After anaerobic treatment, COD of beer wastewater dropped from about 2500 t o 500 mg / L. The use of air blower aerate for further processing in the aeration tank. Wastewater COD reduced to about 50 mg / L and then flow into the sediment pool. After suspended solid of aerobic fermentation were filtered, the reclaimed water qualified discharged to the sewer.

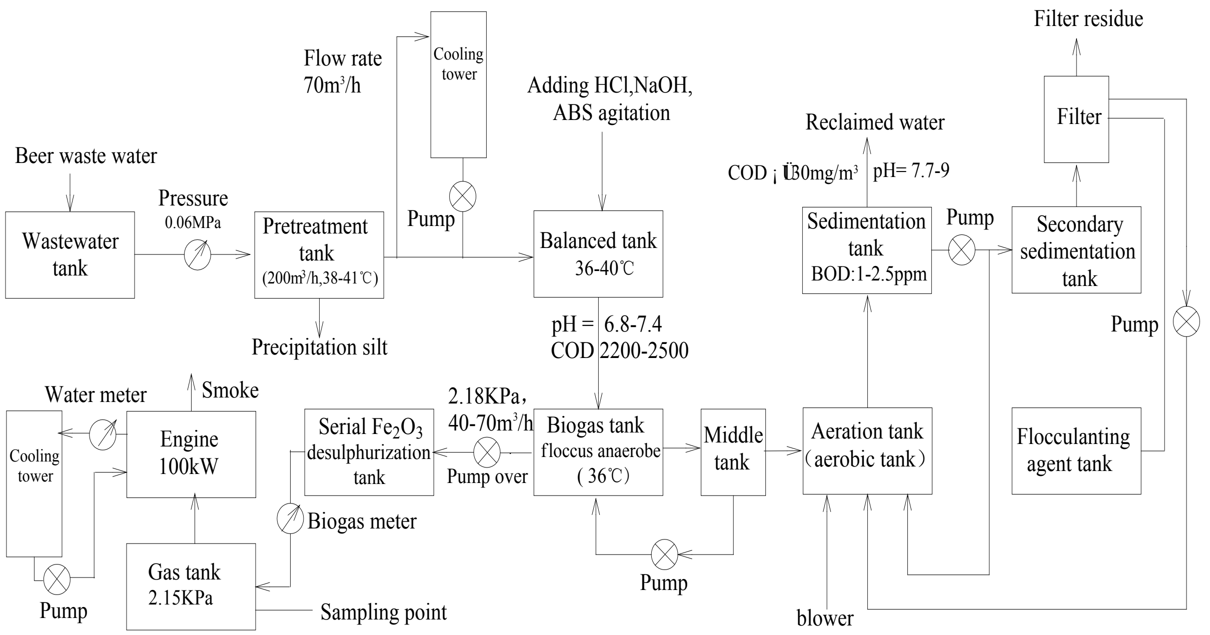


Fig.1. Schematic diagram of processing organic wastewater and generate electricity sets.

2.2. Energy requirement

The brewing process consumes a lot of electricity, steam and chilled water. This process is an intensive process of energy conversion and utilization. Therefore, energy consumption cost accounts for a large proportion of the production cost. Power workshop has 2 sets of 25t steam saturated boiler (burning oil and/or natural gas), steam pressure 7.0-8.0bar. 3 sets of ammonia compression refrigerator, cooling capacity of 496 RT, evaporator pressure of 3.7bar, chilled water supply 4°C, return 9°C. Fig.2 is energy flow diagram of steam and chilled water.

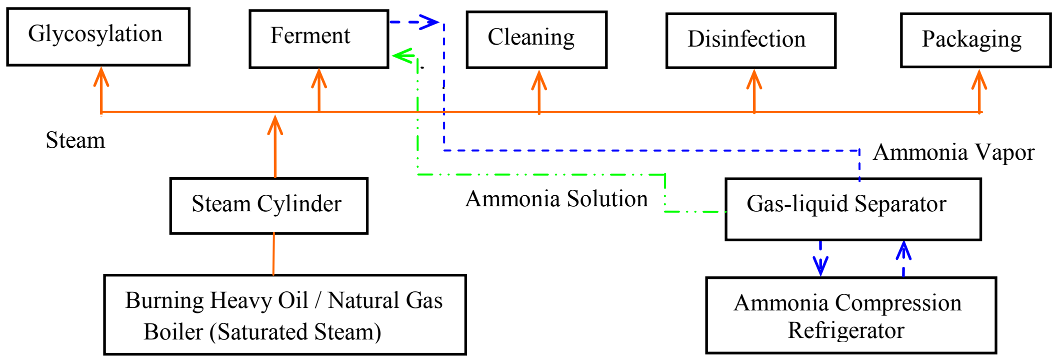


Fig.2. Energy flow diagram of steam and chilled water in breweries.

3. Status of biogas utilization

Shenzhen Kingway brewery (2 plants) and Shenzhen Tsingtao-Asahi brewery could treat beer brewery wastewater of 80-120m^{3}. The amount of biogas produced is 35-60 m^{3} (maximum volume of 80m^{3}) per hour with the measured methane content of 71.2%. Table 1 shows the biogas composition with low heat value of about 25 426 kJ/Nm^{3} and thermal capacity produced as 282.51-423.77kW per hour. Biogas power generation has been running for 1 year period, in order to prevent greenhouse gas emissions before it is used by the torch burning. The heat demand of beer production process provides a choice for biogas CHP and CCHP.

3.1. Engine power generation

Ignition engine was used for power generation in Shenzhen Kingway brewery, Table 2 was the spark ignition engine specifications. Biogas after the removal of H_2S could be generating 70kW (field test) per hour, efficiency of power generation was 28.45%. Table 3 was Composition of engine exhaust for the actual measurement.

Table1. Composition of the biogas

Component	Content (%)	Component	Content (%)
CH_4	71.2	H_2S	＞2500ppm
CO_2	17.1	H_2O,H_2	2.0
O_2	2.39	N_2*	7.31

* Air has leaked into biogas collection cavity over the silt anaerobic digestion pond.

Table2. Specification of 4 strokes and spark ignition engine.

Engine model	Q6135DA$_1$	Generator model	90GFTA$_1$
Rated power (kW)	83	Rated power (kW)	80
Rated speed (rpm)	1500	Rated speed (rpm)	1500
Arrangement/cylinder bore(mm)	6L /135	Rated voltage (V)	400
Displacement (L)	12.9	Nominal current (A)	162
Compression ratio	10.5	Nominal frequency (Hz)	50
Poston travel (mm)	150	Power factor	0.8
Exhaust temperature ($^{\circ}$C)	≤630	Fuel gas consumes (m^3/kW h)	≤0.33

Table3. Composition of the exhaust gas (volume percent).

Item	Test value	Reference value*	
		Gasoline	Diesel
O_2 (%)	6.24	0.3-0.8	2.0-18.0
CO_2 (%)	8.36	5.0-12.0	1.0-10.0
NO (ppm)	1793		
NOx (ppm)	1883	10^5-0.5×10^5	10^3-0.4×10^5
SO_2 (ppm)	32-0		
H_2O (%)	~8.8	3.0-5.5	0.5-4.0
N_2 (%)	~76.6	74-77	76-78

* Reference value from Table 4 of reference [10]

3.2. Heating boiler

There is a biogas fired boiler (model: FBA-080 F) in Shenzhen Tsingtao-Asahi Brewery with the parameters as follows: rated pressure: P = 1.04MPa (saturated steam), the amount of steam produced 1.25 t / h, e xhaust temperature 300°, biogas/ steam ratio = 2:1, boiler efficiency η = 80%. The actual operation pressure was 0. 6MPa.

4. Biogas processing

Because high temperature of biogas fire, slower burning speed, serious ignition delay and higher exhaust temperature, all that resulting in lower efficiency of biogas power generation. biogas purification (removal of CO_2 and H_2S), then compressed and stored as alternative products of CNG, gasoline, diesel and LPG, showing the goods value of biogas through the transport.

4.1. Gas purification, compression and storage

Removal of H_2S in the biogas can be divided into ① dry and oxidation,② ferric oxide adsorption, ③ activated carbon adsorption, and④ liquid-phase oxidation process. A simple adsorption method using activated carbon was used in 3 breweries.

The amine solution of 10% mono-ethanolamine (MEA) and diethanolamine (DEA) are usually used to absorb CO_2. It takes 5min for the solution regeneration to be completed by boiling. The newer approach is the sulfolane method or the Sulfinol method composed by alcohol amine and sulfolane adding water. Method of reclaimed water which was beer wastewater treated when water pressure increased as the absorbent to remove CO_2 is the most simple and less expensive. Efficiency of the scrubber depends on that scrubber specifications, packing and gas pressure in scrubber, composition of raw biogas, the flow rate and purity of water used and so on.

The critical temperature and pressure required to liquefied biogas were: -82.58 °C and 47.5 bar respectively. Purification biogas compressed by the compressor, according to different pressure stored in cylinders, which could be transported with long-distance, may be also build a small scale station on side.

4.2. Power fuel

After CO_2, H_2S and water vapor in biogas were removed, the methane (>90%, heat value equivalent to LNG), could be compressed and stored as fuel for car and other power machines.Table 4 is data of LNG imported to Guangdong province of China from Australia, kindly provided by the Shenzhen Gas Group.

Table 4. Data of physical and chemical for LNG.

Composition	(%)	Data (0℃,1 atm)	Value
CH_4	87.59	HHV (MJ/Nm^3)	45.08
C_2H_6	8.13	LHV (MJ/Nm^3)	40.71
C_3H_8	3.2	Density (kg/Nm^3)	0.8318
C_4H_{10}	0.99	Specific volume (Nm^3/t)	1202
C_5H_{12}	0.05	LHV (MJ/kg)	48.92

Use of CNG instead of gasoline as a motor fuel, the emissions of CO, CH compounds and NO compounds can be decreased by 97%, 72%, and 39% respectively. Performance of resistance to blast for CNG equivalent to gasoline is about octane number of 130, and CNG does not release lead, benzene and other toxic substances all which can cause cancer. Forklift which using LPG as fuel made by Japan Fuji Co. in Shenzhen Tsingtao-Asahi brewery, may also use purified biogas as a substitute.

4.3. Incorporate into LNG pipe network

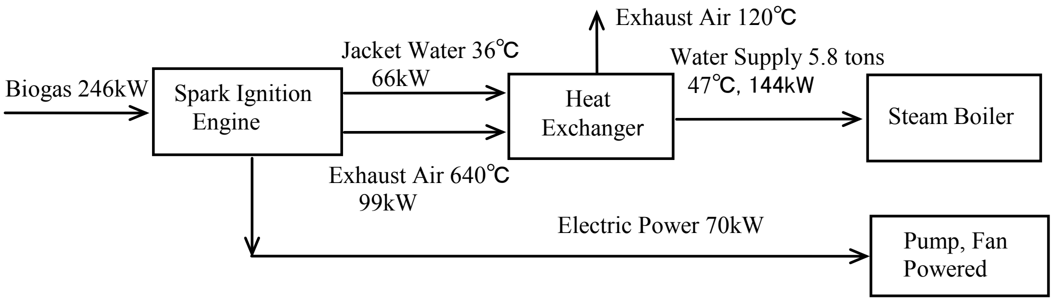
Due to lower productive rate of biogas, gas source instability, lower energy carrier demand load, difficult to manufacture equipment and operation and a long payback time as investment etc., biogas can no effectively use in the IES, so that, it could be considered incorporate into the municipal LNG Network pipe after the quality checked up.

5. Integrated energy system (IES) of biogas

Electricity is the high grade energy. According to the second law of thermodynamics, the electricity generated by biogas is of the highest efficiency, meanwhile, the exhaust gas could be employed for heating or cooling. IES of biogas would adopt the following technologies such as Otto cycle of ignition engine, Brayton cycle of gas turbine, power generation of fuel cells, absorption and adsorption refrigeration, high efficient combustion, high efficiency removal of H_2S and CO_2, as well as recovery and storage for thermal energy.

5.1. CHP project

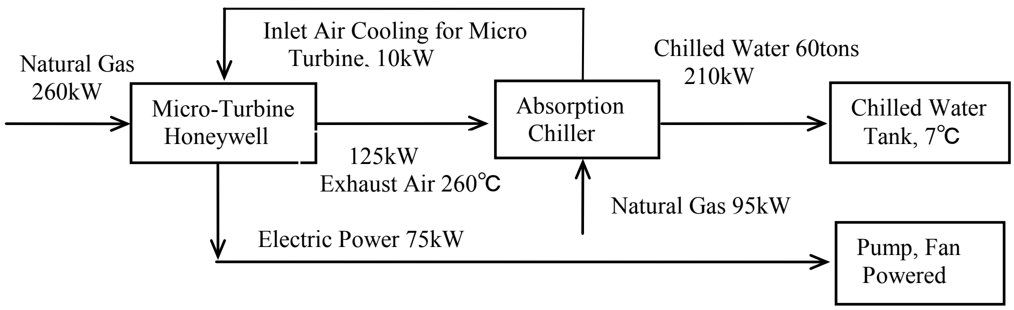
Project 1: Engine + Heat tube exchanger of condensation type
(Shenzhen Kingway brewery)



• Spark Ignition Engine of biogas fueled without removal of CO_2, generate electricity efficiency of 28.45%, discharged heat of 99kW by engine exhaust and of 66kW by jacket cooling water, dispersed heat of 2.8kW by convection and of 4.6kW by radiation.
• If heat of engine exhaust was utilized through heat tube heat exchanger to heat water supply and temperature was reduced to about 120℃, then, overall CHP efficiency may be reached 61.8%, and engine exhaust even could be discharged at the condensation temperature of 57℃.

5.2. CCP project [11]

Project 2: Micro Turbine (Honeywell) + Direct fired double effect chiller



• Turbine efficiency 28.75%. Inlet air cooled to 16℃ to keep constant capacity of turbine.
• Broad absorption chiller using lithium bromide-water, direct fired double effect chiller with COP of 1. Chilled water temperature: supply 7.8-9.4℃, return 12.8-14.4℃.
Performance of MT Honeywell and absorption chiller were shown in Table 5 and Table 6.

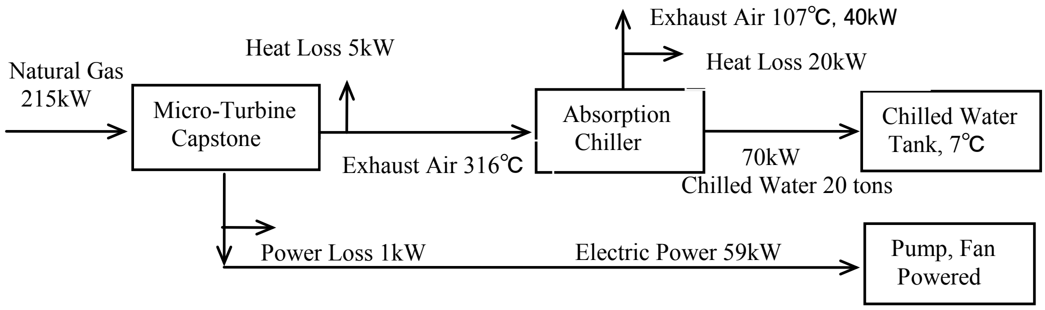
Table 5. Performance parameters of MT (Honeywell).

Item	Parameter	
Rating power (kW)	75	15℃,1atm
NG wastage (m^3/h)	27	≥0.62MPa(absolute)
Thermoelectricity efficiency (%)	28.5	15℃,1atm
Exhaust temperature (℃)	280	
Exhaust flux (kg/s)	0.67/0.76	
Emission of NO_X (ppm)	<13	15℃,1atm, full load

Table 6. Broad LiBr absorption chillers (Mode: BD7N280-15).

Item	Parameter	Item	Parameter
Capacity of refrigeration (USRT)	23	Produce heat (kW)	114
Chilled water outlet/inlet temp. (℃)	6.7/12.2	Warm water outlet temp.(℃)	50
Chilled water flux (m^3/h)	12.8	Warm water flux (m^3/h)	19.6
Cooling water outlet/inlet temp.(℃)	36/29.4	Inlet temp. of exhaust (℃)	280
Cooling water flux (m^3/h)	24.3	Match electricity (kW)	1.2

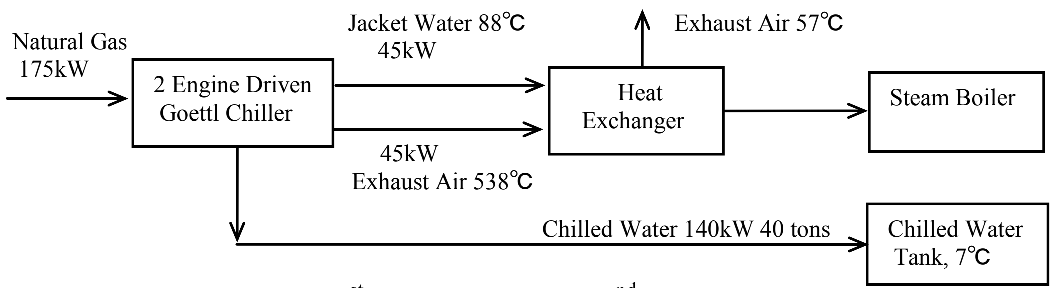
Project 3: Micro Turbines (Capstone) + Single effect chiller



• MT Capstone efficiency 27.9%, with chiller 63.5%. Average exhaust inlet temp.271℃ , outlet temp.113℃.
• Broad absorption chiller driven only by MT exhaust. Single effect chiller with COP of 0.7, nominal capacity of chilled water is 20 tons. Parasitic power is 6.4kW.

5.3. *CCH project*

Project 4: Engine driven Goettl Units + Heat tube exchanger of condensation type



• Engine Driven Goettl Units. 1st stage COPG=1.4, 2nd stage COPG=0.8, Engine output 52kW, engine efficiency 30%.

6. Conclusion

This paper introduced and analyzed biogas utilization for the three large modern breweries, which is not perfect and irrational for use of biogas energy. Based on the current biogas technology and equipments, accordingly to the biogas yield and energy demand in breweries, analyzed and studied the energy utilization technology, equipment configuration, and conversion efficiency on the integrated energy system (IES) . The biogas purification process employs qualified reclaimed water from wastewater treated of the brewery to scrub CO_2 and H_2S in biogas. This process is simple with low operation cost. The resultant biogas is rich in methane content and efficient to improve the efficiency of IES. Both electricity generation and heating efficiency, as well as the cooling efficiency can reach as high as 60%.

Acknowledgements

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Thermoeconomic optimization of absorption chiller cycle

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Abstract: In this paper, absorption chillers are modeled as four heat sources: the generator, the evaporator, the condenser, and the absorber and thermoeconomic issues are examined using the available relations. In order to simplify the calculations, all processes are assumed to be reversible. Since heat exchangers are expensive facilities, therefore, reducing the total heat transfer area is taken as the design criterion. In this paper, first the thermoeconomic criterion, taken as the total cost of unit of refrigeration which includes the capital cost and the energy cost, is defined. In the following, the available relationships are used to calculate the maximum value of the thermoeconomic criterion and the maximum refrigeration load. Next, optimal working conditions are specified for absorption chillers and after that, the effect of the thermoeconomic parameter on the maximum thermoeconomic criterion, coefficient of performance and the specific refrigeration load corresponding to the maximum value of the thermoeconomic criterion are investigated.

Keywords: *thermoeconomic performance, absorption chiller, optimization*

1. Introduction

Nowadays, costs of energy consumption and electricity compared to those of fossil fuels have caused engineers in most countries to consider using absorption chillers instead of compression chillers. However, fuel costs need to be controlled in some way and consequently, economical studies are carried out constantly on opt imization of absorption chillers and reducing their economical costs.

A new criterion has been used in the recent years to evaluate the degree of optimality of thermodynamic cycles. The thermoeconomic criterion economically investigates the phenomena. Capital costs and energy costs are considered in these investigations using thermodynamic relationships and working conditions are designed in a way that the operation is economically optimum. Chen and Schouten (1998) evaluated the optimal value of coefficient of performance in irreversible absorption chiller systems [1]. Next, Chen in 1999 evaluated the optimal value of coefficient of performance for the irreversible 4-heat exchange-surface absorption chiller in the maximum specific cooling load [2]. This was followed by other researches with the aim of optimization of absorption chiller processes and other processes similar to those, including thermoeconomic optimization of the reversible sterling heat pump cycle by Tyagi, Chena, and Kaushikb[3].

The largest portion of capital cost of absorption chiller pertains to the heat exchangers used in the generator, condenser, evaporator, and the absorber.

2. Modeling of the cycle and its relationships

In order to simplify the calculations, absorption chiller cycle is assumed to consist of four heat sources including the absorber, the generator, the evaporator, and the condenser, as illustrated in figure 1. We assume that the processes take place reversibly. It is also assumed that the flow is constant in working parts of the cycle and heat transfer between the elements and heat sources during the time of a complete cycle τ, happen at temperatures T_a, T_c, T_e, T_g, respectively. There are thermal resistances between the external components and the operating elements of the cycle. Temperatures of working components in the generator, evaporator, condenser and the absorber are respectively T_4, T_3, T_2, T_1. Heat transfer coefficients are accordingly U_4, U_3, U_2, U_1. Moreover, heat transfer surfaces are A_4, A_3, A_2, A_1, in the generator, the evaporator, the condenser and the absorber, respectively. The work input for the pump in the cycle Is taken as negligible compared to the heat input to the generator.

It is assumed that the heat transfer between the operating components of the cycle and the external heat sources follows the linear (Newtonian) heat transfer mode and the four processes take place isothermally. Thus, heat transfer equations of all the four processes are written as follows:

$$Q_1 = U_1 A_1 (T_g - T_1)\tau \qquad (1)$$

$$Q_2 = U_2 A_2 (T_e - T_2)\tau \qquad (2)$$

$$Q_3 = U_3 A_3 (T_3 - T_c)\tau \qquad (3)$$

$$Q_4 = U_4 A_4 (T_4 - T_a)\tau \qquad (4)$$

Where Q_4, Q_3, Q_2, Q_1 are heat transfers in the generator, the evaporator, the condenser and the absorber, respectively, From the first law of thermodynamic we have:

$$Q_1 + Q_2 - Q_3 - Q_4 = 0 \qquad (5)$$

Considering the second law of thermodynamic and the reversibility of the cycle we have:

$$\frac{Q_1}{T_1} + \frac{Q_2}{T_2} - \frac{Q_3}{T_3} - \frac{Q_4}{T_4} = 0 \qquad (6)$$

Since the heat exchangers are the expensive component in the cycle, reduction of the heat transfer area (A) is taken as the design criterion. Therefore, by optimizing the total heat transfer area we can obtain optimality.

$$A = A_1 + A_2 + A_3 + A_4 \qquad (7)$$

The parameter (a) is defined as the total distribution rate between the condenser and the absorber:

$$a = \frac{Q_3}{Q_4} \qquad (8)$$

According to the standard definitions of coefficient of performance (COP) and specific cooling load (r) and equations (1) to (8), coefficient of performance can be obtained as follows:

$$\varepsilon = \frac{Q_2}{Q_1} = \frac{T_4^{-1} + aT_3^{-1} - (1+a)T_1^{-1}}{(1-a)T_2^{-1} - T_4^{-1} - aT_3^{-1}} \qquad (9)$$

And the specific cooling load is obtained as follows:

$$r = \frac{Q_2}{A\tau} = \left\{ \frac{1}{U_2(T_e - T_2)} + \frac{T_2^{-1} - T_4^{-1} + a(T_2^{-1} - T_3^{-1})}{U_1(T_g - T_1)[T_4^{-1} - T_1^{-1} + a(T_3^{-1} - T_1^{-1})]} + \left[\frac{1}{U_4(T_4 - T_a)} + \frac{a}{U_3(T_3 - T_c)} \right] \frac{T_2^{-1} - T_1^{-1}}{T_4^{-1} - T_1^{-1} + a(T_3^{-1} - T_1^{-1})} \right\}^{-1} \quad (10)$$

Equations 9 and 10 are the general relationships for absorption chillers with four reversible heat sources. These relationships can be used to obtain thermoeconomical optimum performance for this type of absorption chillers.According to the studies carried out by Kodal and Shahin as given in [5], the thermoeconomic criterion for absorption chillers with four reversible heat sources is defined as the total price of unit cooling load which includes both capital and energy costs. Therefore, the function which is to be optimized is as follows:

$$F = \frac{\frac{Q_2}{\tau}}{C_i + C_e} \quad (11)$$

Where C_i, C_e are capital and energy costs in the unit of time, respectively. The capital cost of absorption chillers is assumed to be proportional to its total heat transfer area:

$$C_i = k_1 A \quad (12)$$

Where k_1 is the capital recovery factor, the capital cost for the unit heat transfer area. Energy consumption cost is directly proportional to the rate of heat input:

$$C_e = k_2 \frac{Q_1}{\tau} \quad (13)$$

Where k_2 is the unit cost of energy. By substituting equations 12 and 13 in 11, we obtain:

$$F = \frac{Q_2/\tau}{(k_1 A + k_2 Q_1/\tau)} = (k_1 r^{-1} + k_2 \varepsilon^{-1})^{-1}. \quad (14)$$

By defining $k = \frac{k_1}{k_2}$ as the thermoeconomic parameter having the dimension $\frac{KW}{m^2}$, when the capital cost increases and the cost of energy consumption reduces, the thermoeconomic parameter k goes up. The optimal relationship for the total refrigeration load and the COP of absorption chillers is as follows:

$$r = U_2 \left[T_e T_c + a T_e T_a - (T_g \varepsilon + T_e) \frac{T_c T_a (1+a)}{T_g (1+\varepsilon)} \right] \times \left\{ \left[(1+b_2)^2 T_c + a(1+b_3)^2 T_a - \frac{a}{1+a}(b_2 - b_3)^2 T_e \right] - (1-b_1)^2 \frac{(1+a) T_a T_c}{(1+\varepsilon) T_g} + \frac{T_e}{\varepsilon T_g} \left[(b_1 + b_2)^2 T_c + a(b_1 + b_3)^2 T_a - \frac{a}{1+a}(b_2 - b_3)^2 T_g \right] \right\}^{-1}, \quad (15)$$

Where: $b_1 = \sqrt{\frac{U_2}{U_1}}$ (16)

By combining (14) and (15), the ration of the optimal value of the thermoeconomic criterion and the COP of absorption chillers with four reversible heat sources is obtained as follows:

$$k_2F = \left\{ \frac{k}{U_2}\left[T_eT_c + aT_eT_a - (T_g\varepsilon + T_e)\frac{T_cT_a(1+a)}{T_g(1+\varepsilon)}\right]^{-1} \right.$$
$$\times \left[(1+b_2)^2T_c + a(1+b_3)^2T_a - \frac{a}{1+a}(b_2-b_3)^2T_e\right] - (1-b_1)^2\frac{(1+a)T_aT_c}{(1+\varepsilon)T_g} \quad (19)$$
$$\left. + \frac{T_e}{\varepsilon T_g}\left[(b_1+b_2)^2T_c + a(b_1+b_3)^2T_a - \frac{a}{1+a}(b_2-b_3)^2T_g\right] + \varepsilon^{-1} \right\}^{-1}.$$

Equation 19 gives the optimum thermoeconomic criterion for a given value of COP and also the optimum coefficient of performance for a given thermoeconomic parameter in reversible absorption chillers. Using equation19, we can evaluate other characteristics of thermoeconomic operation of reversible absorption chillers which obey the linear (Newtonian) heat transfer law.

Equation 19 demonstrates that for the thermoeconomic parameter we have $F = 0$ when $\varepsilon = 0$ or $\varepsilon = \varepsilon_c$, where:

$$\varepsilon_c = \frac{T_a^{-1} + aT_c^{-1} - (1+a)T_g^{-1}}{(1+a)T_e^{-1} - T_a^{-1} - aT_c^{-1}}, \quad (20)$$

is the coefficient of performance for an absorption chiller with four reversible heat sources. When $\varepsilon < \varepsilon_c$, the maximum thermoeconomic criterion is derived. Using (19) and the final condition $\frac{d(k_2F)}{d\varepsilon} = 0$, we can evaluate $COP(\varepsilon_r)$ for the maximum value of the maximum thermoeconomic criteria $(F_{\max})$:

$$\varepsilon_F = \left[1 - \sqrt{1 - \frac{(1+a)T_g^{-1} - T_a^{-1} - aT_c^{-1}}{T_a^{-1} + aT_c^{-1} - (1+a)T_e^{-1}}d_1}\right]d_1^{-1} \quad (21)$$

Where

$$d_1 = \frac{(1+a)(T_g - T_e)d_2}{T_e^2[T_a^{-1} + aT_c^{-1} - (1+a)T_e^{-1}]\{d_3 + [T_cT_g + aT_aT_g - (1+a)T_aT_c]U_2/k\}}$$
$$+ \frac{(1-b_1)^2(1+a)T_aT_c - d_3T_e - [T_eT_c + aT_eT_a - (1+a)T_aT_c]T_gU_2/k}{T_e\{d_3 + [T_cT_g + aT_aT_g - (1+a)T_aT_c]U_2/k\}} \quad (22)$$

$$d_2 = (1+b_2)^2T_c + a(1+b_3)^2T_a - (b_2-b_3)^2T_ea/(1+a) \quad (23)$$

$$d_3 = (b_1+b_3)^2T_c + a(b_1+b_3)^2T_a - (b_2-b_3)^2T_ga/(1+a) \quad (24)$$

Substituting (21) in (19), we can obtain the maximum thermoeconomic limit for a reversible absorption chiller. Substituting (21) in (15), we can obtain the specific refrigeration load (r_F) for the maximum thermoeconomic criterion. Three parameters $F_{\max}, r_F, \varepsilon_F$ are important for the optimum design of reversible absorption chillers. These parameters result in the lowest value of COP and the lowest value of the characteristic refrigeration load and the top limit of the thermoeconomic criterion [5,6,7].

3. Investigation and conclusion

In order to examine the thermoeconomic of the cycle and the impact of its different parameters, a case study was analyzed and the obtained circumstances were compared with each other. The following data were known for the aforementioned case study.

$$T_g = 403K, T_e = 293K, T_c = 313K, T_a = 305K, a = 1, U_1 = U_2 = U_3 = U_4 = 0.5\frac{KW}{K.m^2}$$

By changing any of the following parameters, we take other parameters as constant and equal to the values mentioned above. The characteristic charts of the problem at hand were obtained using the above data. Figure 2 shows the thermoeconomic criteria versus the coefficient of performance of a reversible chiller with $k = 1\frac{KW}{m^2}$. The value of the maximum thermoeconomic criterion $(F_{\max})$ can be obtained from this curve. As you can see, this chart consists of two sections with negative and positive slopes. The part which has a negative slope represents the optimum region for operation of absorption chillers. In figure 3, variations of the thermoeconomic criterion in terms of the characteristic refrigeration load is shown. Here too, we have $k = 1\frac{KW}{m^2}$. From this curve one can easily obtain the maximum value for the thermoeconomic criterion $(F_{\max})$ and the maximum refrigeration load $(r_{\max})$. This curve has three parts. It is obvious that the optimum working conditions for absorption chillers are in the region with negative slope.

Figures 2 and 3 can help one find the optimum region for operation of absorption chillers, which are the regions with negative slopes. This region should abide by the following conditions:

$$F_r \leqslant F \leqslant F_{\max} \quad (25) \qquad \varepsilon_F \leqslant \varepsilon \leqslant \varepsilon_r \quad (26) \qquad r_F \leqslant r \leqslant r_{\max} \quad (27)$$

Where F_r the thermoeconomic criterion for the maximum refrigeration is load $(r_{\max})$ and ε_r is the COP for the maximum value of characteristic refrigeration load for the reversible absorption chiller which can be obtained from the following equation:

$$\varepsilon_r = \left[1 - \sqrt{1 - \frac{(1+a)T_g^{-1} - T_a^{-1} - aT_c^{-1}}{T_a^{-1} + aT_c^{-1} - (1+a)T_e^{-1}} d_4}\right] d_4^{-1} \quad (28)$$

Where:

$$d_4 = \frac{(1+a)\{(1-b_1)^2[T_e T_c + aT_e T_a - (1+a)T_a T_c] + (T_g - T_e)d_2\}}{T_e^2[T_a^{-1} + aT_c^{-1} - (1+a)T_e^{-1}]d_3} - 1 \quad (29)$$

Substituting 28 in 19, we can obtain the maximum value for the characteristic refrigeration load. Moreover, by substituting 28 in (15), we can obtain the value of the thermoeconomic criterion for the maximum characteristic refrigeration load, (F_r). The values of the parameters which influence the operation of the cycle are changed and their effects on the cycle are compared. Figure 4 shows the characteristic curve of the thermoeconomic criterion-coefficient of performance for four different values of the thermoeconomic criterion (k) and figure 5 shows the characteristic curve of the thermoeconomic criterion – refrigeration load for the same four values of the thermoeconomic criterion. We can deduce from these curves that the optimum thermoeconomic criterion for a known value of COP, the thermoeconomic criterion for a specific capacity of refrigeration and optimum coefficient of performance and characteristic refrigeration capacity for a known value of the thermoeconomic criterion, all reduce by increasing the thermoeconomic parameter (k). Figure 6 shows the characteristic thermoeconomic parameter- coefficient of performance curve for four different values of total rate of distribution on heat output (a) and figure 7 shows the characteristic thermoeconomic criterion-refrigeration load curve for the same four values of the total rate of heat output.

It can be deduced from these curve that the optimum thermoeconomic criterion for a known value of COP, the thermoeconomic criterion for a special refrigeration capacity and the optimum coefficient of performance, and the characteristic refrigeration performance for a known value of thermoeconomic criterion all decrease by increasing the total heat output distribution rate (a). As it is evident from figure 7, the maximum value for the thermoeconomic criterion and its corresponding coefficient of performance, reduce by increasing the thermoeconomic parameter (k) and the specific refrigeration load corresponding to the maximum thermoeconomic criterion increases by increasing the thermoeconomic parameter (k).

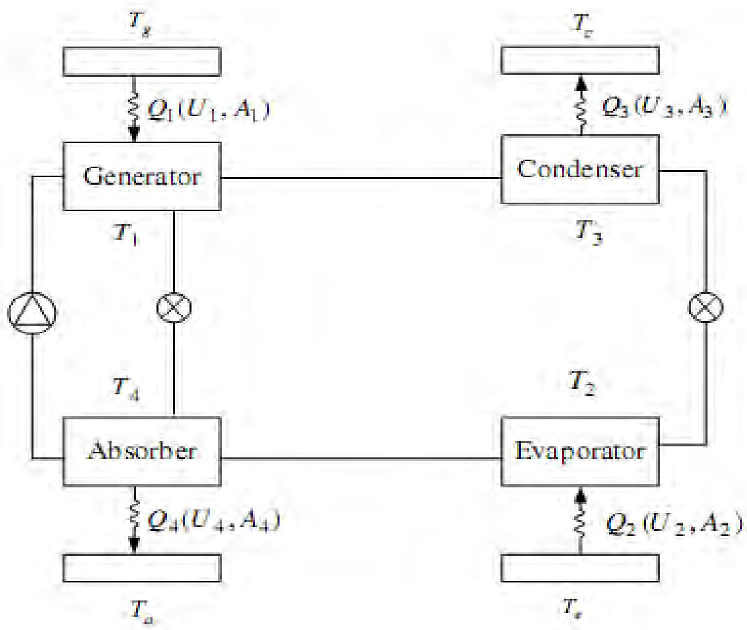

Fig 1: modeling of the cycle

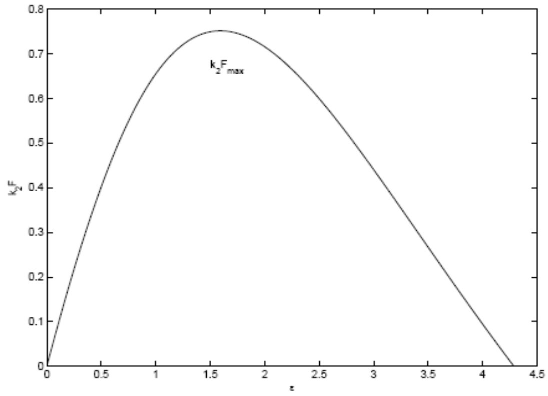

Figure 2: the thermoeconomic criterion in terms of coefficient of performance

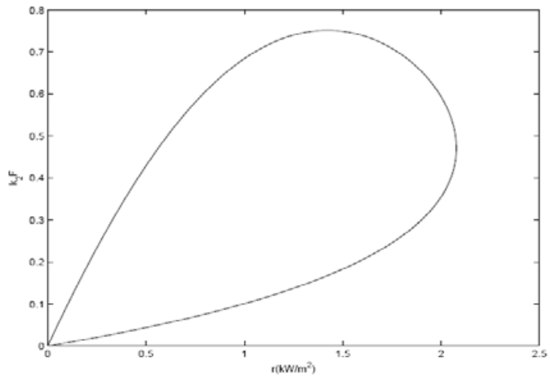

Figure 3: the curve of the thermoeconomic criterion in terms of the characteristic curve of the system.

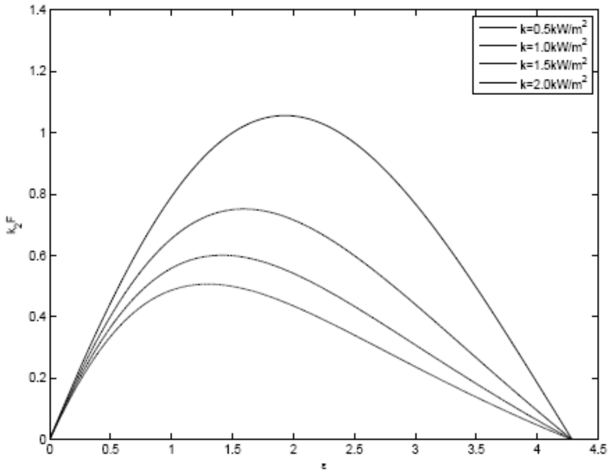

Figure 4: the effect of the thermoeconomic parameter on the ration of the thermoeconomic criterion and the coefficient of performance

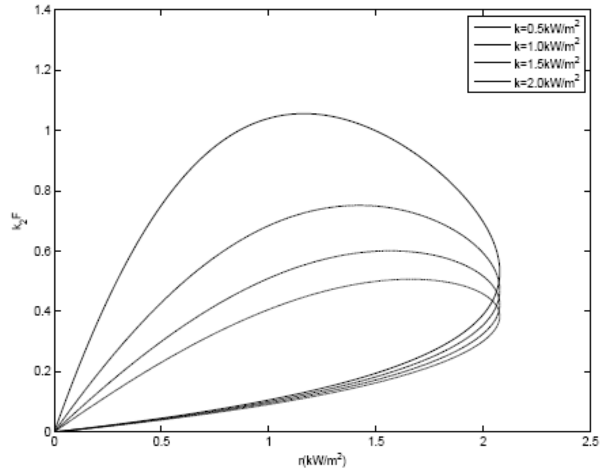

Figure 5: the effect of the thermoeconomic parameter on the thermoeconomic criterion and refrigeration capacity

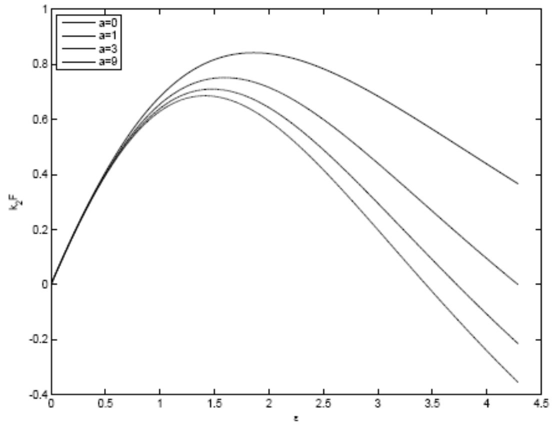

Figure 6: the effect of the total rate of heat output on the ratio of the thermoeconomic criterion and coefficient of performance

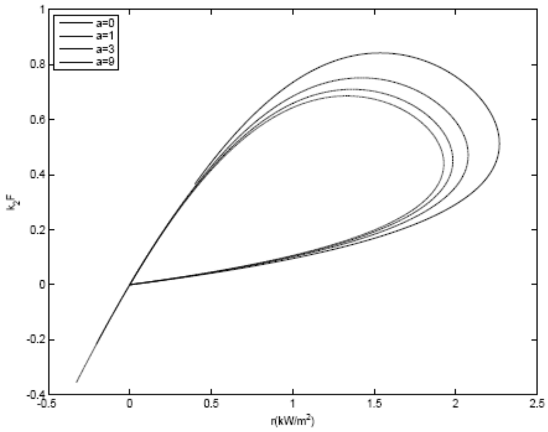

Figure 7: the effect of the total rate of heat output on the ratio of the thermoeconomic criterion and refrigeration capacity

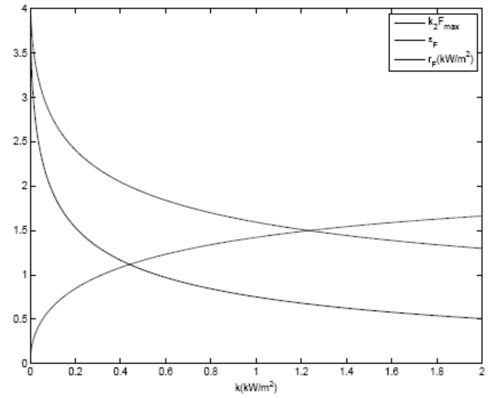

Figure 8: the effect of the thermoeconomic parameter on $F_{\max}, r_F, \varepsilon_F$

4. Conclusion

In this paper, the performance of absorption chillers with four reversible heat sources was analyzed and optimized with the existing relationships. The range of the important parameters for the absorption cooling cycle with four reversible heat sources for its optimum operation was determined. The obtained results can be used as a theoretic guide for further studies on the thermoeconomic optimization and further development of performance of absorption chiller cycles.

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Simulation and optimization of steam generation in a pulp and paper mill

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Abstract: A mathematical process integration model for the steam generation part (recovery boiler, bark boiler, and turbine) was developed based on a pulp and paper mill in the Northern Sweden. The material and energy balances were calculated theoretically and then the operation data from a pulp and paper mill in the Northern Sweden were used to validate the simulation results. By implementing it into the whole plant, the effect of the operation conditions on the whole plant performance were investigated. The introductory studies were carried out with an objective function to minimize the energy cost. The influence of different parameters was rigorously studied. The correlation between economic and energy optima was discussed.

Keywords: *Pulp and Paper Mill, Steam Generation, Simulation, Optimization*

1. Introduction

The pulp and paper industry is a very energy-intensive industrial sector where it is crucial to improve the material and energy efficiency to the greatest possible extent. Process integration methods represent useful tools for evaluating possible process alternatives. Many process integration studies in the pulp and paper industry have previously been carried out mainly by using Pinch analysis[1,2] and mathematical programming[3,4]. However, the scope of modeling and simulation of the energy and material balances is not as complete as it is in other modern process industries. More detailed work is required especially as large efforts are currently put on turning pulp mills into bio-refineries.

Based on the mixed integer linear programming (MILP) combined with ReMIND[5] and CPLEX[6], mathematical process integration models of steelmaking industries have been developed in our research groups. The developed model has been successfully applied, for example to give suggestions on choosing a new blast furnace, to reduce the CO_2 emission by using alternative production routines, etc[7,8]. Recently, the research work has been extended to mining industries also[9,10].

To extend researches to pulp and paper mill, a complete plant model was developed based on a pulp and paper mill in the Northern Sweden and described briefly in our previous work[11]. In this work, a mathematical process integration model for the steam generation part (recovery boiler, bark boiler, and turbine) was developed in which the material and energy balances were performed theoretically and the operation data (measurements) from the mill were used to validate the model results, which was presented in detail. By implementing it into the complete plant model, the effects of the operation conditions in the steam generation part on the whole plant performance were investigated. Furthermore, introductory studies were carried out with the main objective to minimize the energy cost, and the correlation and differences between economic and energy were also discussed.

2. Process description and model construction

The pulp and paper mill in the Northern Sweden is illustrated in Fig. 1. The lignin is removed to produce the brightness pulp by passing through the digester, O_2 delignification, and bleaching plant. Paper is produced from pulp in paper making section. The by-product extracted from pulping chips in the digester, i.e. the black liquor, is concentrated in a multi-effect evaporation plant and burned in a recovery boiler (RB) where the combustion of organics provides energy and recovers chemicals which are used to generate the solution of NaOH and Na_2S by passing through the causticizing plant. Bark boiler (BB) provides additional high pressure steam to satisfy the steam demand for the whole plant. The high pressure steam produced in the RB and BB is expanded in a steam turbine producing process steam of 10 and 4 bar. Steam of 30 bar is extracted from the turbine for soot-blowing in the RB and steam 10 bar is used for soot-blowing in the BB. Biomass in form of bark or forest residues and fuel oil are used in the BB. Fuel oil is also used to start up the RB.

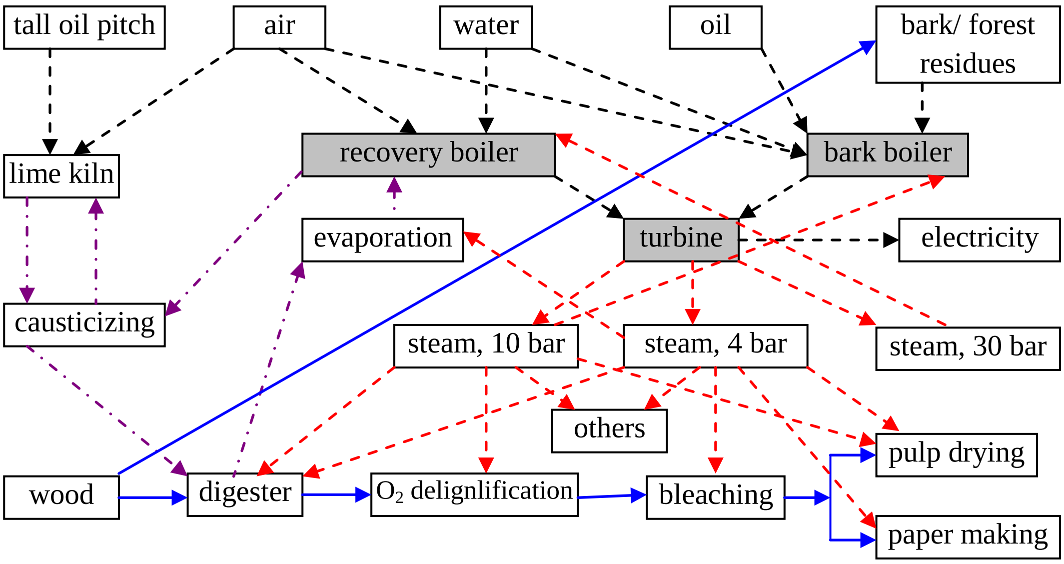

Fig. 1. Schematic representation of the pulp and paper mill.

To perform the process integration, each process unit was modeled as separate modules and thereafter linked. The construction of modules was based on a mathematical programming, i.e. mixed integer linear programming (MILP), and the equation editor used was a Java based programming — ReMIND[5]. In ReMIND, the model structure is represented as a network of nodes and branches, which represent process units and energy/material flows, respectively. The different nodes are connected depending on the input and output to/from each process unit. Each node contains linear equations to express the energy and mass balances required in the process unit. There are two options to express the energy and mass balances for each node, i.e. representing theoretically (option one), or obtaining an equation from the operation measurement under a set of conditions (option two). We chose the option one. The steam generation part including RB, BB, and back pressure turbine is the heart of energy utilization in the plant, and it was studied in the present work.

For RB and BB (boilers), the energy and mass balances were estimated from the chemical compositions of the fuels, the effective heat value of the fuels (H_{eff}) and the corresponding thermodynamic properties of all the related flows. This has been described in detail in literature[12] under operation conditions, such as the temperature of water, air, and flue gas, and the temperature and pressure of steam generated. From the chemical composition of the fuel and the amount of the excess air, the air demand and the amount of flue gas were calculated based on the mass balances. The fuel demand (ton fuel/ ton steam) was calculated from the air demand, the amount of the flue gas, the heat value of fuels together with conditions for the air, flue gas, water and steam. The principle was briefly summarized in Fig. 2, and the brief description was given in the following text. The properties of the fuels and the related heat capacities were taken from public references and listed in Tables 1 and 2, respectively.

Table 1. Properties of fuels.

	C	H	O	S	Na	K	Slagg	N	H_2O	$H_{eff,dry}$, kJ/kg
black liquor	36.4	3.7	34	5.2	19.9	0.8	0	0	0	12400
fuel oil 5	85.9	11.4	0.9	1	0	0	0.03	0.3	0.5	40700
forest residues	51.9	6.15	40.5	0.02	0.05	0.3	0.86	0.22	0	19300

Table 2.Heat capacity.

substance	heat capacity (kJ/(kgK))		heat capacity (kJ/(Nm^{3}K))
black liquor	3.74	air	1.29
Na_2CO_3	1.09	flue gas	1.40
Oil	1.92		
bark	2.97		

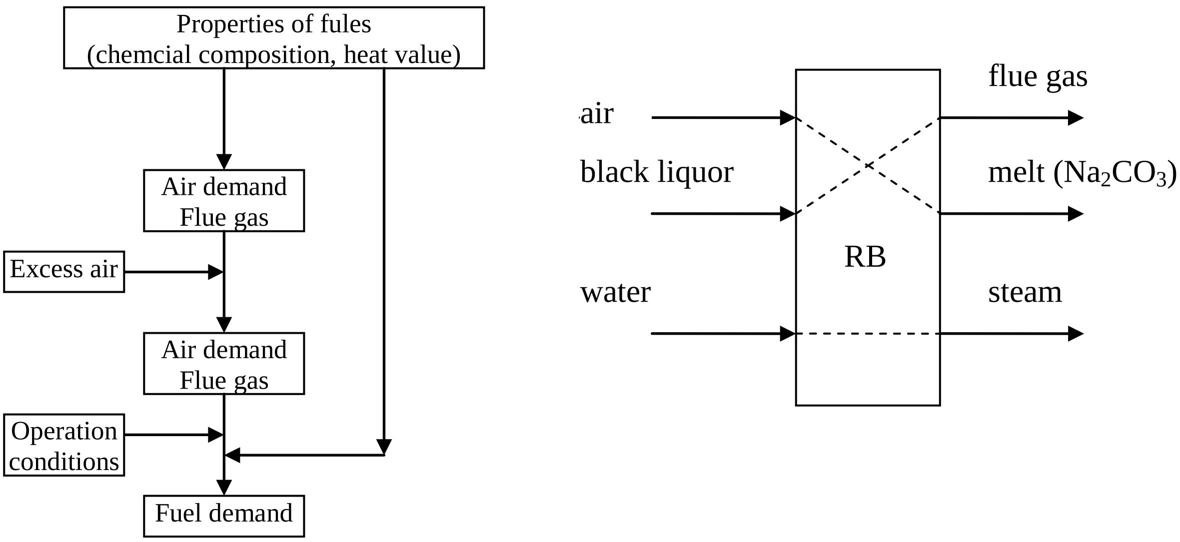

Fig. 2. Schematic representation of mass and energy balance for RB and BB.

$$f_{air,\min} = 22.7 \cdot \left(\frac{w_C}{12} + \frac{w_H}{2} + \frac{w_S}{32} - \frac{w_O}{32} \right) \quad (1)$$

$$f_{air} = f_{air,\min} \cdot (100 + c\%)/100 \qquad \text{m}^3\text{(n)/kg dry fuel} \quad (2)$$

$$f_{flue\ gas} = 22.7 \cdot \left(\frac{w_C}{12} + \frac{w_H}{2} + \frac{w_{H_2O}}{18} + \frac{w_S}{32} + \frac{w_N}{28} \right) + f_{air,\min} \cdot \left(\frac{0.791}{0.209} + c \right) \ \text{m}^3\text{(n)/kg dry fuel} \quad (3)$$

where f is the flow rate, w is the composition in mass fraction, and c is the excess air in percentage. The flow rate of the flue gas in Eq. (3) is based on the assumption that all the elements of C, H, S, N will leave the boiler as the flue gas. However, in some case, some elements may leave the boiler more than one form. For example, in the recovery boiler, the elements of C and O leaves boiler as the flue gas and melt in the form of Na_2CO_3. In this case, the following equation was used:

$$f_{flue\ gas} = 22.7 \cdot \left(\frac{w_C}{12} + \frac{w_H}{2} + \frac{w_{H_2O}}{18} + \frac{w_S}{32} + \frac{w_N}{28} \right) + f_{air,\min} \cdot \left(\frac{0.791}{0.209} + c \right) - f_{CO,melt} \quad (4)$$

where $f_{CO,melt}$ is the consumption part because the element of C and O leaves in the form of Na_2CO_3 ($Na+C+O \rightarrow Na_2CO_3$). To calculate the flow rate of Na_2CO_3, the totally amount of Na is assumed to be the summation of those for Na and K. Based on the mass balance, we got Eq. (5) in which *TS*% is the dry content of black liquor, and we assumed the same flow rates for water and steam, i.e.: $f_{water} = f_{steam}$.

$$f_{Na2CO3} = 0.53 \frac{(w_{Na} + w_K)}{\left(1 + \frac{1 - TS\%/100}{TS\%/100}\right)} \quad \text{(kg/kg wet fuel)} \quad (5)$$

To represent the energy balance, the reference temperature was chose as 20 °C, and the enthalpy for the components except water and steam at a certain temperature was calculated with the Eq. (6) where *f* is the flow rate, C_p is the heat capacity, and *t* is the temperature in °C:

$$h = fC_p(t - 20) \quad (6)$$

In ReMIND, the equation representing mass and energy balances should be linear, while the enthalpy of water or steam depends on both temperature and pressure. Therefore, the enthalpies of water/ steam at different temperatures and pressures were calculated firstly from the NIST online database[13] and then the calculated enthalpies were fitted to an equation that is a function of temperature and pressure by assuming the pressure effect is a linear. The fitted equation was input in the equation editor in ReMIND. For water, we obtained:

$$h = (4.2354t + 0.892) + (0.1008 - 2.51 \times 10^{-4} t)(P - 75) \quad \text{(kJ/kg)} \quad (7)$$

where *P* is the pressure in bar. For high pressure steam (60 bar), we obtained:

$$h = (2216.2 + 2.4309t) + (7.76 \times 10^{-3} t - 4.94)(P - 55) \quad \text{(kJ/kg)} \quad (8)$$

The total energy balance for the RB was:

$$h_{air} + h_{blackliquor} + f_{water} h_{water} + f_{blackliquor} \cdot h_{heatvalue} + h_{heatloss} = h_{fluegas} + h_{melt} + f_{water} h_{steam} \quad (9)$$

For the BB, we neglected the energy in ash, and the flow rate of the flue gas was calculated with Eq. (3), and total energy balance was:

$$h_{air} + h_{fuel} + f_{water} h_{water} + f_{fuel} \cdot h_{heatvalue} + h_{heatloss} = h_{fluegas} + f_{water} h_{steam} \quad (10)$$

The mass and energy balances for the turbine are much easier to generate compared to those for the boilers. The enthalpies of steams were obtained with the same method as those in the boilers, and results for medium pressure steam (30bar), low pressure steam at 10 bar, and low pressure steam at 4 bar were shown as Eqs. (11), (12), and (13), respectively.

$$h = (2313.5 + 2.3058t) + (1.395 \times 10^{-2} t - 7.15)(P - 28) \quad \text{(kJ/kg)} \qquad (11)$$

$$h = (2400.1 + 2.1856t) + (2.910 \times 10^{-2} t - 11.00)(P - 9) \quad \text{(kJ/kg)} \qquad (12)$$

$$h = (2443.9 + 2.1157t) + (8.06 \times 10^{-2} t - 20.5)(P - 3) \quad \text{(kJ/kg)} \qquad (13)$$

The material and energy balances for the turbine were:

$$f_{60bar} = f_{30bar} + f_{10bar} + f_{4bar} \qquad (14)$$

$$f_{60bar} h_{60bar} \eta = f_{30bar} h_{30bar} + f_{10bar} h_{10bar} + f_{4bar} h_{4bar} + EL + h_{loss} \qquad (15)$$

where the flow rate of the 30 bar steam was obtained from the plant, and η is the mechanical efficiency, and h_{loss} is the heat loss, and EL is the electricity generation in MW.

3. Model validation and process integration

The developed model for the steam generation part was implemented into the complete plant model in our previous work[11]. By running the process integration model for the complete plant, the model results were compared with the operation measurements for the model validation. To run the process integration model, an objective function has to be set. In the present work, the objective function was the minimization of the energy cost for the studied pulp and paper mill, and the prices of fuels and electricity used were the same as those we set in our previous work[11].

3.1. Model validation

For the RB, by assuming the heat loss 3.5% and 5% excess air with a certain flow rate of black liquor, the process integration was carried out. The steam generation calculated from model is 220.9 ton/h which is 3.8% higher than the measurement from the mill. For the BB, by assuming the heat loss 3.5%, 5% excess air and 45% dry content of bark, the ratio of the steam generation to bark consumption (dry) calculated from the model is 5.15 ton steam/ ton dry bark, and the corresponding measurements from the mill is 6.07 (ton steam/ ton dry bark). The discrepancy for the BB may be from assumption of the dry content of bark. Generally, the dry content of the bark is from 40 to 50%, and the bark consumption increases with increasing water content of bark. For the turbine, by assuming the mechanical loss 5%, the model calculation agrees well with measurements.

3.2. Process integration

The running of the BB is to satisfy the process steam demand for the whole plant. The operation conditions in the RB will affect the energy consumption for the RB itself, and then affect the performance of the BB. While the operation conditions in the BB will only affect the performance of the BB.

For the RB, the temperature of the flue gas, the temperature of the liquid into the RB, the temperature of the water into the RB, the amount of the access air, the temperature of the air, the water content of the liquor, and the heat loss of the RB will affect the steam generation from the RB. Since the RB is insulated well, the heat loss may be in the range of 1 to 5%. Meanwhile, the amount of the excess air may be from 5% to 15%. The model calculation results show that the variations of these two operation conditions do not affect the performance of the RB a lot, and the discussions were not shown. In addition, the influence the water content of the liquor to the RB has been discussed in our previous work[11].

Fig. 3 illustrates the influence of the temperature of the flue gas on the performance of the RB and the BB. The utilization of the waste heat from the flue gas is very promising. If the temperature of the flue gas decreases from 250 to 125 °C by using heat exchanger to exchange the heat with flows to the RB, the steam generation will increase from 215 to 232 ton/h, and the corresponding bark consumption (wet basis) will decrease from 22.6 to 15.6 to/h. How to utilize the waste heat is a big challenge, and the following text will give the discussion.

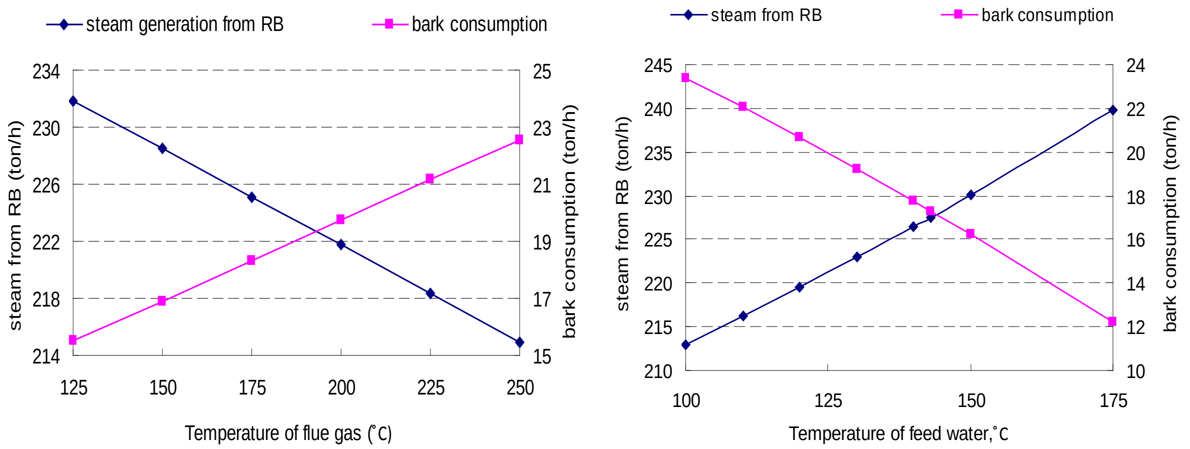

Fig.3. The effects of temperature of flue gas and feed water on the performance of the RB and the BB.

The influence of the temperature of the water on the performance of the RB is also shown in Fig. 3. If the temperature of water increases from 100 to 175 °C, the steam generation from the RB will increase from 213 to 240 ton/h, and the corresponding bark consumption will decrease from 23 to 12 ton/h. This is one possibility to utilize the waste heat in the flue gas. Sometimes, the waste heat from flue gas may not be enough to preheat water, which means that how to reasonably use the waste heat for the whole plant to preheat water is a vital issue to save the energy. On the other hand, the improvement of process performance by adding new heat exchangers and/or changing the existing routines always requires additional investment. It is worth or not? The model results can provide the possibility for the process improvement, and then make the cost estimation to help people to make a decision, which is just the goal of our work.

The temperature of the liquor to the RB will affect the performance of the RB and BB. When the liquor leaves from the evaporation plant, the temperature of the liquor is around 125 °C. From the energy point of view, if the temperature of the liquor can be further increased, the steam generation from the RB will be increased obviously as shown in Fig. 4. However, from the practice point of view, the temperature of the liquor should be lower than the boiling temperature of the liquor which is around 130 °C. Because of this reason, the insulation of the pipe for the black liquor distribution from the evaporation plant to the RB is very important. For example, if the black liquor is cooled to 100 °C to enter the RB, the steam generation will decrease to 3.5 ton/h and the bark consumption will increase 1.5 ton/h compared to 130°C.

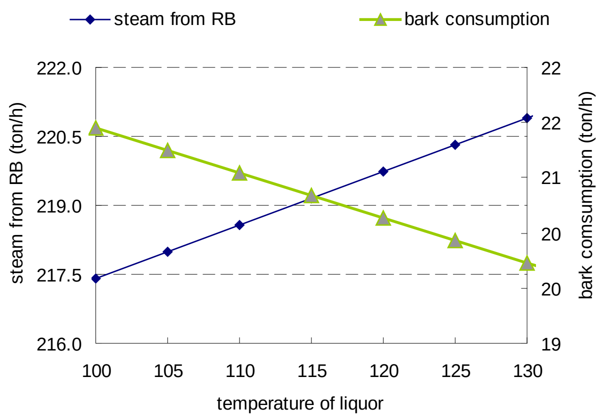

Fig.4. The effect of the temperature of the liquor on the performance of RB and BB.

For the BB, the influences of the temperature of the flue gas, the temperature of the water into the boiler, the amount of the excess air, the temperature of the air, and the heat loss of the boiler on the performance of the BB is the same as those for RB. The effects of the temperature and the water content of the bark are illustrated in Fig. 5, respectively. The increases of temperature of the bark will decrease the bark consumption. Although the energy saving is not so obviously, but it should be very easy to increase the temperature of the bark from 20 to 80 °C. On the contrary, the effect of water content on the bark consumption is considerable, and this explains the possible reason for the discrepancies of the model results from the measurement in model validation part.

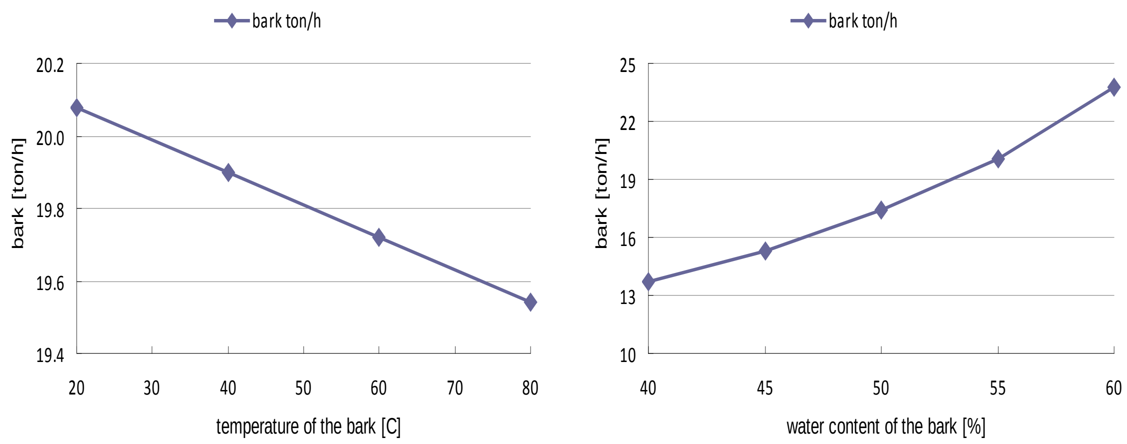

Fig.5. The effect of the temperature and water content of the bark on the performance of BB.

4. Conclusions

A mathematical process integration model for the steam generation part was developed. The material and energy balances were obtained theoretically. The model of the steam generation part was implemented into the previous developed whole plant model, and the model results of the steam generation part were validated with the operation data by running the process integration model with the low energy cost as the objective function. The effects of the operation conditions in the steam generation part on the whole plant performance were investigated. It shows that the utilization of the waste heat from the flue gas to increase the temperature of the feed water into the boiler is an option to decrease the bark consumption, and the insulation of the pipes for the black liquor distribution from the evaporation plant to the RB is very important. For the BB, the water content of the bark affects the bark consumption considerably.

Acknowledgements

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A simplified energy management system towards increased energy efficiency in SMEs

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Abstract: Swedish companies have since 2003 been able to get certified by an energy management system (EEMS) and companies that have been certified, can now show savings in energy use. The downside of today's EEMs is that too few small and medium-sized enterprises (SMEs) have chosen to certify such a system in the organization. To increase awareness and interest among SMEs, a simplified version of the EEMS would be desirable. This article presents a simplified EEMs for SMEs developed from the original European standard (SS-EN 16 001). The article describes how the simple EEMS was developed and how the system was validated, i.e. how different companies responded to test-runs of the developed simplified EEMS. By testing the simplified EEMS in practice among various SMEs, different needs from the industry have been documented. The requests that were of greatest importance was how different incentives can be designed to increase the certification level, e.g. tax exemptions etc. The Swedish LTA for energy-intensive industries includes tax exemptions, as well as the certification of the European EEMS standard, and has shown to lead to large energy savings. An examples of a future energy policy could thus be a Long-Term Agreement (LTA)s program for SMEs including the simplified EEMS.

Keywords: *Energy management, SME, Industrial energy efficiency, PFE*

1. Introduction

Increased global warming is posing a major threat to global environment. The industry is a large emitter of carbon dioxide emissions, the major green house gas, and accounting for about 78 percent of the world's annual coal consumption, 41 percent of the world's electricity use, 35 percent of the world's natural gas consumption, and nine percent of global oil consumption [1]. Industrial energy efficiency is one of the most significant means of reducing the threat of increased global warming [2]. During the last decade, energy prices rose significantly for the Swedish industry. Between 2000 and 2006, electricity prices in Swedish industry almost doubled and oil prices rose by about 70 percent [3]. Even more price increases are to be expected, not least as a consequence of planned tax increases in the nation. The electricity price increase has partly been due to the liberalization of the European electricity markets. The liberalization caused the domestic markets to converge and Sweden has for a long time enjoyed one of the lowest electricity prices in Europe, see, e.g. [4]. Oil price increases may not create competitive disadvantages solely for Swedish industry. Electricity price increases on the contrary most likely will. This is particularly related to the Swedish industries and the fact that the historically low electricity prices have resulted in a higher use of electricity than for their European competitors in many Swedish industrial sectors, see [4] for a comparison in the European foundry industry.

Two main means exist of overcoming the threat of rising energy prices for the Swedish industry. One is to focus on managing the energy supply side with diversified portfolios etc. and, the other means is energy management focusing on a reducing energy end-use at the company. In regard to the latter, an EnErgy Management System (EEMS) may be a tool supporting companies in this important work. However, for most companies, not the least small- and medium-sized enterprises (SMEs), the certification of an EEMS is far too costly. The cost for an EEMS certification in Sweden is approximately 8 000 EUR. The need for developing an EEMS for SMEs can thus not be understated. The aim of this study has been to develop an EEMS for SMEs. The conducted research has been inspired by the European standard for EEMS but is a stand-alone product with a graphical interface. The paper is outlined as follows. Initially, the background to the paper (introduction) is presented, followed by a presentation of energy efficiency in SMEs, and a presentation of the methodology. After that, the developed EEMS is presented, and finally, results and major conclusions are presented.

2. Energy efficiency in SMEs

Even though energy management is stated to be an important means for reducing industrial energy costs and reducing negative environmental impact [5-6], with some exceptions, e.g. [5-10], energy management in industry may be considered a scarcely researched subject. In regard to SMEs having limited resources to work with energy efficiency and energy management, a full-scale, in-house energy management program may not be justifiable [11]. For example, the cost of an energy management program, e.g. certification of an EEMS etc., may be in parity with the annual energy cost at an SME. A simplified EEMS for SMEs could thus be a means for increased energy management practices.

In Sweden, a few studies on barriers to energy efficiency among SMEs have been conducted [4,12-13]. Major barriers include: lack of time or other priorities/other priorities for capital investments, lack of access to capital/lack of budget funding, cost of production disruption/hassle/inconvenience, technical risk such as risk of production disruptions, difficulty/cost of obtaining information on the energy use of purchased equipment [9,22-23]. High-ranked barriers to energy efficiency among SMEs such as lack of time and other priorities, outlines the need for support, support which should not be too costly due to the barriers lack of access to capital, and moreover should involve information (difficulty/cost of obtaining information) [9,22-23]. A simplified EEMS developed for SMEs may overcome many of the barriers to energy efficiency and facilitate the adoption and governance of energy management in the sector.

3. Methodology

Swerea SWECAST conducts a research project named ENIG (Energy Efficiency In Group) together with Swerea IVF and FSEK (Association of Swedish Regional Energy Agencies). Project ENIG includes a number of research and development tasks to promote energy efficiency in Swedish industry [14].

A task in the project ENIG is "To develop a simplified EEMS for SMEs ", which means that a system promoting industry for energy efficiency will be developed based on the existing European standard for energy management systems, EN 16001. The new EEMS will serve as guidance for companies in their work with management systems. Most companies that have adopted energy management are outside the definition of SMEs. The reason for this is that many companies lack the resources to establish management systems, but also the lack of incentives that could increase the level of certification within the SMEs.

At a later stage, there are expectations that the simple EEMS in turn could help SMEs with the introduction of the real European standard, EN 16001, or the coming international standard ISO 50001 [15] .

SIS Publishing Co. owns the copyright to SS-EN 16 001 and because of legal reasons, an interconnection with the original standard had to be excluded. The application has been developed considering that it could be upgraded meaning that SMEs could get certified according to SS-EN 16 001. The management system is based on the PDCA-method (Plan-Do-Check-Act-method). Figure 1 shows an illustration on the PDCA-method and how it leads to continuous improvement.

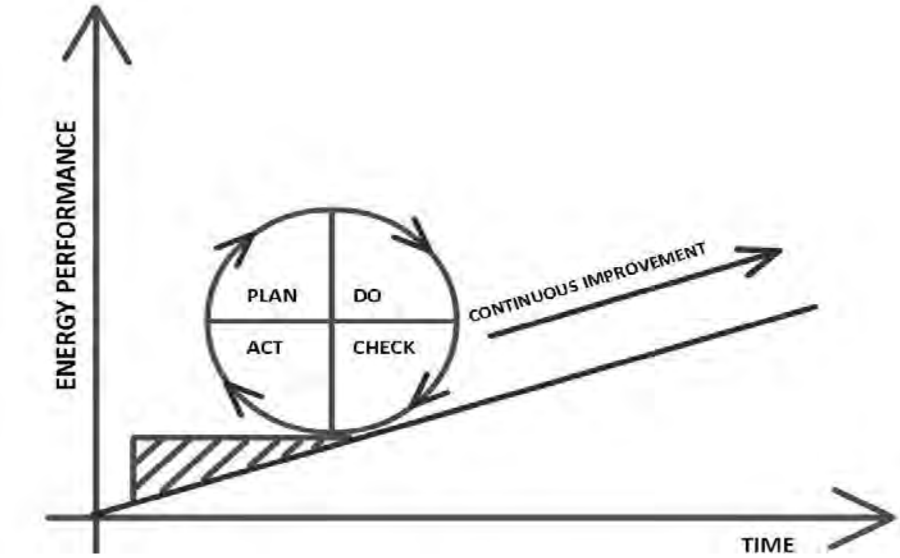

Figure 1: Continuous improvement with the PDCA-method. [16]

The simplified EEMS is built using lean production as a way of thinking when introducing energy use in EEMS [17] and its graphical interface is developed using Adobe Flash and Adobe Acrobat. It is developed as a presentation of the EEMS, and the SMEs should by working through the presentation; learn how to start working with EEMS. The simplified EEMS is more or less a self-learning system. To make the program more interesting and user-friendly, focus on how to build the interface resulted in the use of Adobe Acrobat. The EEMS program takes the user through the EEMS step by step by linking the slides with each other. The linking is made following the PDCA-method, see figure 2.

To improve the simplified EEMS even more, different companies in different sectors were visited and were asked to test-run the program. Interviews were held concerning how the SMEs would like to work with a management system and why they didn't certify in accordance with the original standard. During the test-run, the EEMS was demonstrated and a review on how it differed from the real standard was explained. The results were documented and from the testing results, changes were made in the EEMS. The testing of the simplified EEMS was divided into two phases, the first one with companies that have worked with EEMS for a while and have experience on how to organize their work with energy improvements. The second phase included SMEs, mainly without any experience with management systems. With results from the site visits and test runs, the EEMS could be developed even further and included a validation of the developed program, i.e. how compatible it was in practice for SMEs.

4. Results – simple EEMS program

SMEs can benefit from a simplified EEMS, because they usually have lack of resources and time to look for the best practices that are relevant to their sector [18]. Figure 2 shows how the system is built and how every part of the system is linked together.

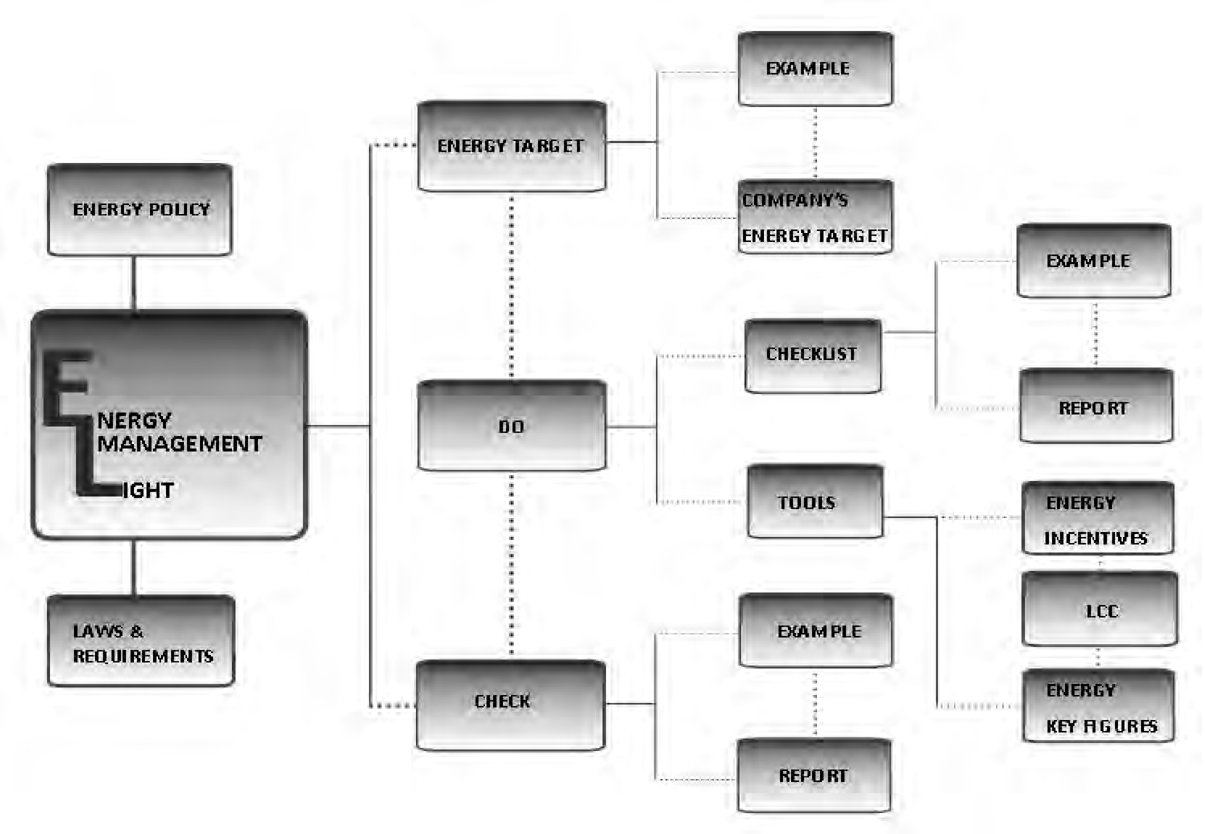

Figure 2: How the different parts from the simple EEMS are linked together.

To implement the simplified EEMS, companies should go through the management system in the following order:

1st. *Energy Policy:* The company should define an energy policy. Some requirements for an energy policy are that, it should be simple, easy and possible to communicate to everyone in the company. The Energy Policy will be the document that is published and it shows how the company plans to work with energy efficiency. It is important to write an easily understandable to understand policy and it is desirable that all the staff from the company agrees on what is expressed in the policy.

2nd. *Laws and standards:* Update the laws and requirements that could affect the company's work. Documenting a record of national, but also international laws and standards is a way to identify what rules the company should adjust its energy use for. The laws and requirements that concern the company will be documented and saved for future monitoring.

3rd. *Implementation:* The implementation part of the EEMS consists of two parts, checklist and energy tools. Introducing a checklist could be used as guidance for companies in their energy use, see figure 3. By introducing different energy tools in the company, they will have more alternatives to improve the work with energy efficiency. The energy tools that the company could use in their energy work are energy incentives, LCC and key energy figures etc.

4th. *Follow up:* In the follow-up, companies should review their results, through a review of the energy management practices conducted. The review should address the energy policy and work with energy efficiency at the company. In order to facilitate the revision an example paper was developed to show which parts that are the most important to review. A proper follow up of the management system should find different discrepancies that exist in the energy targets. By eliminating the discrepancies, companies could improve their level of energy efficiency.

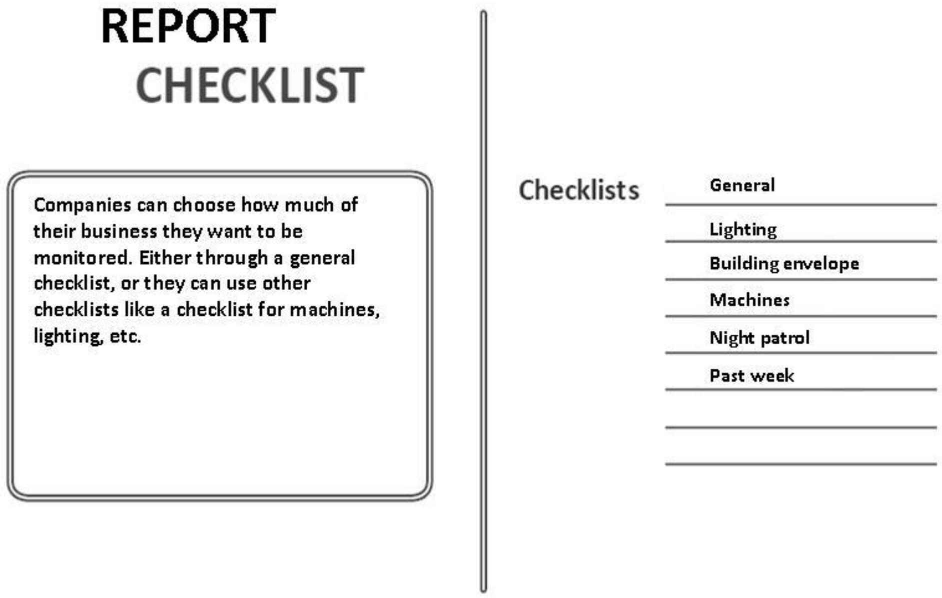

Figure 3: How EEMS presents the different checklists.

5th. Continuous improvement: The companies should always work with continuous improvement of the simple EEMS, see figure 4.

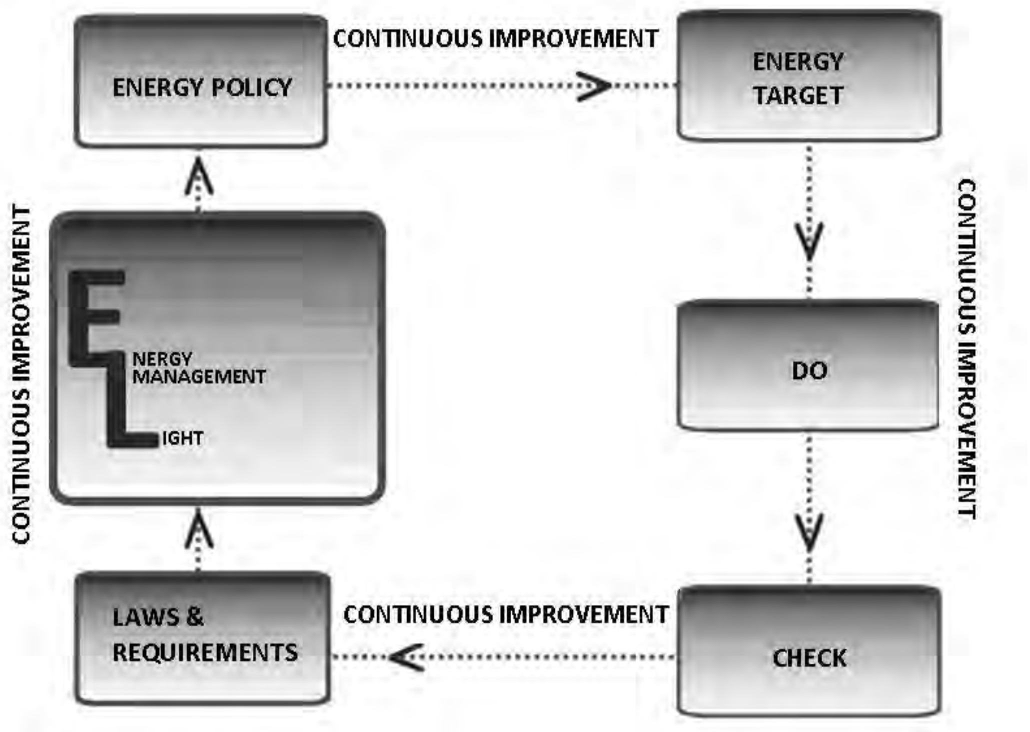

Figure 4: Continuous improvement of the simple EEMS.

If the company wants to do an effective work with their management system they have to dare to act and improve. In order to improve the simplified EEMS, anomalies in the system could be reduced and the the energy efficiency could be increased.

4.1. Validation of the developed EEMS program

Test runs of the simple EEMS have contributed to a continuous improvement of the program on how they would like to use an energy management system.

In early development of the simple EEMS, people with a greater insight on how to work with management functions were visited. The people who attended the first testing may be seen as either energy experts at the Swedish Energy Agency or staff from large industries with a well-known reputation from decades of successful energy management practices.

The improvements that were made during the test runs in the first phase were how the simplified EEMS could be more easily understood and user friendly. An idea from one of the industrial respondents was that if companies were trying to work according to the lean-production philosophy, they would automatically understand how EEMS is supposed to work. By implementing a presentation on how lean production and EEMS are linked together a more user friendly approach could thus be achieved.

During the meeting with respondents from the Swedish Energy Agency, ideas resulted in adapting checklists in the simplified EEMS, arguing that a checklist is an easy way to do an energy audit of the energy use in a SME. The meeting with another industry respondent helped to develop an EEMS towards a more user-friendly interface. The respondent working full time with certified environmental and energy management systems could contribute with thoughts and ideas about how the workflow should be improved.

After the site visits and meetings with respondents at the Swedish Energy Agency, the EEMS was now ready to go into phase two, which was testing the EEMS among SMEs. Four companies were visited during the test phase.

Feedback from the test runs in phase two was solely positive. The test-runs gave a useful view on how the SMEs would like to work with an EEMS. All of the four companies thought that the simplified EEMS was easier to use, smoother, based on common sense and required less resources to implement than the original SS-EN 16 001.

The Swedish LTA for energy-intensive industries includes tax exemptions, as well as the certification of the European EEMS standard (SS-EN 16 001), and has shown to lead to large energy savings (about 1.4 TWh electricity annually). A request from one of the company respondents test runs was to use the simplified EEMS in an LTA (Long-Term Agreements) specially tailored for SMEs in the future. The main reason why the company participating in the test-run did not participate in the current LTA was due to too high certification EEMS costs.

5. Conclusion

This work together with previous research by Thollander and Dotzauer (2010) [11], indicates that a simple and less costly version of an EEMS is desirable among SMEs. By developing an EEMS suited for smaller organizations, it could help companies to increase their level of knowledge on how to organize their business in regard to energy management, and thus enabling increasing levels of energy efficiency in the company. Increased understanding of energy management could contribute to more companies seeing the potential for energy efficiency and energy management.

Even if companies do not consider that they need an EEMS, a shorter training or insight into the simplified EEMS would help companies to realize the importance of organizing their energy management work. By trying to reduce inventories, increase productivity, improve quality, they can become more competitive and (energy) efficient in their business. Moreover, by increasing awareness on how production is managed, this may contribute to a reduction of energy use.

One incentive could be an LTA with tax exemption if companies used the simplified EEMS, like the Swedish PFE for energy-intensive industries.
PFE was found to show large energy savings among the participating companies and the project showed that companies succeed in saving energy through certification of an EEMS. However, PFE for SMEs should have greater demands for education and training in management systems and a required implementation of an energy audit. By informing companies how to use an EEMS, they could implement routines on how to use the data they receive through an energy audit.

According to the company-visits, the simplified EEMS program proved easy to use, none of the visited SMEs who made test-runs of the program thought it was inconceivable. However, more test-runs are needed to further shape the program into a final form. The estimation is that about 20 test runs would be needed to get an insight into how well the simplified EEMS performs among SMEs. Another interesting test-run, which was not performed, is to let a few companies use the simple EEMS for a longer period. This test run could be a good feedback on how well a simple EEMS actually works for a longer period and if the companies can achieve savings in their energy use.

A final conclusion is that a simplified EEMS can help companies to start implementing the measures that are deduced from an energy audit. An obstacle for energy audits to become useful is that they may end up in a "desk drawer", i.e. the company has not been able to use the new information. The main reason is that companies lack tools for how to deal with all of the new data obtained from an energy audit. By using a simplified EEMS, companies have now a tool that creates routines that measure and document their use of energy and their work to increase energy efficiency. Thus, companies can, through the developed program, achieve a support to spot inefficiencies in their energy use and realize that they can increase profits by reducing their energy use.

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Pinch Analysis of a Partly Integrated Pulp and Paper Mill

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Abstract: The pulp and paper industry, with its wood biomass feedstock, has promising opportunities to become a key player in the biorefinery arena. A successful implementation of biorefinery pathways requires optimization of the energy system through process integration, and can lead to both increased and diversified revenues as well as a r eduction of global CO_2 emissions. This paper presents the results from a pinch analysis of a partly integrated Kraft pulp and paper mill. The objective was to identify the potential for energy efficiency improvements, focusing on possibilities to save steam. Another objective was to identify practical retrofit solutions for the mill heat exchanger network and to estimate the costs for the required investments. The potential for energy savings at the mill is estimated at 18.5 MW, i.e. 12% of the current steam demand. Two alternative retrofit options are presented in the paper. A straightforward retrofit that is easy to implement enables 5.8 MW of steam to be saved at a cost of €0.13 million per MW of saved steam. A second more extensive retrofit option is also presented which could achieve steam savings of 11 MW at a cost of €0.14 million per MW of saved steam. Assuming that the steam savings lead to a reduced use of bark fuel in the power boiler, the pay-back period of both energy saving retrofit investments is estimated to be less than about 16 months.

Keywords: *Pinch analysis, Pulp and paper industry, Retrofit, Steam savings.*

1. Introduction

Extensive research aiming at improving energy efficiency and heat integration of pulp and paper plants has been conducted during the past decades. The pulping industry, with its wood biomass feedstock, has clear opportunities to become a key player in the biorefinery arena. Successful implementation of biorefinery concepts requires maximized heat integration, and can lead to increased and diversified revenues as well as reduced global CO_2 emissions.

There are many possible biomass conversion paths in biorefineries, including thermo-chemical, biochemical, mechanical and chemical processes. Thermo-chemical conversion usually involves gasification, pyrolysis or direct combustion, with significant excess heat flows at different temperature levels. Pinch analysis is an essential tool for investigating opportunities for heat integration both within the thermo-chemical biorefinery plant, and between the thermo-chemical biorefinery plant and other nearby industrial process plants with significant heat flows, such as a Kraft pulp mill.

Integration of biorefinery operations within a pulp and paper plant is a typical application of heat cascading, whereby heat for one plant is supplied by excess heat from another. Opportunities for biorefinery-related heat-cascading in the pulping industry have been widely discussed in the literature. A review report published in 2008 [1] discusses general issues for process-integrated biorefineries and also discusses the following specific examples:
Drying of biomass (e.g. forest residues, bark)
Pelletizing in connection with drying and forest residues leaching
Energy combine with ethanol production
Energy combines with other industries
A chemical market pulp mill with optimized energy consumption could achieve a surplus of energy which can be utilized to produce electricity, enable decreased firing of bark fuel in the mill's power boiler which can be dried and sold on t he biomass fuel market, or enable

integration of appropriate biomass energy combine process concepts. An integrated chemical pulp and paper mill, on the other hand, needs to import energy, since the paper machine is a large consumer of heating steam. However, energy savings within an integrated mill also lead to economical savings and decreased environmental impact since they provide a way to reduce the fuel import demand. The mill studied here is a partly integrated pulp and paper mill which means that part of the produced pulp is sold as market pulp and the rest is used to produce paper. One objective of this study was therefore to contribute to the knowledge base about the energy situation in such a partly integrated pulp and paper mill. It is important to note that very few published studies in the literature address energy efficiency at partly integrated pulp and paper mills based on the Kraft process. Therefore, it is important to contribute to further development of the knowledge about the energy situation in this type of mill. The main objective of this work was to identify potential energy savings through pinch analysis at a partly integrated pulp and paper mill. The aim was also to suggest practical retrofit solutions for how to achieve a reduced energy demand, or alternatively, how to release excess heat at higher temperatures. The costs of the proposed measures were also estimated.

The results presented in this paper are based on the results of an MSc thesis project conducted by two students at Chalmers University of Technology in close co-operation with mill personnel at the Billerud Karlsborg mill. The thesis report by Eriksson and Hermansson, *Pinch analysis of Billerud Karlsborg, a partly integrated pulp and paper mill* [2] provides a detailed description of the work and results of the energy systems analysis.

The pinch study was part of a larger project conducted in co-operation between research groups at several Swedish universities[1], the Swerea MEFOS Research Institute and the pulp and paper mill Billerud Karlsborg. The aim of the project, hereafter called the Billerud project, was to establish a framework for process integration studies with a regional perspective in the pulp and paper industry. One of the objectives of the project was to improve co-operation between different institutions and actors who use and develop process integration tools such as pinch technology and reMIND (see for example reference [9]). The results of the pinch analysis presented in this paper are therefore planned to be used in connection with other models developed within the project. The opportunities for this model interaction are discussed in Section 5.2.

2. Methodology

This study was conducted using pinch technology, and it is assumed that the reader is familiar with the basic concepts. For a comprehensive description of the theory, the reader is referred to references [3] and [4]. The principal steps of the methodology are described below [5]:
Define the process stream system to be investigated with respect to opportunities for improved energy efficiency.

Extract stream data and establish energy saving targets using pinch analysis.
Analyze the existing heat exchanger network in order to identify pinch rule violations.
Make changes to the existing network so as to solve some of the pinch violations.
Evaluate the profitability of the proposed changes to the heat exchanger network.
Process data representing typical average winter operation was retained for the study. Most of the data required was available directly in the plant's process data-log, but some additional

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measurements were needed. Manufacturer specifications, engineer estimations, and mass and energy balances were also used to complete the data set required. Stream-specific minimum temperature differences for heat exchanging and heat transfer coefficients were used in accordance with previous studies [5].

The costs of the proposed heat exchanger network retrofits were calculated based on area requirements, with surface area costs taken from recent pinch studies of similar mills [6]. The cost of piping was estimated at 50% of the installed heat exchanger cost based on typical cost estimation factors presented in [4], since the distances between streams were not investigated. Additional costs for e.g. instrumentation, control and pumping costs were also neglected.

3. Mill description

The studied mill is a partly integrated Kraft pulp and paper mill situated in northern Sweden, producing 300 000 tonnes/year of pulp and paper (40% pulp and 60% paper). Electricity is cogenerated in a back-pressure steam turbine unit. The mill was built over 80 years ago, but the main parts still in use were built in the early 1980's. Continuous energy improvements have been made during the lifetime of the plant. However, given the availability of new research results and the continuous changes of energy market conditions, it is of interest to re-investigate the potential for process integration and energy savings on a regular basis. Pinch analysis provides a good tool for this type of investigation and has now been used at the Billerud Karlsborg mill for the first time.

4. Results

4.1 *Theoretic potential for energy savings*

A large number of heat exchangers supplying heating or cooling to mill process streams were identified (27 cold and 35 hot streams). Adopting stream-specific values of $\frac{1}{2}\Delta T_{min}$ for different stream types, ranging from 0.5 K for utility steam to 8 K for air, the process pinch temperature is 148˚C. This means that the mill has a net deficit of heat above 148˚C and a net surplus below. The theoretical minimum external heating requirement is 135.4 MW.
The composite curves for the mill are shown in Fig. 1. The potential internal heat exchange is illustrated by the overlap of the hot and cold curves. In a theoretical case with maximum heat exchange between the curves, the hot streams should be able to provide all heat to the process except for the actual steam demand. Achieving this for a retrofit design would, however, require far too many new heat exchangers to be profitable.

In the grand composite curve (Fig. 2), the composite curves are merged. The horizontal line below the pinch represents the surface condensers, which provide about 41 MW of heat at 60˚C. This heat is currently used for warm water production from raw water. This heat could be released by making use of the hot streams in the heat pocket below the surface condensers' temperature. These streams are hot effluents from the evaporation and bleaching plant and outgoing air from the pulp dryer and the paper machine. There is also a heat pocket at around 70˚C which could enable heat integration for several streams in this region.

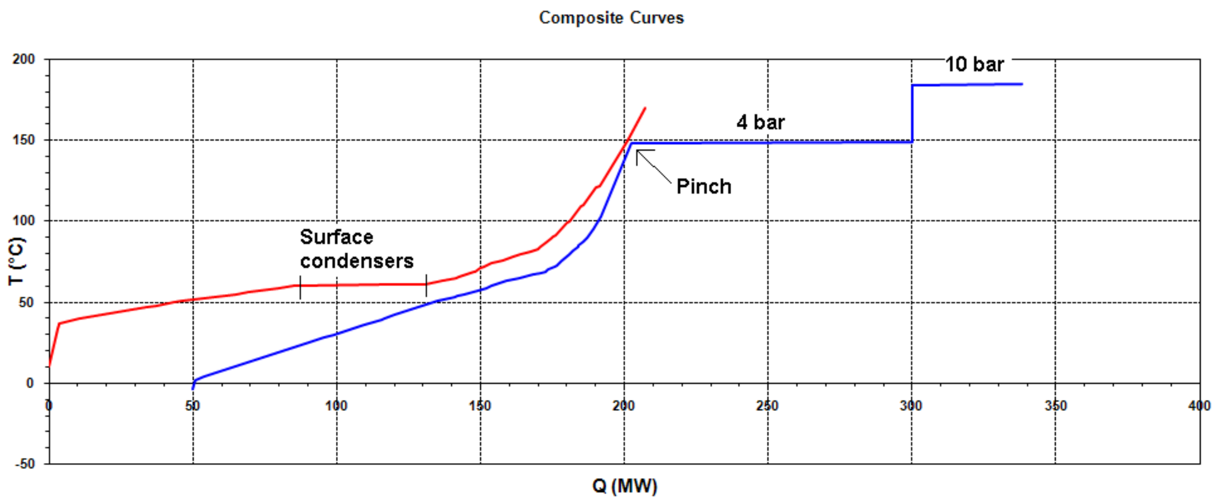

Fig. 1. Composite curves for the process.

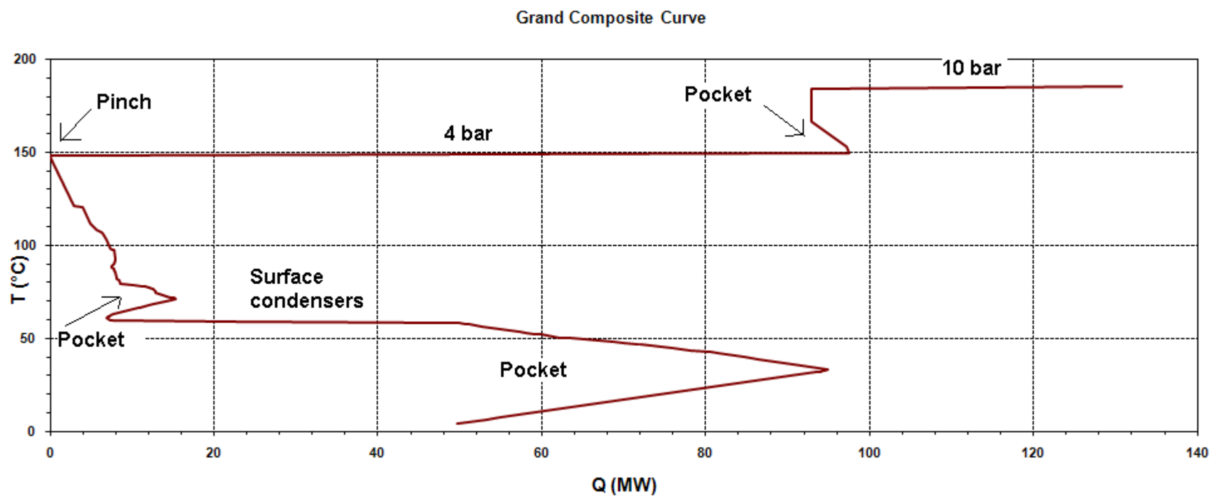

Fig. 2. Grand composite curve for the process.

4.2 *Pinch violations*

The difference between the actual steam demand and the minimum demand for hot utility is due to pinch violations i.e. non-optimal heat exchange. With a minimum hot utility of 135.4 MW and a current steam demand of 153.9 MW, the resulting pinch violations for the plant are 18.5 MW. This corresponds to a theoretical steam-saving potential of 12% of the current steam demand. All violations are due to heating below the pinch.

4.3 *Retrofit suggestions*

In this section, two retrofit options are presented: Retrofit I involves relatively straightforward changes whereas Retrofit II is more extensive. The focus of both retrofit options is on eliminating steam users below the pinch temperature. This could be achieved by improved heat recovery from high temperature water effluent streams in drains or by heat exchanging streams differently in the network. The major difference between the proposals is that in Retrofit I only changes that do not affect the hot and warm water system (HWWS) are considered, whereas in Retrofit II this process section is included.

4.3.1 *Retrofit I*

In Retrofit I, the main focus has been to save as much steam as possible without interfering with the HWWS. This retrofit could achieve steam savings of 5.8 MW of low-pressure (LP) steam, which corresponds to 4% of the present steam demand and 32% of the pinch violations. In Table 1, the cold streams are presented together with the hot stream that, according to the proposal, should replace the LP steam that is currently used. The resulting steam savings are also indicated. In this proposal, steam is replaced by condensate streams and hot effluents from the evaporation plant. Costs for new heat exchangers include costs for new heat exchanger area and piping. The total cost for the Retrofit I proposal is estimated at €759 000 and the resulting specific cost is €130 000 per MW.

Table 1. Steam savings resulting from retrofit measures in Retrofit I.

Cold stream	**New hot stream**	**Steam saved (MW)**
E2 filtrate	Condensate from stripper	1.0
E2 filtrate	Condensate from stripper	1.3
White water for pulp dryer and paper machine	B-condensate	2.1
White water for paper machine	Condensate cooling pulp dryer	1.5
Total		**5.8**

4.3.2 *Retrofit II*

The more extensive heat exchanger network retrofit results in larger energy savings than Retrofit I. In addition to the steam savings of Retrofit I, changes that affect the HWWS are also included in Retrofit II. The replaced steam users are shown in Table 2. In total it is possible to save approx. twice as much steam as in Retrofit I, i.e. about 11 MW of LP steam. This corresponds to 7% of the present steam demand and 60% of the pinch violations. The total cost of the Retrofit II proposal is estimated at €1 580 000, or €143 000 per MW.

Table 2. Steam savings resulting from retrofit measures in Retrofit II.

Cold stream	**New hot stream**	**Steam saved (MW)**
E1 filtrate	Liquor cooling	1.6
E2 filtrate	Condensate from stripper	1.0
E2 filtrate	Condensate from stripper	1.3
D0 filtrate	Hot water	2.6
White water for pulp dryer and paper machine	B-condensate	2.1
Local heating	Digester liquor	1.0
White water for paper machine	Condensate cooling pulp dryer	1.5
Total		**11.0**

In addition to the changes made in Retrofit I, it is necessary to modify or build seven additional heat exchangers. When replacing a heat exchanger in the HWWS it is important that the new network still can achieve the same temperatures in the hot and warm water tanks.

4.4 *Other findings from the pinch study*

4.4.1 *The paper machine*

There is a lack of information regarding how the heat recovery in the paper machine is currently implemented. A thorough investigation of the heat recovery system would most probably identify further opportunities for improvement. Using a system similar to the one used in the pulp dryer, with a fluid transferring heat from the outgoing air to the incoming air, could improve efficiency and provide operational flexibility with respect to outdoor temperature. At present, there are large amounts of energy released to the surrounding with the outgoing air effluent stream due to its high humidity content.

4.4.2 *Bleaching plant*

The bleaching plant is the largest user of hot water in the mill. A comparison with other mills indicates that there is a potential for energy savings at the studied mill and that there are reasons to investigate the bleaching plant more thoroughly. Using presses instead of filters when washing the pulp and keeping the temperature at a more even level between the bleaching steps are two ways of lowering the demand for steam and hot water and thus improving the energy efficiency.

4.4.3 *Hot and Warm Water System (HWWS)*

It would be possible to reach a higher temperature in the hot water tank with some changes in the heat exchanger network. This would lead to lowered steam demand in the subsequent hot water users. This option was not included in the study, since traditional pinch analysis is not the best approach to such tank temperature optimization. It would, however, be interesting to further analyze this opportunity.

4.5 *Economic evaluation*

There are several ways for the mill to benefit from potential energy savings. The most obvious and straightforward is to simply reduce the amounts of oil and bark fired in the power boiler. Due to large seasonal variations it is, however, not possible to reduce the boiler load during all parts of the year, since during summer, it already runs at minimum load. Other options include investing in a condensing turbine, delivering district heating or integrating a biorefinery process.

To make an initial assessment of the profitability of the proposed energy-efficiency measures, a simple calculation was performed for the option of bark savings. Assuming bark savings can be achieved during two thirds of the year, the economic savings will be €107 000 per MW and year and hence the payback period will be less than 16 months for both proposals. Considering that the fuel reduction is likely to be oil rather than bark during parts of the year, the payback period could well be even lower.

5. Discussion

5.1 *Seasonal variations*

The study was carried out for winter operating data. The summer steam demand is lower because of increased ambient temperatures. Therefore this study is not representative for the whole year.

No detailed investigation of possible economic benefits through, for example, reduced burning of bark or district heating delivery were made. To analyze these options, more information regarding yearly variations in bark boiler firing, steam system and demand of heating and cooling in general are required. The effect of these seasonal variations on the steam-saving potential could, however, be estimated using the results of previous studies [6]. The effect on the overall energy balance of the mill could, for example, be studied using the reMIND tool, thereby connecting the results from this pinch analysis to other studies within the Billerud project.

5.2 *Pinch-reMIND interaction*

It is possible to use the results of the pinch analysis presented in this paper in an energy system model developed using the reMIND simulation and optimization tool (see e.g. [7]). This model interaction is based on what has previously been shown to be a good way to use the results from pinch analysis in optimization studies using reMIND, see for example [8] and [9]. For a more general discussion of the role of optimization for efficient implementation of process integration measures in industry, see [10].

In reMIND, optimization is carried out by using mixed integer linear programming in order to minimize the system cost. The system cost includes amongst others, the investment costs of different measures that can be taken to change the system. The structure of the energy system is represented as a network of nodes and branches where branches represent energy or material flows. One node may represent, for example, a process line or a single equipment unit. It may also represent a possible steam-saving investment which will be the case when representing the results from the pinch analysis. Multi-period optimization can be modelled in reMIND which makes it possible to consider seasonal variations in the overall energy system studied.

The two retrofit alternatives identified in the pinch analysis could, for example, be modelled as two different investment options in the reMIND model, each resulting in a certain steam saving[2] which can be achieved for a specified investment cost.

6. Conclusions

The theoretical potential for energy savings at the studied mill was estimated at 18.5 MW, corresponding to 12% of the current steam demand. Two retrofit proposals to accomplish parts of this theoretical potential were suggested. Assuming that the steam savings lead to a reduced use of bark in the power boiler, the pay-back period of the energy savings investment is estimated to be less than about 16 months.

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Power Yield Processes: Modeling, Simulation and Optimization

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Abstract: Classical thermodynamics is capable of determining limits on energy production or consumption in terms of the exergy change. However, they are often too distant from reality. Yet, by introducing rate dependent factors, irreversible thermodynamics offers enhanced limits that are closer to reality. Thermodynamic analyses lead to important formulas for imperfect efficiencies. In this paper power limits for generation or consumption of thermal, solar, chemical energy are obtained by application of the optimal control theory.

Power limits define maximum power released from energy generators and minimum work supplied to separators or heat pumps. In this research we consider power limits for both devices of energy generator type (engines and fuel cells) and of energy consumer type (heat pumps, separators and electrolysers). Each process is driven either by a simple heat exchange or by the simultaneous exchange of energy and mass fluxes. We stress the link of these problems with the classical problem of maximum work. Particular attention is devoted to fuel cells as electrochemical flow engines. Amongst a number of new results, notion of certain special controls (Carnot variables) plays an important role. In particular, we demonstrate their role in the analysis of heat and radiation engines, chemical power generators and fuel cells.

Keywords: *efficiency, power generation, entropy, thermal machines, fuel cells.*

Nomenclature

A_v	*generalized exergy per unit volume*	Jm^{-3}
a_0	*constant related to the Stefan-Boltzmann constant*	$Jm^{-3}K^{-4}$
a_v	*total area of energy exchange per unit volume*	m^{-1}
$\dot{G}$	*resource flux*	gs^{-1}, $mols^{-1}$
g	*conductance*	$Js^{-1}K^{-a}$
h	*numerical value of Hamiltonian*	$Jm^{-3}K^{-1}$
n	*flux of fuel reagents*	gs^{-1}, $mols^{-1}$
q	*heat flux between a stream and power generator*	Js^{-1}
Q	*total heat flux involving transferred entropies*	Js^{-1}
S_σ	*entropy produced*	JK^{-1}
s_v	*volumetric entropy*	$J\,K^{-1}m^{-3}$
T	*variable temperature of resource*	K
$T_{1,2}$	*bulk temperatures of reservoirs1 and 2*	K
$T_{1',2'}$	*temperatures of circulating fluid*	K
T'	*Carnot temperature control*	K
t	*physical time*	s
W	*work produced, positive in engine mode*	J
w	*specific work at flow or power per unit flux of a resource*	J/mol
α	*heat coefficients*	$Jm^{-2}s^{-1}K^{-1}$
ε	*total energy flux*	Js^{-1}
μ	*chemical potential*	$Jmol^{-1}$
μ'	*Carnot chemical potential*	$Jmol^{-1}$
Φ	*factor of internal irreversibility*	-
σ	*Stefan-Boltzmann constant*	$Jm^{-2}\,s^{-1}K^{-4}$
σ_s	*entropy production of the system*	$JK^{-1}s^{-1}$
ζ	*chemical efficiency*	-

1. Introduction

In a previous work (Sieniutycz 2003 [1]) we discussed basic rules for modeling power production and energy limits in purely thermal systems with finite rates. In particular, radiation engines were analyzed. In the present work we treat generalized systems in which temperatures T and chemical potentials μ^k are essential. This is associated with engines propelled by fluxes of both energy and substance. When one, say, upper, reservoir is finite, its thermal potential decreases along the stream path, which is the consequence of the energy balance. Any finite reservoir is thus a resource reservoir. It is the resource property or the finiteness of amount or flow of a valuable substance or energy which changes the upper fluid properties along its path. Then, in the engine mode of the system, one observes fluid's relaxation to the equilibrium with an infinite lower reservoir, usually the environment. This is a cumulative effect obtained for a resource fluid at flow, a set of sequentially arranged engines, and an infinite bath Downgrading or upgrading of resources may occur also in electrochemical systems of fuel cell type. Fuel cells working in the power production mode are electrochemical flow engines propelled by chemical reactions.

In a process of power production shown in Fig. 1 two media differing in values of T and μ interact through an energy generator (engine), and the process is propelled by diffusive and/or convective fluxes of heat and mass transferred through 'conductance' or boundary layers. The energy flux (power) is created in the generator between the resource fluid ('upper' fluid 1) and, say, an environment fluid ('lower' fluid, 2). In principle, both transfer mechanisms and values of conductance of boundary layers influence the rate of power production (Curzon and Ahlborn 1975[2]; De Vos 1994 [3], Sieniutycz and Kuran 2005 [4], 2006 [5]).

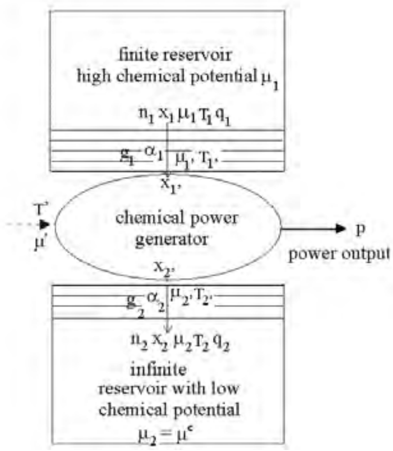

Fig. 1. A scheme of chemical and/or thermal engine.

2. Carnot Control Variables in Power Systems

Diverse controls can be applied in power systems to represent the propelling fluxes of heat and mass transfer. Here we shall recall and then use definitions of Carnot control variables (Carnot temperature and chemical potential) whose derivations and applications were originated in our previous work (Sieniutycz 2003 [8]). We begin with the simplest case of no mass transfer, i.e. we shall consider a steady, internally reversible ('endoreversible') heat engine with a perfect internal power generator characterized by temperatures of circulating fluid $T_{1'}$ and $T_{2'}$, Fig.1. The stream temperatures, attributed to the bulk o each fluid are T_1 and T_2. The inequalities $T_1 > T_{1'} > T_{2'} > T_2$ are valid for the engine mode of the system. With an effective temperature called Carnot temperature

$$T' \equiv T_2 \frac{T_{1'}}{T_{2'}} \tag{1}$$

entropy production of the endoreversible process, takes the following simple form

$$\sigma_s = q_1 \left(\frac{1}{T'} - \frac{1}{T_1} \right) \tag{2}$$

This form is identical with the familiar expression obtained for processes of purely dissipative heat exchange between two bodies with temperatures T_1 and T'. In terms of temperature T' of Eq. (1) thermal efficiency assumes the classical Carnot form containing the temperature in the bulk of the second reservoir and temperature T':

$$\eta = 1 - \frac{T_2}{T'} \tag{3}$$

This property substantiates the name "Carnot temperature" for control variable T'. In terms of T' description of thermal endoreversible cycles is broken down to formally "classical" equations which contain T' in place of T_1. In irreversible situations Carnot temperature T' efficiently represents temperature of the upper reservoir, T_1. Yet, at the reversible Carnot point, where $T_{1'} = T_1$ and $T_{2'} = T_2$, Eq. (1) yields $T' = T_1$, thus returning to the classical reversible theory. These properties of Carnot temperature render descriptions of endoreversible and reversible cycles similar. They also make the variable T' a suitable control in both static and dynamic cases (Sieniutycz 2003 [8]).The notion of Carnot temperature can be extended to chemical systems, where also the Carnot chemical potential emerges (Sieniutycz 2003 [8]), where instead of pure heat flux q the so called total heat flux (mass transfer involving heat flux) Q is introduced. The heat flux equals the difference between total energy flux ε and flux of enthalpies of transferred components, $q = \varepsilon - h$, satisfying an equation

$$Q \equiv \varepsilon - \mu_1 n_1 ... \mu_k n_k ... - \mu_m n_m . \equiv \varepsilon - G \tag{4}$$

where G is the flux of Gibbs thermodynamic function (Gibbs flux). The equality $\varepsilon = Q + G$ is fundamental in the theory of chemical engines; it indicates that power can be generated by two propelling fluxes: heat flux Q and Gibbs flux G, each generation having its own efficiency. The related driving forces are the temperature difference and chemical affinity. Assuming a complete conversion we restrict to power yield by a simple reaction $A_1 + A_2 = 0$ (isomerisation or phase change of A_1 into A_2). We have a chemical control variable

$$\mu' = \mu_2 + \mu_{1'} - \mu_{2'} \tag{5}$$

which has been used earlier to study an isothermal engine (Sieniutycz 2008 [9]). After introducing the Carnot temperature in accordance with Eq. (1), total entropy production of the endoreversible power generation by the simple reaction $A_1 + A_2 = 0$ takes the following form

$$\sigma_s = Q_1\left(\frac{1}{T'} - \frac{1}{T_1}\right) + n_1 \frac{\mu_1 - \mu'}{T'} \tag{6}$$

where $Q_1 = q_1 + T_1 s_1 n_1$ is the total heat flux propelling the power generation in the system. The resulting equation is formally equivalent with a formula obtained for the purely dissipative exchange of energy and matter between two bodies with temperatures T_1 and T' and chemical potentials μ_1 and μ'.

3. Energy Systems with Internal Imperfections

Carnot variables T' and μ' are two free, independent control variables applied in power maximization of steady and dynamical generators. Ideas referring to endoreversible systems may be generalized to those with internal dissipation. In such cases a single irreversible unit can be characterized by two loops shown in Fig. 2 which presents the temperature–entropy diagram of an arbitrary irreversible stage. Each stage can work either in the heat-pump mode (larger, external loop in Fig. 2) or in the engine mode (smaller, internal loop in Fig. 2).

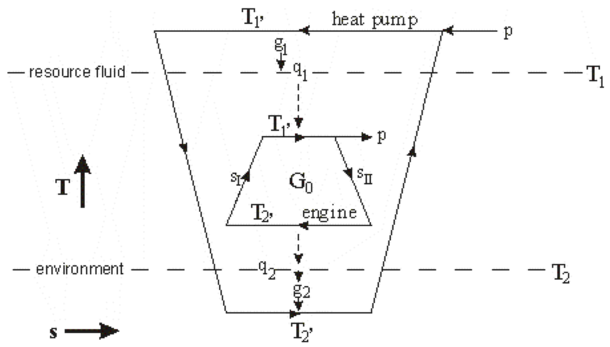

Fig. 2. Two basic modes with internal and external dissipation: power yield in an engine and power consumption in a heat pump. Primed temperatures characterize the circulating fluid.

The related analysis follows the earlier analyses of the problem which take into account internal irreversibility by applying the factor of internal irreversibility, Φ. By definition, $\Phi = \Delta S_{2'}/\Delta S_{1'}$ (where $\Delta S_{1'}$ and $\Delta S_{2'}$ are respectively the entropy changes of the circulating fluid along the two isotherms $T_{1'}$ and $T_{2'}$ in Fig. 2) equals the ratio of the entropy fluxes across the thermal machine, $\Phi = J_{s2'}/ J_{s1'}$. Due to the second law inequality at the steady state the following inequalities are valid: $J_{s2'}/J_{s1}$ >1 for engines and $J_{s2'}/J_{s1}$ <1 for heat pumps; thus the considered ratio Φ measures the internal irreversibility. In fact, Φ is a synthetic measure of the machine's imperfection. Φ satisfies inequality Φ >1 for engine mode and Φ <1 for heat pump mode of the system. A typical goal is to derive efficiency, entropy production and power limits in terms of Φ.

3.1. Power yield and entropy production in systems with internal imperfections

The thermal efficiency component of any endoreversible thermal or chemical engine can always by written in the form $\eta = 1 - Q_2/Q_1$. After defining the coefficient $\Phi = 1 + T_{1'}\sigma_S^{\text{int}}/Q_1$ called the internal irreversibility factor the internal entropy balance takes the form usually applied for thermal machines

$$\Phi \frac{Q_1}{T_{1'}} = \frac{Q_2}{T_{2'}} \tag{7}$$

One can evaluate Φ from averaged value of the internal entropy production that describes the effect of irreversible processes within the thermal machine. Clearly, in many cases Φ is a complicated function of the machine's operating variables. In those complex cases one applies the data of $\sigma_s^{\text{int}} = dS_\sigma^{\text{int}} / dt$ to calculate averaged values of the coefficient Φ. In our analysis the quantity Φ is treated as the process constant. This corresponds with the observation that it is an average value of Φ, evaluated within the boundaries of operative parameters of interest which is used in most of analyses of thermal machines. In terms of the Carnot temperature T' and factor Φ the efficiency η , Eq. (7), assumes the simple, pseudo-Carnot form which is quite useful and general enough to describe thermal, radiative and chemical engines:

$$\eta = 1 - \Phi \frac{T_2}{T'} \qquad (8)$$

A particularly interesting role of the above formulas is observed for radiation engines which are energy systems driven by black radiation. In these systems Gibbs flux $G = 0$, whereas total heat flux Q is identical with the energy flux ε, i.e. $Q = \varepsilon$. The majority of research papers on power limits published to date deals with systems in which there are two infinite reservoirs. To this case refer steady-state analyses of the Chambadal-Novikov-Curzon-Ahlborn engine (CNCA engine) in which energy exchange is described by Newtonian law of cooling, Curzon and Ahlborn 1975 [2], or of the Stefan-Boltzmann engine, a system with the radiation fluids and energy exchange governed by the Stefan-Boltzmann law (De Vos 1994 [3]). In a CNCA engine the maximum power point may be related to the optimum value of a free (unconstrained) control variable which may be efficiency η, heat flux q_1, or Carnot temperature T'. When internal irreversibility within the power generator play a role, the pseudo-Carnot formula (8) applies in place of Eq. (3), where Φ is the internal irreversibility factor (Sieniutycz and Kuran 2006 [5]). In terms of bulk temperatures T_1, T_2 and Φ one finds at the maximum power point

$$T'_{opt} = \left(T_1 \Phi T_2\right)^{1/2} \qquad (9)$$

For the Stefan-Boltzmann engine exact expression for the optimal point cannot be determined analytically, yet, this temperature can be found graphically from the chart $p = f(T')$. A pseudo-Newtonian model, Sieniutycz and Kuran 2006 [5], Kuran 2006 [6], which treats the state dependent energy exchange with coefficient $\alpha(T^3)$, omits to a considerable extent analytical difficulties associated with the use of the Stefan-Boltzmann equation.

4. Dynamical Energy Yield

4.1. General Issues

When resources are finite and/or the propelling fluid flows at a finite rate, the Carnot and resource temperatures decrease along the process path. The previous (steady) analysis is replaced by a dynamic one, and the mathematical formalism is transferred from the realm of functions to the realm of functionals. Here the optimization task is to find an optimal profile of the Carnot temperature T' along the resource fluid path that assures an extremum of the work consumed or delivered and – simultaneously – the minimum of the integral entropy production. Dynamical energy yield requires the knowledge of an extremal curve rather than an extremum point. This leads us to variational methods (to handle extrema of functionals) in place of static optimization methods (to handle extrema of functions). For example, the use of a pseudo-Newtonian model to quantify the dynamic power yield from radiation, gives rise to a non-exponential optimal curve describing the radiation relaxation to the equilibrium. The non-exponential shape of the relaxation curve is the consequence of nonlinear properties of the radiation fluid. Non-exponential are also other curves describing the radiation relaxation, e.g. those following from exact models involving the Stefan-Boltzmann equation (Kuran 2006 [6], Sieniutycz and Kuran 2005 [4], 2006 [5]). Optimal (e.g. power-maximizing) state $T(t)$ is accompanied by optimal control $T'(t)$; they both are components of the dynamic optimization solution.

Energy limits of dynamical processes are inherently connected with exergies, the classical exergy and its rate-dependent extensions. To obtain the classical exergy from work functionals it suffices to assume that the thermal efficiency of the system is identical with the

Carnot efficiency. On the other hand, non-Carnot efficiencies, influenced by rates, lead to 'generalized exergies'. The benefit from generalized exergies is that they define stronger energy limits than those predicted by classical exergies (Berry *at al* 2000 [7]).

4.2. Radiation Systems

Radiation engines are thermal machines driven by the radiation fluid, a medium exhibiting nonlinear properties. Energy transfer rates in reservoirs containing nonlinear media can be described by various models. Usually one assumes that the energy transfer in a reservoir is proportional to the difference of absolute temperatures in certain power, a. The case of $a = 4$ refers to the radiation, $a = -1$ to the Onsagerian kinetics and $a = 1$ to the Fourier law of heat exchange. As the first case of the radiation engine modeling we consider a "symmetric nonlinear case" in which the energy exchange process in the energy exchange in each reservoir satisfies the Stefan-Boltzmann equation. Next we consider "hybrid nonlinear case" in which the upper-temperature fluid is still governed by the kinetics proportional to the difference of $(T^4)_i$ whereas the kinetics in the lower reservoir is Newtonian.

Here are equations of *symmetric nonlinear case*. For the "symmetric" kinetics governed by the differences in T^a, the Carnot representation of the total entropy production has the form

$$\sigma_s = g_1 g_2 \frac{T_1^a - T'^a}{\Phi g_1 (T'/T_2)^{a-1} + g_2} \left(\frac{(\Phi - 1)}{T'} + \left(\frac{1}{T'} - \frac{1}{T_1} \right) \right) \tag{10}$$

Superiority of Carnot control T' over the energy flux control ε_1 may be noted. Analytical expressions for the energy-flux representation of the entropy production or the associated mechanical power p cannot generally be found in an analytical form. The work expression to be minimized is

$$W = \int_{t^i}^{t^f} \varepsilon_1 \eta dt = \int_{t^i}^{t^f} g_1 g_2 \frac{T_1^a - T'^a}{\Phi g_1 (T'/T_2)^{a-1} + g_2} \left(1 - \Phi \frac{T_2}{T'} \right) dt \tag{11}$$

In the case of analytical difficulties which occur for a different from the unity the maximization can be performed numerically by dynamic programming using Carnot T' as the free control.

We consider now *hybrid nonlinear case*. It involves the radiative heat transfer ($a = 4$) in the upper reservoir and a convective one in the lower one. To obtain an optimal path associated with the limiting production or consumption of mechanical energy the sum of the above functionals i.e. the overall entropy production

$$S_\sigma = -\int_{\tau^i}^{\tau^f} c(T_1) \left(\frac{\Phi}{\left(T_1^a + \dot{T}_1^a\right)^{\frac{1}{a}} + \dot{T}_1 \Phi g_1 / g_2} - \frac{1}{T_1} \right) \dot{T}_1 d\tau_1 \tag{12}$$

has to be minimized for a fixed duration and defined end states of the radiation fluid. The most typical way to do accomplish the minimization is to write down and then solve the Euler-Lagrange equation of the variational problem. Analytical solution is very difficult to obtain, thus one has to rest on numerical approaches.

5. Finite Rate Exergies and Finite Resources

We are now in position to formulate the Hamilton Jacobi Bellman theory for systems propelled by energy flux ε. Two different kinds of work: first associated with the resource downgrading during its relaxation to the equilibrium and the second – with the reverse process of resource upgrading, are essential. Total power obtained from an infinite number of infinitesimal stages representing the resource relaxation is determined as the Lagrange functional.

5.1. Some Hamilton Jacobi Bellman Equations for Energy Systems

We shall display some Hamilton Jacobi Bellman (HJB) equations for radiation power systems. A suitable example is a radiation engine whose power integral is approximated by a pseudo-Newtonian model of radiative energy exchange. For the *symmetric* model of radiation conversion (both reservoirs composed of radiation), where $\Phi' \equiv \Phi g_1/g_2$ and coefficient $\beta = \sigma a_v c_h^{-1}(p_m^0)^{-1}$ is related to molar constant of photons density p_m^0 and Stefan-Boltzmann constant σ, we obtain a HJB equation

$$\frac{\partial V}{\partial t} = \max_{T'(t)}\left\{\left(\dot{G}_c\left(1-\Phi\frac{T^e}{T'}\right)+\partial V/\partial T\right)\beta\frac{T^a-T'^a}{\left(\Phi'(T'/T_2)^{a-1}+1\right)T^{a-1}}\right\} \tag{13}$$

For *a hybrid model* of the radiation conversion (upper reservoir composed of the radiation and lower reservoir of a Newtonian fluid the related Hamilton-Jacobi-Bellman (HJB) equation is

$$-\frac{\partial V}{\partial t^f} + \max_{T'(t)}\left\{-\left(\dot{G}_c(T)(1-\frac{\Phi T^e}{T'})+\frac{\partial V}{\partial T^f}\right)u\right\} = 0 \tag{14}$$

5.2. Chemical Power Systems

The developed approach can be extended to chemical and electrochemical engines. Here we shall make only a few basic remarks. Yet, as opposed to thermal machines, in chemical ones generalized streams or reservoirs are present, capable of providing both heat and substance. Large streams or infinite reservoirs assure constancy of chemical potentials. Problems of extremum power (maximum of power produced and minimum of power consumed) are static optimization problems. For a finite "upper stream", however, amount and chemical potential of an active reactant decrease in time, and considered problems are those of dynamic optimization and variational calculus. Application of chemical Carnot control μ' in terms of fuel flux n_1 and its mole fraction x to the Lagrangian relaxation path leads to a work functional

$$W = -\int_{\tau_1^i}^{\tau_1^f}\left\{\zeta_0 + RT\ln\left(\frac{X/(1+X)+dX/d\tau_1}{x_2 - jdX/d\tau_1}\right)\right\}\frac{dX}{d\tau_1}d\tau_1 \tag{15}$$

whose maximum describes the dynamical limit of the system. Here X = x/(1-x) and j equals the ratio of upper to lower mass conductance, g_1/g_2. The path optimality condition may be expressed in terms of the constancy of the following Hamiltonian

$$H(X,\dot{X}) = RT\dot{X}^2\left(\frac{1+X}{X}+\frac{j}{x_2}\right) \tag{16}$$

For low rates and large concentrations X (mole fractions x_1 close to the unity) optimal relaxation rate of the fuel resource is approximately constant. Yet, in an arbitrary situation optimal rates are state dependent so as to preserve the constancy of H in Eq. (16).

6. Concluding Remarks

This research provides data for power production bounds (limits) which are enhanced in comparison with those predicted by the classical thermodynamics. As opposed to the classical thermodynamics, these bounds depend not only on changes of the thermodynamic state of participating resources but also on process irreversibility, ratios of stream flows, stream directions, and mechanism of heat and mass transfer. The methodology familiar for thermal machines has been extended to chemical and electrochemical engines. Extensions are also available for multicomponent, multireaction units (Sieniutycz 2009 [10]).

The generalized bounds, obtained here by solving Hamilton Jacobi Bellman equations, are stronger than those predicted by thermostatic. They do not coincide for processes of work production and work consumption; they are 'thermokinetic' rather than 'thermostatic' bounds. Only for infinitely long durations or for processes with excellent transfer (an infinite number of transfer units) the thermokinetic bounds reduce to the classical thermostatic bounds. A real process which does not apply the optimal protocol but has the same boundary states and duration as the optimal path, requires a real work supply that can only be larger than the finite-rate bound obtained by the optimization. Similarly, the real work delivered from a nonequilibrium work-producing system (with the same boundary states and duration but with a suboptimal control) can only be lower than the corresponding finite-rate bound. This is a direction with many open opportunities, especially for separation and chemical systems.

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Application of oxygen enrichment in hot stoves and its potential influences on the energy system at an integrated steel plant

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Abstract: The purpose of the presented paper is to investigate oxygen enrichment in hot stoves for an integrated steel plant. The application of oxygen enrichment in hot stoves will lead to lower coke or PCI rate by increased blast temperature. With oxygen enrichment, the high calorific value COG, could be saved while keeping the same blast temperature. Several alternatives of using the saved COG are presented. Furthermore, an analysis of how oxygen enrichment into hot stoves will have influence on the whole energy system has been carried out by means of an optimization model. Different strategies have been suggested to minimize the total energy consumption at the studied steel plant and the nearby CHP plant.

Keywords: *Oxygen enrichment, Hot stoves, Blast furnace, Energy system*

1. Introduction

In the process of iron-making, hot stoves (HS) are used to preheat air used in the blast furnace (BF). The preheated air is called hot blast. A higher blast temperature will lead to lower coke consumption in BF operation, hence, the energy consumption and CO_2 emission from BF will be reduced. Hot stoves work as counter-current regenerative heat exchangers. Hot stoves typically use low calorific blast furnace gas (BFG) combined with higher calorific value coke oven gas (COG). BFG is generated from BF when producing hot metal. COG is a valuable fuel being high in hydrogen (H_2) and methane (CH_4). At an integrated steel plant, COG is often delivered from the coking plant.

Basically, using oxygen enrichment in the air for combustion in the hot stoves offers three advantages. First, the hot blast temperature may be increased due to higher flame temperature which reduces the blast furnace reductant consumption. Secondly, the lower volume of flue gas reduces the loss of sensible heat via the flue gas. Thirdly, COG or other higher value fuels could be used more effectively elsewhere.

The purpose of this paper is to investigate the application of oxygen enrichment in hot stoves and its potential influences to the total energy system at an integrated steel plant. This is done by performing calculations of mass and heat balance for the HS-BF system, and also by means of an optimization model.

In next section, the HS-BF system is described followed by the description of BF performance with oxygen enrichment in hot stoves. In section 4, an optimization model has been applied to present the potential influences on the total energy system of the studied steel plant and a nearby combined heat and power plant (CHP). Finally, in section 5 concluding remarks are made based on the presented work including some recommendations.

2. Description of hot stove – blast furnace system

The hot stove often includes two separate parts, a combustion chamber and a check chamber. They work as a counter-current regenerative heat exchanger. The fuel gas is first combusted in the combustion chamber. The flue gas passes through the check chamber and heats it up, then leaves the stack to the ambient. This progress is often called on-gas time. When the check chamber is fully heated up during on-gas time, the blast time is started. During the blast time, the cold blast is blown into the system in opposite cycle and is heated by the check chamber. It then passes through the combustion chamber. Before blowing into the blast furnace, it is often mixed with cold blast to get the required and stable hot blast temperature. BFG is a process gas with low calorific value. It has to be blended with COG to get a higher calorific value before entering the combustion chamber. After blending, the average heating value is around 4.3 MJ/Nm^3.

Traditionally the combustion air is used in hot stoves for fuel combustion. For the studied plant, the hot blast produced is 254 kNm^3 per hour with a temperature of 1104 °C, which is required by the blast furnace to produce hot metal with a production rate of 275 tonnes per hour during the reference period.

The combustion air can be enriched with gaseous oxygen, oxygen enrichment. Compared to traditional combustion, less N_2 will be generated which will absorb less reaction heat from combustion. This will lead to a higher adiabatic flame temperature (AFT) with the same amount of fuel gas. As for the hot stove, therefore, a higher blast temperature can be achieved. On the other hand, the low caloric value fuel gas can also be combusted alone without mixing with any enrichment gas to get the same flame temperature with the use of oxygen enrichment instead. The common enrichment gases used at hot stoves are, for example COG, LPG or NG.

3. BF performance with oxygen enrichment in hot stoves

In the studied steel plant, the hot stoves are fuelled with BFG together with some amounts of COG. The calculations for oxygen enrichment in HS-BF system were carried out by using a spreadsheet model [1].

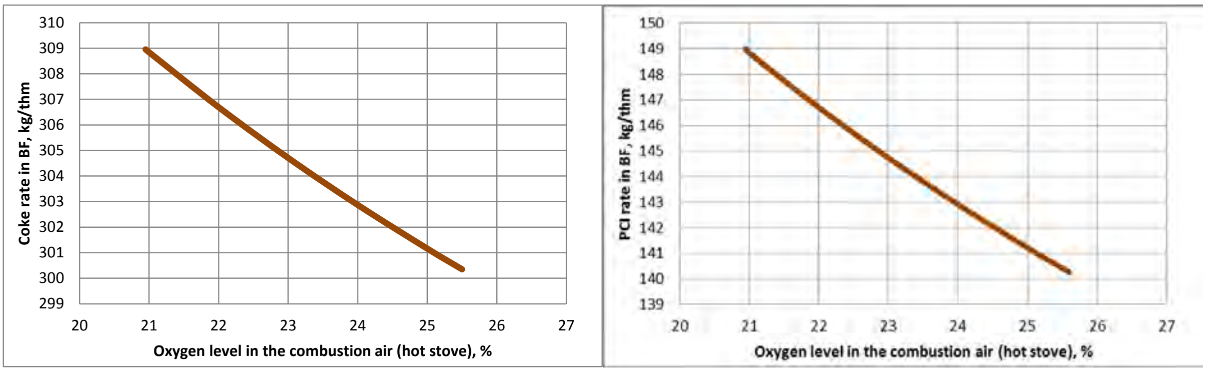

Fig. 1. The correlation between oxygen level in the air and coke rate (left) and PCI rate (right) in BF.

3.1. Increased blast temperature with oxygen enrichment

For the studied hot stoves, the hot blast temperature is assumed to increase to 1200 °C with the enriched oxygen in the combustion air. A higher hot blast temperature will lead to a lower reductant in the blast furnace. In the studied BF blast furnace, coke is used as reductant and charged from the top with other burden materials such as iron ore pellet and fluxes. Besides coke, pulverized coal (PCI) is also injection into BF via tuyers as fuel and reductant. Therefore, it's interesting to study the potential coke and PCI saving due to a higher hot blast temperature. Fig. 1 presents potential coke and PCI saving with enriched oxygen in the combustion air, which corresponds to 9.01 kg coke or 9.15 kg PCI with per ton hot metal per increased 100 °C blast temperature, respectively.

3.2. COG saved with oxygen enrichment

At a fixed blast temperature, increased oxygen level in the combustion air will lead to decreased COG flow in hot stoves, while BFG flow rate has to increase to provide enough energy, as shown in Fig.2. The high caloric value COG can be saved and used for other purpose.

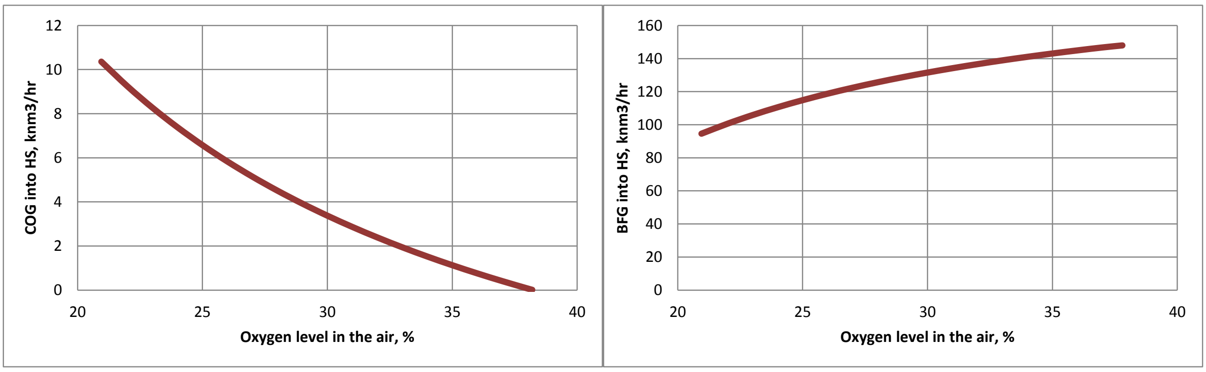

Fig.2. The correlation between oxygen level in the combustion air and COG (left) and BFG (right) flow in the hot stoves.

Previous studies showed that a lower reducant in BF could be achieved by injecting COG through tuyers [1-3]. Fig.3 shows the potential coke or PCI saving if saved COG in hot stoves instead is injected into BF via tuyers.

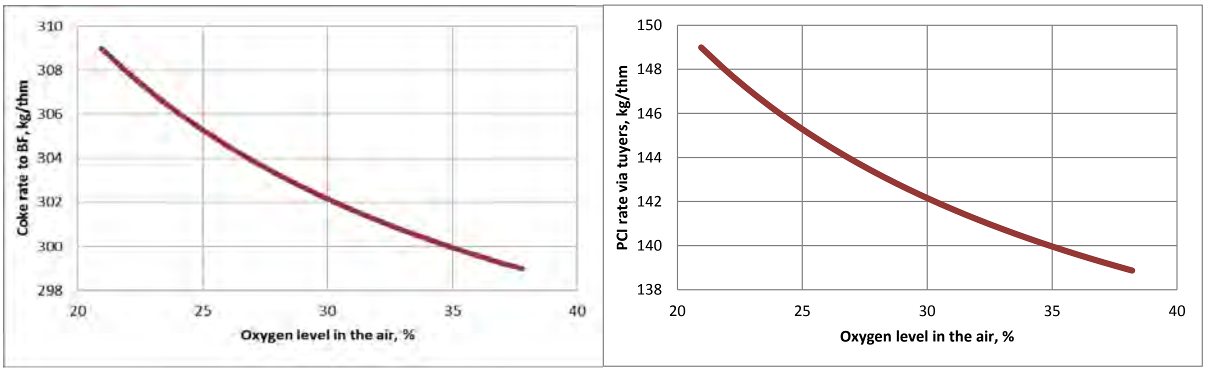

Fig.3. The correlation between oxygen level in the combustion air and coke and PCI rate in BF.

Table 1 gives a summary of key parameters for all scenarios discussed above. It's been noticed that a higher amount of BFG could be generated when COG is injected into BF via tuyers. At the same time, this will also lead to a higher heating value of BFG.

For the studied steel plant, there is another scenario to utilize the saved COG from the hot stove. That is to use it at the nearby combined heat and power (CHP) plant, which corresponds to Scenario 4 in Table 1. This will be presented in Section 4.

Table 1. Key parameters in hot stove – blast furnace system for different scenarios.

	Unit	Ref. case	Fixed COG_coke saving	Fixed COG_PCI saving	Fixed BLT_to PP	Fixed BLT_coke saving	Fixed BLT_PCI saving
	Scenarios	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Coke	kg/thm	309.0	300.4	309.0	309.0	299.0	309.0
PCI	kg/thm	149.0	149.0	140.3	149.0	149.0	138.9
COG to BF via tuyers	MJ/thm	0.0	0.0	0.0	0.0	642.6	642.6
BFG generated	knm3/thm	1.47	1.43	1.43	1.47	1.51	1.50
Heating value	MJ/Nm^3	2.97	2.97	2.96	2.97	3.08	3.07
Blast generated	Nm^3/thm	924.2	886.5	885.5	924.2	917.7	916.4
Blast temperature	°C	1104	1200	1200	1104	1104	1104
BFG consumed in HS	nm^3/thm	332.9	358.2	358.6	332.9	524.7	525.5
COG consumed in HS	MJ/thm	642.6	642.6	642.6	0	0	0
O_2 in combustion air	Nm^3/thm	0	14.8	15.0	39.0	32.8	33.1

4. System analysis of the energy system in the studied steel plant

The studied integrated steel plant consists of the following main process units: coking plant (CP) → blast furnace (BF) → basic oxygen plant (BOF) → secondary metallurgy (SM) → continuous casting (CC). The final product is slab from CC. In addition, there are also some other process units, a lime kiln for lime production, an oxygen plant and a combined heat and power plant (CHP). All these process units are connected through material flows and a process gases network. Besides COG and BFG, there is also recovered process gas from the BOF, called basic oxygen furnace gas (BOFG). Fig. 4 shows the structure of the process gas network

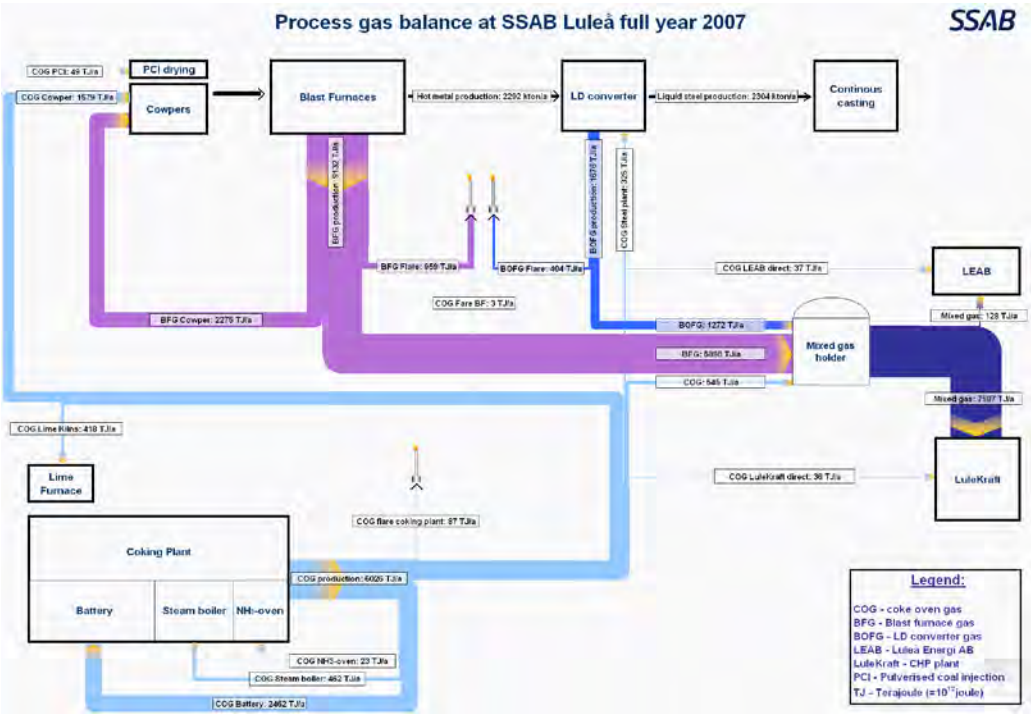

Fig. 4. The structure of process gas network at the studied plant

An optimization model has been applied to analyze the energy system in the studied steel plant. More details about the model can be read in previous publications [4-5]. The objective function set in the model is to minimize energy consumption for the total steel plant. There are two driving forces to run the model. The first is to produce the final product slabs, at 263 ton/hour as a year average. The second is to produce hot water at the CHP plant to the district heat network used by the nearby city. The CHP plant also produces electricity which is used at different process units within the plant. Therefore, it also provides electricity for oxygen production at the oxygen plant. When there is excess electricity generated from the CHP plant, the extra electricity is sold externally to the grid.

Before entering the CHP plant, the process gases of BFG, COG and BOFG are blended in the mix gas holder to get the required heating value and a stable gas flow before entering the boiler. Oil is used when heat load is higher or when there is lack of mixed gases. The electricity can be generated from the steam turbine by two different modules, a back pressure module and a condenser module, mainly depending on the heat demand from the district heat network. The alpha value of the back pressure module is 0.44 ($\alpha = P_{el}/P_{heat)}$), and the electricity efficiency of the condenser module is 0.32. The boiler efficiency, η, is 0.9. In the model, the maximum fuel limitation for the boiler is 350MW, which is set by the regulation to control emissions, e.g. NO_x, SO_x and CO_2. The other limitation set for the boiler is the maximum flow rate of process gas, 90 Nm^3/s.

Fig. 5 illustrates the heat demand curve versus the out-door temperature. As shown in the figure, the maximum heat supply from the CHP plant is 220 MW, and the minimum heat supply is 20 MW. When the out-door temperature varies in the internal of [-18;16] °C, the heat demand curve can be linearized.

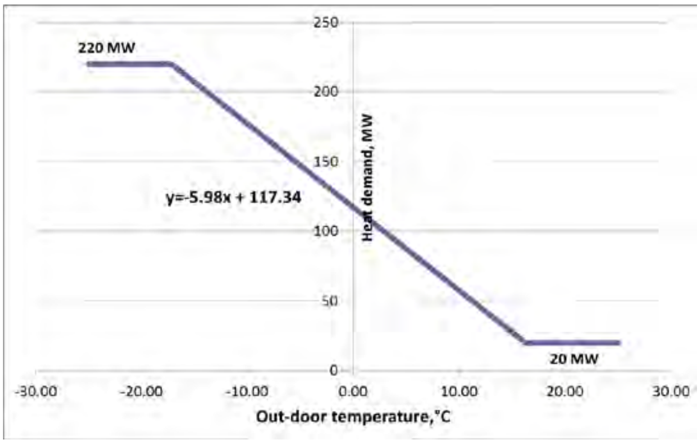

Fig.5.The correlation between out-door temperature and heat demand in the district heat network.

The optimization model is based on hourly data with a time span of one full year for the reference period. For example, the average heat demand is 85.7 MW, corresponding to an average out-door temperature of 5.3 °C. However, to illustrate how heat demand changes will have influence on the process gas network, the average value cannot be used because it varies with the seasonal out-door temperature especially in the Nordic region. Therefore, in this presented work 5 different values of heat demand are chosen: 20, 70, 120, 170 and 220MW respectively.

The model is set to run for the reference case and the optimized case to minimize the energy use for the total energy system. The energy content of the used energy carriers are presented in Table 2.

For the reference case, the model is run based on the operational data during the reference period to simulate for different heat demand levels. For the optimized case, the model will choose one scenario and combined scenarios listed in Table 1 (Scenario 1-6). Compared to the reference case, more freedoms are given in coal blending in the coke plant in the optimized case. Stable production is assumed, meaning there are no variations in each process unit, except for the CHP plant.

Table 2. Key parameters in hot stoves, GJ/ton.

Energy carrier	Value	Energy carrier	Value
TCMT petcoke coal	35.9	Bachatsky PCI coal	28.7
Peak downs coal	29.6	El Cerrejon PCI coal	27.0
Riverside coal	29.3	External coke	40.9
Massey powellton coal	30.2	PCI	28.2
Rocklick Eagle coal	30.4	Oil, GJ/MWh	3.6
Gonyella coal	29.2	Electricity, GJ/MWh	3.6
Gusare PCI coal	28.2	Flaring, GJ/unit	1.0

Fig. 6 shows the specific energy consumption (SEC) both for the reference and the optimized case. It indicates that a lower SEC will always be achieved in the optimized case. It's been found that BF behaviors in the optimized case are changing when heat demand is increasing at the CHP plant. The model prefers oxygen enrichment for COG saving to get the fixed BLT the same as the reference into BF. However, the way to use the saved COG varies between the scenarios of injecting into BF for coke saving (Scenario 5) and delivering to the CHP plant (Scenario 4) to avoid oil consumption in boiler. As indicated in Fig. 8 (right), before the heat demand is increased to 153.3 MW which corresponds to an out-door temperature of -6°C, BF will always be operated as Scenario 5. Scenario 4 starts when heat demand is greater than 153.3 MW. The percentage of Scenario 4 operation increases to 100% when the heat demand rises to 183.8 MW, meanwhile, operating of Scenario 5 decrease from 100% to 0%. The model will keep running Scenario 4 when heat demand is higher than 183.8 MW to get the minimum energy consumption.

The comparison between reference case and optimized case at a same level of heat demand may explain why minimum energy consumption could be achieved for the model. The following factors contribute for this. First in the coke plant, the coal blending is changed. In principle, the types of coal chosen are with lower volatile energy content. Lower volatile content coal will lead to a higher coke production rate, which will also lead to a lower amount of coking coal required in the coke batteries to produce the same amount of coke as the reference case. Thus, the energy consumption from the coke plant could keep as low as possible. Lower volatile type coal will generate less COG, consequently there will less COG to the CHP plant. However, this will compensate when saved COG from hot stoves instead is injected into BF to have a lower coke rate in BF. This has been proved when comparing the purchased coke amount between reference case and optimized case for example at the heat demand level of 20 MW. This solution will be kept the same until the heat demand is up to 153.3 MW at which point the model has to adopt a strategy of mixing Scenario 5 and Scenario 4 with a varying weighting ratio in order to keep the minimum energy consumption for the total energy system. At the point of 183.8 MW, the solution is completely switched to 100% of Scenario 4 because at such a high level heat demand it is more energy effective to use the saved COG in the CHP plant instead of injecting into BF and by that avoiding use of oil at the CHP plant. However, some amount of oil has to be used even in the optimized case when the heat demand is over 185.7 MW.

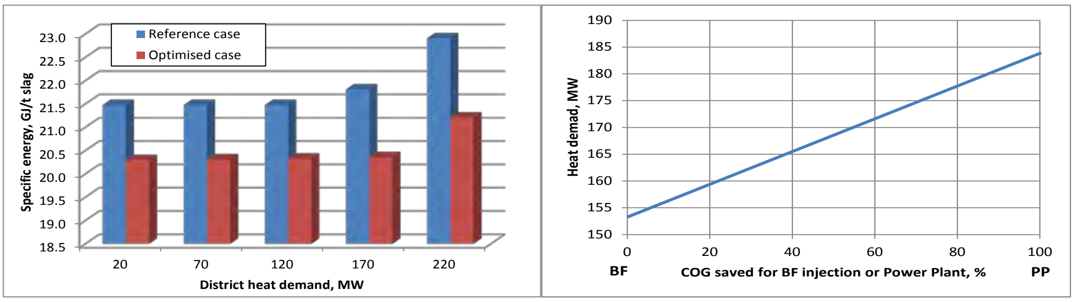

Fig.6. Left: Comparison of SEC between reference case and optimized case;
Right: BF behavior in the optimized case.

Fig. 7 illustrates the comparison of heat supply from the CHP between the reference case and the optimized case. It is found that oil will be replaced by COG in the optimized case at a high levels of heat demand. However, some amount of oil is still needed when the out-door temperature is lower than -11 °C.

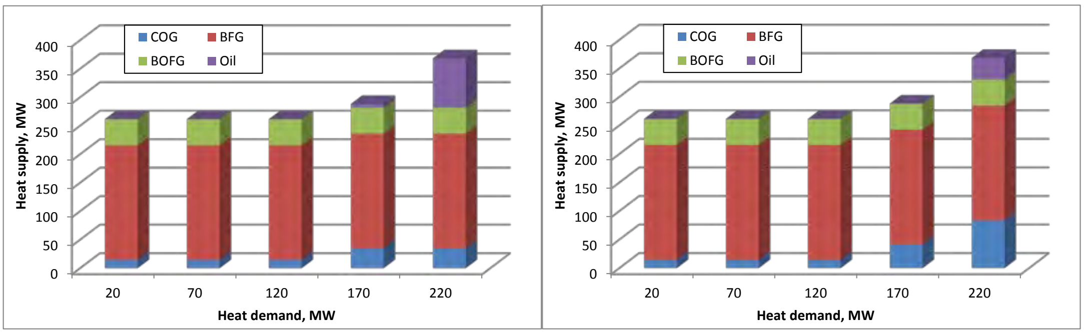

Fig.7. Left: Heat supply in the reference case; Right: Heat supply in the optimized case.

5. Concluding remarks

The presented work shows that the application of oxygen enrichment into hot stoves could lead to a lower coke or PCI rate in BF if the blast temperature is allowed to increase. High calorific value COG can also be saved by use of oxygen enrichment. Therefore, it is possible to use the saved COG in other process units. For the studied steel plant, the alternatives are, for example, inject COG into BF via tuyers or deliver it to the nearby CHP plant for district heat and electricity production. There are also other alternatives to use COG, such as at the reheating furnace in the rolling mill, or in the electric arc furnaces (EAF) to replace other fuels such as natural gas, LPG or oil. However, this depends on the site specific and is not applicable on the studied site.

An analysis of how oxygen enrichment into hot stoves will influence the total energy system has been carried out by means of an optimization model. Different strategies have been suggested from the model to achieve the minimum energy consumption for the studied steel plant and the nearby CHP plant.

The optimization made for the studied plant is to minimize the energy consumption for the total energy system. However, it does not mean that optimal solutions also are cost effective, which in fact is interesting to study.

In the current model, the availability of process gases and their flaring are set at a fixed value, based on hourly average value with a yearly time span. In addition, each process unit is assumed operating continuously and steadily. However, in reality there is normal varations.

Therefore, it might be of importance to take these factors into account for energy system optimization.

As for the CHP plant, only a few heat demand corresponding to a few out-door temperatures, are included in this optimization work. The performance of CHP plant, such as heat loads curve, is therefore limited. Solution space based optimization can provide a better resolution for the studied energy system [6].

The HS-BF system is a very important part in the optimization model, and it's also the most complicated process unit in an integrated steel plant with the BF-BOF route. The mass and energy balance for HS-BF system are first carried out in a spreadsheet, key operating parameters generated from the spreadsheet then put into the HS-BF sub-model of the optimization model. Different operating conditions generate a list of key operating parameters as input to the model. Thus, the optimal solution from this sub-model can either be one case or a mixed case. This, however, may lead to less dynamic. For instance, the model only shows the oxygen amount into hot stoves at which COG will be fully substituted by BFG. What happen in between oxygen enrichment starting and maximum level cannot be predicted in model. Therefore, it could not show the results if the optimum level of oxygen enrichment is in between when modeling the total energy system although it may not be the case. Further model improvement in HS-BF system is needed towards a dynamic response.

Acknowledgements

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Economical analysis of a chemical heat pump system for waste heat recovery

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Abstract: Industrial chemical heat pumps (ICHPs) provide an ability to capture low - grade heat rejected from industrial sources and to reuse the heat increased temperature in industrial processes. Also it can be used for residential heating, cooling, water heating and energy storage. Several temperature boost levels can be obtained according to chemical reaction couple chosen. It can be either single source system or dual source system connected with available reject heat source. Dual source system is more effective than single source system and higher output temperature levels can be obtained. Reject heat source temperature and desired temperature boost are important in chemical reaction couple selection. Chemical reaction couple must be chosen carefully to provide the highest efficiency in all candidate systems. Economical feasibility of industrial chemical heat pump can be determined after calculations according to heat pump capacity. In this study, economical analysis of an industrial chemical heat pump system was accomplished compared with a steam boiler. Economical calculations was carried out and curves that show the relations between investment cost and capacity of chemical heat pump, investment cost and capacity of steam boiler, reject heat capacity and net savings were obtained for waste heat capacities below 2000 kW. It is determined that the chemical system is feasible if the waste heat capacity is higher than a certain value according to economical parameters and lifetime. Also, net gain increases almost linearly with increasing waste heat capacity.

Keywords: *Chemical heat pump, Economical analysis, Waste heat*

1. Introduction

Industrial chemical heat pumps can utilize waste heat at lower temperatures and use it at increased temperatures for industrial processes. An extensive literature study was performed by Wongsuwan et. al. [1]. Industrial chemical heat pumps requires up to one-fifteenth of electrical power input when compared to conventional vapor compression cycle heat pumps [2]. Chemical heat pumps consist of two different reactions which run at two different temperature levels [3]. For this aim, dehydrogenation of alcohols and hydrogenation of acetone can be used in chemical heat pumps [4]. The feasibility of the isopropanol/acetone/hydrogen chemical heat pump system was investigated theoretically by Gastauer and Kameyama [5]. Reverse reaction for isopropanol/acetone/hydrogen chemical heat pump system is

$$CH_3\text{-}CHOH\text{-}CH_3 \leftrightarrow CH_3\text{-}CO\text{-}CH_3 + H_2 \qquad (1)$$

Dehydrogenation of isopropanol is endothermic reaction which occurs at 55-85 ^oC in liquid phase and hydrogenation is exothermic reaction and occurs at maximum 202 ^oC in gas phase. A typical isopropanol/acetone/hydrogen heat pump is given in Figure 1. In this study a comparative economical analysis was performed. Maximum $COP_t=Q_{out}/Q_{in}$ of the isopropanol/acetone/hydrogen heat pump is 18.2% depending on isopropanol concentration [6].

In this study, an economical analysis was conducted as a function of waste heat flux. Total costs including investment and operational and maintenance costs of the chemical heat pump system and the steam boiler is obtained. Net gain is defined as the difference between the total costs of the chemical heat pump system and the steam boiler.

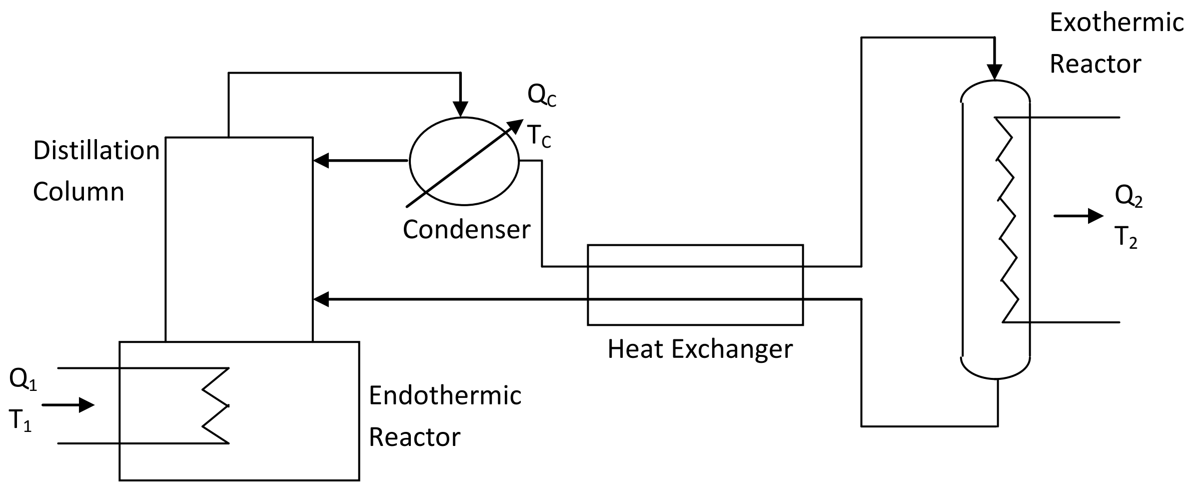

Figure 1 Isopropanol/acetone/hydrogen chemical heat pump flow diagram [5]

2. Economical Analysis of Chemical Heat Pump System

2.1. Investment Cost

Figure 2 derived from [7] can be used for determination of the investment cost of the chemical heat pump system.

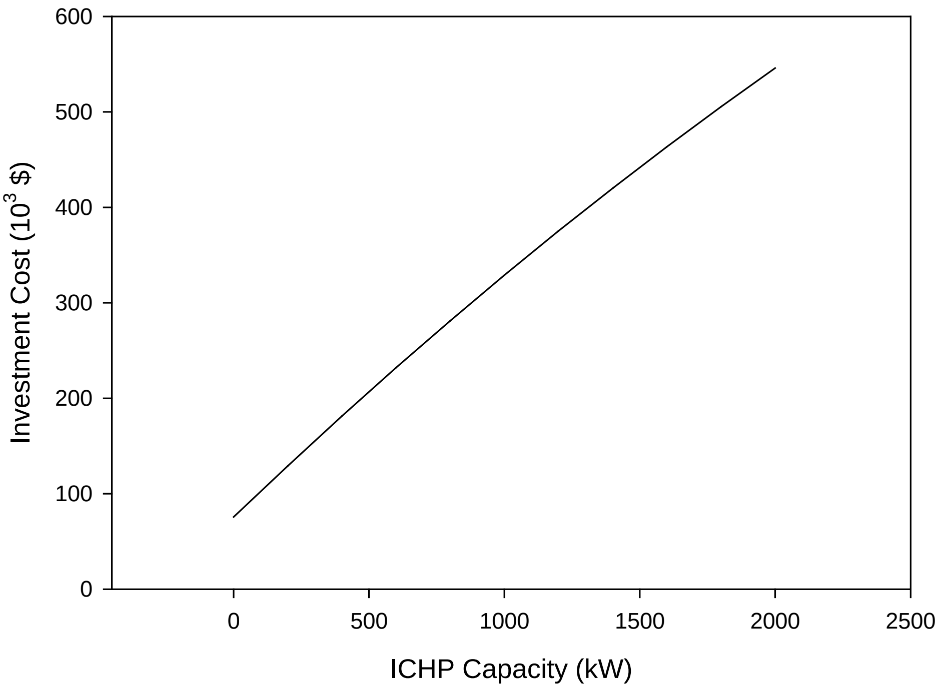

Figure 2 Relationship between industrial chemical heat pump capacity and investment cost

The equation that gives the function in Figure 2 is of the form

$$I_{CO} = -0.01832Q^2 + 271.77Q + 75567.3 \qquad (2)$$

where ICO is the investment cost ($) and Q is the capacity (kW).

Figure 2 was obtained using economical values for 1988. In order to use it for the present calculations, it is required to make some modifications. For this aim a correction factor was defined as below:

$$f = (1 + i_1)(1 + i_2)(1 + i_3) \ldots\ldots (1 + i_n) \tag{3}$$

where i represents the inflation rate in corresponding year after 1988.
If the inflation rate is constant for all years from 1988 to the present, in that case;

$$f = (1 + i)^n \tag{4}$$

n is the number of the years from 1988 to present. Then, the investment cost of the chemical heat pump system in the present year, I_C (\$), is calculated from

$$I_C = f.I_{CO} \tag{5}$$

2.2. Equivalent Annual Cost

Equivalent annual cost is obtained as a function of interest rate, i and lifetime of investment, n (year) from

$$EAC = I_C \frac{i(1+i)^n}{(1+i)^n - 1} \tag{6}$$

2.3. Operating and Maintenance Cost

Operating and maintenance cost of the chemical heat pump is calculated from [7]

$$OM = \frac{ES.CE.OT}{16} + 0.05 I_C \tag{7}$$

Here, ES, CE and OT are equipment size (kW), cost of electricity (\$/kWh) and operating time (h) respectively. The number 16 is used for industrial chemical heat pump which uses a fan to operate a cooling tower. If groundwater is used for cooling then a value of 20 should be used [7]. Maintenance cost is assumed 5% of investment cost.

2.4. Total Cost

Total cost is the sum of the equivalent annual cost and operating and maintenance cost.

$$TC = EAC + OM \tag{8}$$

3. Economical Analysis of Boiler

3.1. Investment Cost

Investment cost is the price of a boiler which has the same thermal capacity as the chemical heat pump system. The investment cost of boiler was derived from present steam boiler prices available in the market. The variation of the boiler price (\$) with thermal capacity (kW) is given in Figure 3 and can be calculated from the Eq. 9 as a function of boiler capacity Q (kW) for the capacities up to 2000 kW.

$$I_C = -0.00453216 Q^2 + 21.9991 Q + 3367.2 \tag{9}$$

3.2. Equivalent Annual Cost

Equivalent annual cost is obtained as a function of interest rate, i and lifetime of investment, n (year) from

$$EAC = I_C \frac{i(1+i)^n}{(1+i)^n - 1} \quad (10)$$

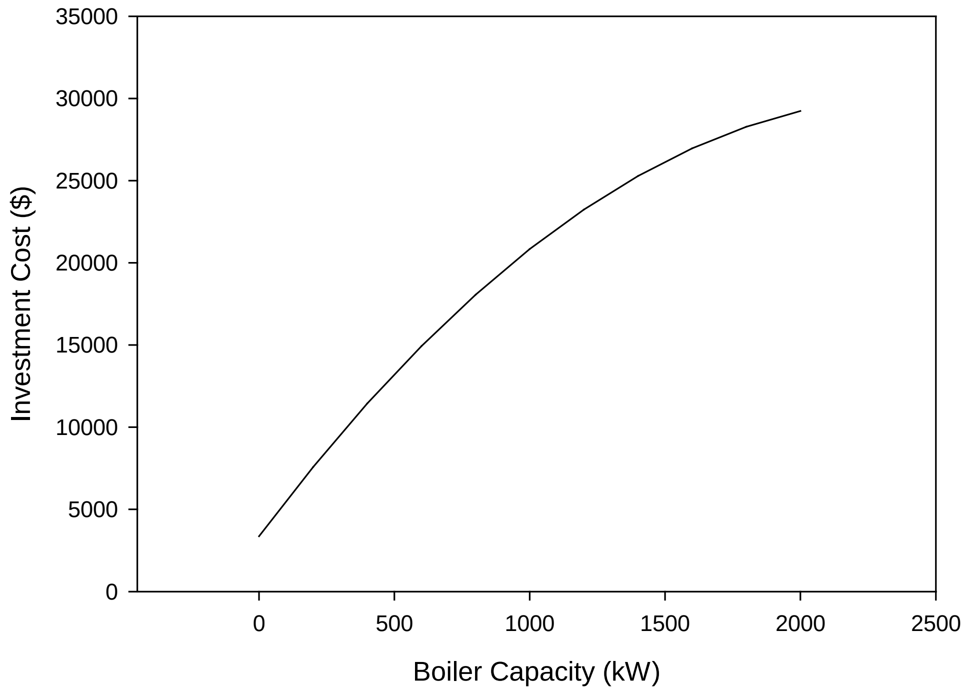

Figure 3 Relationship between boiler capacity and investment cost

3.3. Annual Energy Consumption

Annual energy consumption is the amount of fuel which is consumed during the operation of boiler and can be calculated from

$$AEC = \frac{Q.OT}{\eta_B.LHV} \quad (11)$$

where η_B is the boiler efficiency and LHV is the lower heating value of fuel (kJ/kg). The cost of the annual energy consumption is

$$AC = AEC.CF \quad (12)$$

and CF is the cost of the fuel ($/kg).

3.4. Operating and Maintenance Cost

Operating and maintenance cost of the boiler is calculated from

$$OM = AC + 0.05 I_C \quad (13)$$

Maintenance cost is assumed 5% of investment cost.

3.5. Total Cost

Total cost is the sum of the equivalent annual cost and operating and maintenance cost.

$$TC = EAC + OM \quad (14)$$

4. Results

Net gain is calculated from the difference between total costs of the chemical heat pump system and the boiler.

$$NG = TC_{CHP} - TC_B \tag{15}$$

where TC_{CHP} and TC_B are total annual costs of chemical heat pump and boiler respectively. The parameters used in the analysis are as below:

Waste heat flux, 550 – 11200 kW
Effectiveness of chemical heat pump, 18% [6]
ICHP capacity, 100 – 2000 kW
Boiler efficiency, 90%
Fuel, Fuel-Oil
Lower heating value of fuel, 39774.6 kJ/kg
Fuel price, 0.87 $/kg
Electricity price, 0.125 $/kWh
Inflation rate, 8%
Operating time, 5475 h/year
Lifetime, 6 – 15 years

Figure 4 represents the relation between ICHP capacity and net gain. It is seen that net gain increase almost linearly with increasing ICHP capacity.

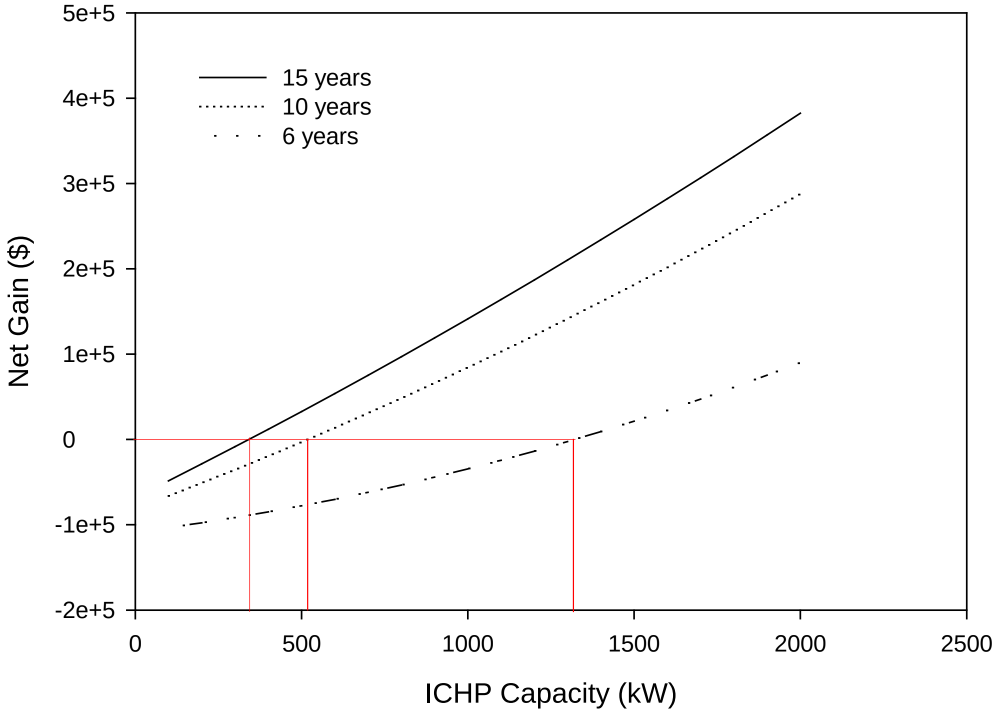

Figure 4 Relationship between ICHP capacity and net gain for lifetime 6, 10 and 15 years

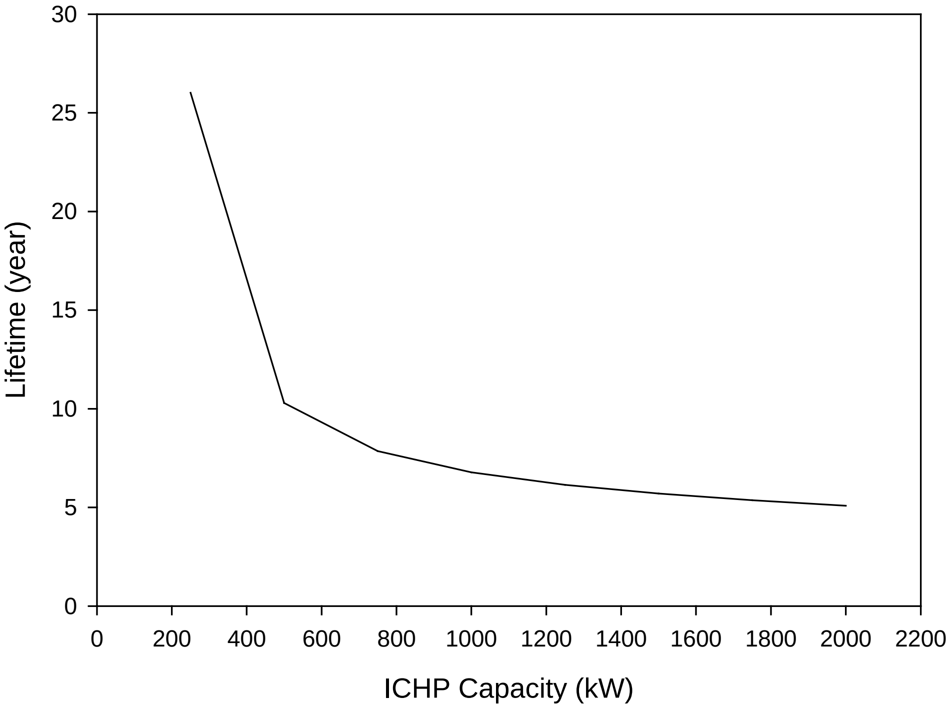

Figure 5 Relationship between ICHP capacity and lifetime where the net gain is zero

Figure 5 shows the relation between ICHP capacity and lifetime for zero net gain. It is seen that if the ICHP capacity is higher than 1000 kW, lifetime is asymptotically approaches 5 years.

5. Conclusion

Economical feasibility of industrial chemical heat pumps can be determined after calculations according to heat pump capacity. Economical calculations were carried out and curves show the relations between investment cost and capacity of chemical heat pump, capital cost and capacity of steam boiler, ICHP capacity and net savings were obtained. It is determined that the chemical system is feasible if the waste heat capacity is higher than a certain value according to lifetime of investment. Also, net gain increases linearly with increasing waste heat capacity. In Figure 5, the upper region of the net gain zero curve shows the feasible zone and it is seen that the payback period is almost constant for the capacities higher than 1000 kW.

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Avoiding loss of energy in a petrochemical industry, operation and design

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Abstract: The challenge of economic and environmental sustainability demands a better way to manage production in the industry when treating energy consumption and emission of greenhouse gases. The reduction of greenhouse gases promoters are using: renewable energy matrix that can capture the CO_2, renewable energy resources and, production activities with better efficiency in thermal systems. The industry segment contributes over 33% for CO_2 emissions and it can be reduced through: energy integration in designs, intensifying the process and, better efficiency of utilities in the routine. The objective is demonstrates that, if global industry reduce at least 25% of thermal energy losses, 20% of losses of steam, and if change combustible oil to renewable in 33,8% proportion, the greenhouse effect reduce in 33%. The methodology to achieve reduction of CO_2 emission includes: Preliminary assessment, Strategies, Specific Programs, Restrictions analyzes and measurement of results. Between strategies are actions on operation, design and business chain. Between programs there are: evaluations about utility control and management; biomass economic chain viability; and, actions to recover steam losses on design. The restrictions are to implement politic programs in society and industry segment to change patterns becoming possible thermal energy reduction and renewable combustible substitution. The projected results on reduction of CO_2 in industry emissions are summed and almost overcome target of 21,6 (20,4) GTY. The segments of society can prepare similar programs and transform exercise in practice giving better quality of life for earth population.

Keywords: Energy efficiency, Utility management, Industry Sustainability

Nomenclature

GTY Giga ton per year
IEA International Energy Agency
BRIC Brazil, Russia, India and China
MMI Man Machine Interface
CW Cooling Water
Biom Biomass

1. Introduction

This paper aims to demonstrate that, integrated actions of industries can achieve the target reduction in CO_2 generation by greater energy efficiency in unit operations and by replacing the oil and gas fuels by biomass. After discussion about the industrial segment impact causing the greenhouse effect, topics of thermal efficiency and renewable energy resources are discussed. Then some activities and calculation methods are suggested for achieving the goals of reducing the generation of CO_2.

According to Johan Rockstrom and others [1] [2] the challenges to sustaining life on planet earth (sustainable) depend on the care of large environmental requirements. These requirements are conditions for the stabilization of the atmosphere and return to equilibrium between the species and nature as they did before the uncontrolled growth of world economy. Climate change is one of the uncontrolled factors indicating the need for urgent action to reduce emissions of CO_2, the main reason. Several programs and initiatives such as the gradual change of the current oil energy by renewable resources should be performed to prevent the growth and maintenance of the economy causing uncontrolled situations in nature and in particular in global climate.

To avoid the impact of gases contributing to air pollution, scientists seek to reduce its generation at source and reduce its inventory too. So they propose a series of actions resulting from studies that treat about the possible sources of energy and energy transformations, from

2010 to 2050, by IEA - International Energy Agency [3]. According to the IEA study, in 2005 CO_2 emissions to the atmosphere were the order of 28 GTY (Giga Ton per year), and imagining that, with the growth of global economies and emerging countries especially BRIC, the issue will be 62 GTY CO_2. With the work proposed here and in several initiatives by the conscious world, we intend to achieve by 2050 a situation of greater sustainability by reducing CO_2 emissions to around 14 GTY, or, half emission of 2005. Humanity needs to cut emissions from 2010 to 2050 on 48 GTY of CO_2 (considering that very little was achieved from 2005 to 2010). Scientists from IEA [3] estimated options about contribution of human activities to emission reduction. From this study, the opportunities to reduce inventory of CO_2 on atmosphere are located in different sectors of the economy. Energy sector has more potential for reduction with 20 GTY of CO_2, industrial sector with half the quota, 10 GTY of CO_2, transportation sector with 13 GTY, and urban areas with 15 GTY of CO_2.

Within the industrial sector, the opportunities to reduce CO_2 generation are: end-use efficiency of fuel utilization and use of new renewable energy resources, using as knowledge base some researches and services in petrochemical, refine and metallurgical industries in Brazil at TECLIM, clean technology research group inside UFBA, Engineering School. These issues are very important to the industry and can be classified as strategic to their survival. The best efficiency in the end-use of fuel is due reductions achieved from thermal energy consumption in furnaces and boilers allowed by new criteria to control these operations proposed to petrochemical industry. New scenery of combustible changing is constructed with substitution of oil by regional biomass in petrochemical industry (thermal-power facility).

2. Methodology

The Methodology to achieve the reduction of this green house gas presented in Figure 1, is divided in: definition of target (total quantity of emission that will be reduced), preliminary assessment, principal strategies, for each strategy definition of a program to be implemented at industrial segment, restrictions analyzes, and, expected results and respective measurement tools. This paper develops programs that treat these strategies: (1) reduction of thermal energy consumption and (2) use of biomass to decrease emissions of CO_2.

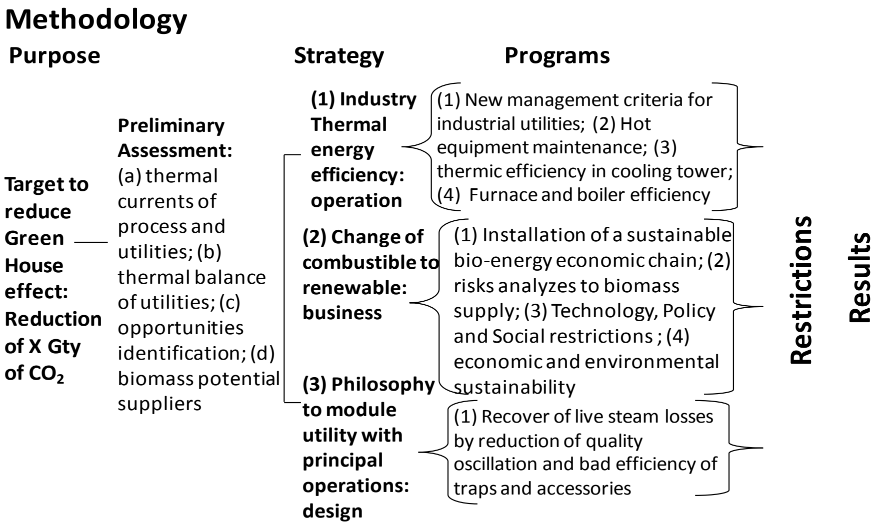

Figure 1. Methodology to investigate about reduction of CO_2 emission by energy control

In these exercises the responsibility to exchange energy type and reduction of thermal energy loss causing reduction in fuel use are of industry. These exercises can point the way for new business with respect to energy consumption and reduction in CO_2 generation. It means that industry intends to achieve a reduction of 12 GTY of CO_2 from burning fuel and 8.4 GTY of free captured CO_2 by photosynthesis after CO_2 balancing with burning biomass.

2.1. Strategy 1: Thermal Energy Efficiency at Industry, a research case

The methods to increase energy efficiency depend on knowledge about energy balance and tasks related to control of thermal energy, cooling and heating systems at industry. Apart from knowledge availability and tasks well-planned, it is important reviewing conduct of the technical groups about management of utilities in the industry. A research about energy control was performed in a local Petrochemical Company [8] and proposes activities: (1) Planning and programming of Production allowing best decision-making in production scheduling (distribution of energy to activity); (2) Greater efficiency in cooling towers and systems allowing reduction of volatile products and hot energy consumption (temperature profile of separation columns); and (3) Efficiency of heat transfer in hot systems (boilers, furnaces, steam distribution, traps, condensate, and turbines) due to criteria of: projects, assemblies, operation, and thermal charge not compatible with the scale causing heat stress.

Although some of these issues involve the operation and maintenance of plants, the criteria of new projects must be adjusted using above standards, leading to a lower investment, to achieve the goal of greater efficiency in the use of fuel at industry and services. The article by Richard Doornbosch [3] present that the part concerning the reduction of fuel consumption is 12 GTY of CO_2, reference number for the industrial sector. The purpose is to work in a more efficient use of cold and hot energy to reduce consumption combustible thus generating smaller quantity of CO_2 into the atmosphere.

To achieve better thermal performance in cooling and heating systems, heat balances were made in research cases at petrochemical [8], oil and metallurgical industry, where: (A) in the balance of the cooling towers are pointed out possibility of recovery losses, improving the thermal performance; (B) in the balance of boilers was identified recovery energy due to: incomplete burning, and failure on steam generation (bad operational procedures ➔ low availability); (C) in the balance of furnace, the heat is too large by radiation, and the use of thermal energy to heat the reaction depends on: configuration of the tubes, complete burning of the furnace, and good insulation to prevent passage of heat through the equipment walls. Figure 2 descript part of topologies to study thermal performance.

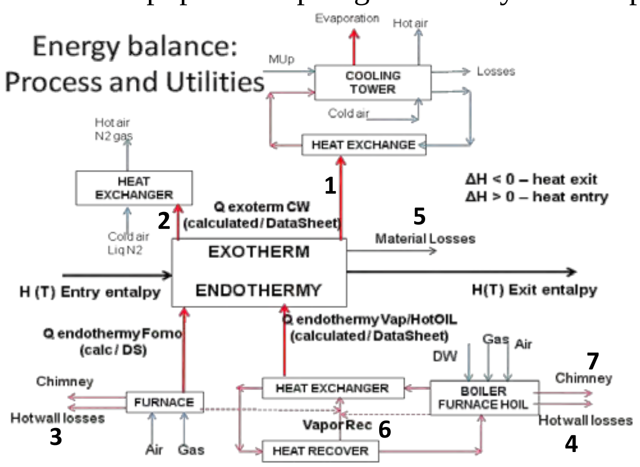

Figure 2. Topology of direct and indirect heat transfer [9]

1 - Quality of CW and reflux; 2 - Removal of excess heat - thermal inadequate planning; **3 - Losses at wall furnace** due to ingress of cold process fluid; **4 - Losses at wall boiler** and operational inefficiency in purges; **5 - Losses due flare materials** by higher volatile content at the top of separation equipment; **6** - Traps, separators, process control, incorrect scale of equipments causing **loss of alive steam**; **7 - Losses in chimneys** by not recover of residual heat.

2.2. Strategy 2: Energy substitution, combustible mineral oils by biomass, a case

With the forecast that world oil reserves are exhausted in about 100 years, there will be, in the medium and long term, environmental and economic viability to greater utilization of available biomass energy and currently is found in nature generating methane, most striking than carbon dioxide to the greenhouse effect. The total use of biomass as fuel for industry depends on some difficult to be worked as: complicated logistics, model of business, and need to increase the efficiency of combustion in furnaces and boilers. Biomass has the advantage of being a natural process that performs photosynthesis where the removal of CO_2 occurs from the atmosphere, thus promoting favorable carbon balance. Assuming that each kilogram of CO_2 generated from burning of biomass has direct equivalence for each kilogram of CO_2 captured from atmosphere, we try to relate in Table 1, different types of Brazilian biomass.

Table 1- Comparison between different biomass and diesel

Biomass	gCO_2/kg Biom	MJ/kg Biom	Quantity Biom GTY	*CO_2 GTY
Sugar can bagass	0,075	15,49	200 E-3	0,08
Black liquor	998,79	13,40	2 E-3	0,002
Coconut fiber	1310,87	17,59	0,42 E-3 (peel, fiber)	0,0002
Cake/ Glycerin	1885,77	25,30	2,2 E-3 (5% biofuel)	0,0023
Total			204,62 E-3 = 0,2 GTY	0,0845

The biomasses chosen are present in abundance in Brazil, due to the large production of sugar cane industry, producing about 200 million tons of bagasse, the pulp industry producing about 9 million tons of black liquor, and the incipient biodiesel industry that generates about 2 million tons per year of glycerin and cake. The marketing of coconuts is quite common in Brazil and the waste generated, coconut peel and fiber, are good source of biomass.

2.3. Proposed activities to be performed

The Programs to increase Energy Efficiency and Mineral Combustible Replacement in the Industrial Segment are presented in table 2 and 3 to discussions.

Table 2 – Energy Efficiency Program

- ✓ Energy balance for process integration and definition of production scheduling;
- ✓ Thermal performance in cooling systems and towers to reduce the temperature of water;
- ✓ Thermal performance in heating systems, boilers, furnaces, steam / condensate and oil, in an attempt to reduce wall losses, loss of live steam, the reuse of energy, equipment reliability through proper drainage, and additional measures;
- ✓ Review the criteria for equipment design in operation by reducing the size of the plants and allowing to work with adjusted modules and not unequal growth of utilities;
- ✓ Review the criteria for management of maintenance and operation (tasks with more human reliability) in industrial plants intending to increase the operational availability of systems for cooling and heating.

Table 3 – Renewable biomass replacement program

✓ Mapping the biomass availability;	✓ Installation of local clusters by biomass type;
✓ Installation of processing plants to adequacy the biomass;	✓ Define national and global economic architecture for using biomass;
✓ Prepare managers in biomass area;	✓ Promote the establishment of cooperatives;
✓ Construct logistics scheme;	✓ Training the cooperative managers.

3. Program of activities to increase thermal energy efficiency, Strategy 1, research case

Assuming that the petrochemical plants and industry in general are in high charge/load, under thermal stress, the plants need to install additional equipment, or practicing high reflux flow in the distillation unit operations or similar. After performance tests conducted in the thermal cooling systems, some recommendations about proper operation can reduce by 15% or more, the temperature of cold water. Thus, fitting temperatures at the top of the decanter vessels, it reduces the reflux without losing the quality of final products, in bottom and top of equipments. If the premise that the proportion of decreasing the need for reflux ratio is equivalent to decreasing for hot utility at the bottom of the equipment, means that the reduction of steam consumption achieve the same, 15% (%RTEP1).

Some investigations are performed to reduce top temperature as result of cooling system (based on research case [9] and services): audit programs, calculations, process and operation investigations, and thermal performance tests discussed in Figure 3. The probably activities suggested are: change distribution of top cold pool, maintenance of top valves, vibration analyzes of fans, installation of side filters, temperature control measure with minimum of one decimal, calculation of concentration cycle based on good precision parameters, check of humidity of atmosphere and others. Other possibilities to reduction of losses are due to recovering of energy from: better insulation of hot equipment wall, increase of continuity in furnaces and boilers caused by increasing of human and operational reliability, diminish of mass losses to flare with cold temperature at column top, diminish of loss on energy recovery systems (condensate) by better control of steam quality. All these possibilities can increase the yield from 88% to 93%, saving 10% of fuel consumption to generate steam and fuel consumption in furnaces (%RTEP2). Summing possibilities of energy economy from cooling tower (15%) with better operation and design of hot systems (10%), we can achieve 25% of decreasing of combustible consumption (%RTEP=%RTEP1+%RTEP2).

The hot utility project (steam and condensate) have flexibility to increase 15% when compared with the design capacity, different from the case of large equipment (cooling towers, reactors, separators, heat exchangers and others) with the possibility to lift charges between 50 to 80% more than project charge. Thus, in debottlenecking design, the review of projects is poorly made for utilities generating non conformities with loss of live steam above 25% (%RSE). We consider, in the calculations, the possibility of recovery at least of 25% of live steam lost to the atmosphere.

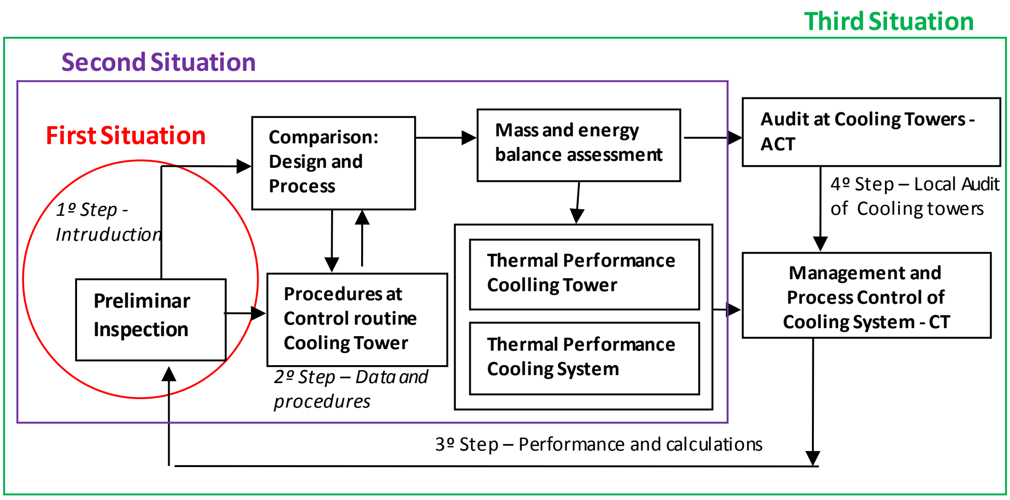

Figure 3. Energy management and audit of cooling system, based on research cases/services

Join knowledge from operation of equipments with technology, including knowledge about human factors in MMI of equipments and including process intensification concerns, is possible to change the design criteria for equipment and processes increasing certainty and decreasing rate of the flexibility of capacity (reducing the engineering coefficients of ignorance in design). So with project of smaller equipments in conjunction with the project of appropriate utility systems increase the load of plant in industrial modules instead of debottlenecking, reducing than, the losses of live steam and reducing factory investment.

Estimation based on Petrochemical Industry X in Brazil and Global Ones (Table 4). Based on data from large petrochemical X in Brazil, the annual production of ethylene is around 142,000 tons per year, and global ethylene production in 2010 was 142 million ton per year [4]. Thus, the calculation of fuel oil consumption and CO_2 generation for petrochemical industries can be multiplied, for exploratory calculations, by 1000 (thousand) that represents all the petrochemical companies worldwide. Thus, for the production of plant X of 260 thousand tons/year and consumption index 16.5 GJ / ton, this means all the energy consumption of around 4.3 million GJ/year. Whereas the average fuel PCI is (43000 KJ/Kg) 43 GJ per ton of fuel for the plant X. Annual consumption of fuels is 100 thousand tons of fuel per year for one plant in place X (*0,0001 Gton/Y)*. For calculation to all petrochemicals, in exploratory way, it is considered *0,1 GTY* of fuel.

Table 4 – Data an formula for calculation Petrochemical Industry (Local X and Global)

Pet EGP (Ethylene Global production) = 142.000.000 ton per year
Pet EXP (Ethylene Local production X) = 142.000 ton per year
RelG/X (Relation Global/Local) = PetEGP/PetEXP=1000 petrochemical estimated world
PPetX (Production of Petrochemicals at X) = 260.000 Ton/Y
CIPetX (Consumption Energy/Mass Index, Petrochemical X) = 16,5 GJ/Ton
*CcombX (Consumption of combustible per year at X) = PPetX * CIPetX= 4.300.000 GJ/Y*
COPCI (Combustible Oil - PCI) = 43 GJ/Ton of oil
FCPetX (Consumption of fuel to Petrochemical X) = CcombX/COPCI= 100.000 Ton of oil/Y
FCPetX = 0,0001 Gton/Y =1E-4 Gton/Y
FCPetGlobal(Global Consumption fuel to 1000 Petrochemical)=100.000.000 Ton/Y=0,1GTY

$$RelG/X = PetEGP/PetEXP \quad (1)$$
$$CcombX = PPetX*CIPetX \quad (2)$$
$$FCPetX = CcombX/COPCI \quad (3)$$
$$FCPetGlobal = FCPetX * RelG/X \quad (4)$$

General Equation to consumption fuel at Global Petrochemicals indystries

$$FCPetGlobal = ((PPetX * CIPetX) / COPCI))* (PetEGP / PetEXP) \quad (5)$$

Estimation based on Global Industry (Table 5). Considering that 1 kg of Carbon (C) generates 3 kg of CO_2, giving approximately 2.5 kg of CO_2 per kg of fuel. Thus 0,1 GTY of fuel generates 0,25 GTY of CO_2. If we consider that 1% of industry is of petrochemical type [8] then total industry generates 25 GTY of CO_2. If recovery of 25% of CO_2 by thermal efficiency and recovered is equivalent to 6.25 GTY, fulfilling the quota of efficiency in fuel consumption (12 GTY) for 1000 of petrochemicals X. This recovery is possible with better thermal performance of the separators from better operation of cooling systems and reduction of heat stress. If you consider the projected area, where you can recover 50% of live steam lost in the area, is reduced 25% of total CO_2, since no generation of 12.5 GTY which is higher than the target of 25% from 25 GTY of CO_2, or 6.25 GTY.

Table 5 – Data an formula for calculation Global Industry and decrease of CO_2

GICCO2 (Generation Index CCO2) = 3 kg CO_2/ 1 kg of Carbon
GICO2Fuel (Generation Index CO2Fuel) = 2,5 kg CO_2/1 kg fuel= 2,5 ton CO_2/ ton fuel
*PCO2PetX (Production of CO2 at X) = GICCO2Fuel * FCPetX = 2,5 E-4 Gton CO_2/Y*
PCO2GTotalIndX (Total Ind Production of CO_2 at X) = 2,6 E-2 Gton CO_2/Y [1][8]
Relation (Pet/Total Ind X)= (PCO2PetX/ PCO2GTotalIndX) = 1%
*PCO2PetG (Production of CO_2) = FCPetGlobal * GICO2Fuel= 0,25 Gton/Y of CO_2*
PCO2IndG (Prod of CO_2) = PCO2PetG/ Relation = 25 GTY
%RTEP = %RSE = 25% (recovered steam by thermal programs – operation and design)
*RTEP, Recovered by Thermal Energy Production= (%RTEP*PCO2IndG) = (25% * 25 GTY) = 6,25 GTY of CO_2; RSE (Recovered by Steam economy) = production and design = (%RSE*PCO2IndG) = (25%*25 GTY)=6,25 GTY of CO_2; Total Recovered (TR)=12,5 GTY*

TR ={*(%RTEP+%RSE)*[(FCPetGlobal*GICO2Fuel)/(PCO2PetX/PCO2GTotalIndX)] }(6)*

4. Program of Activities to combustible substitution: biomass related to strategy 2

Brazil [5] [6] [7] is an agricultural country and has large area of land available for food crops, has ample opportunity to use the biomass generated as a natural substitute of petroleum. Because of this trend, in very near future, there is a need for the government to invest in productive arrangements to provide this biomass for energy and industrial segment. For this change in the energy supply chain, it is required to mapping sources of biomass, defining the inventory economically feasible to tie their strategies, including political, technical, economic, environmental, ethical and seasonal risks. This Petrochemical Industry in study intends to meet the environmental paradigms to reduce greenhouse gases (carbon balance favorable due to increased carbon sequestration), and meet global energy demand.

There are some steps that the government, together with the industries and society in general must accomplish: • Develop network of institutions and companies with roles to enable installation of a sustainable bio-energy economic chain; • Analyze risks to regular supply of biomass; • Identify restrictions in: Technology, Policy and Social aspects; • Ensure the economic and environmental sustainability. Between policy challenges, there are: prepare economic local clusters, check on the participation of society (cooperatives in logistics and sorting) in this new economic activity, and development of technology to Bio-energy.

5. Discussion of results

In the global, if it is possible to reduce 25% of fuel consumption resulting from energy efficiency program and reduces 20% absolute of live stream to atmosphere is sufficient to meet the challenge posed by the IEA, a reduction of 12 GTY. In the biomass, considering the estimated of last four cases (sugar can bagass, coconut, cake/glycerin from biodiesel, and black liquor), achieves a 0.0845 GTY of CO_2, needing a biomass matrix at least 100 times bigger, including other biomass and other countries like China and India in trying to reduce carbon emissions into the atmosphere. If you reach this goal, with 8.45 GTY versus 9.6 GTY CO_2, quota demanded to be reduced. As mentioned before, the industry emits 25 GTY of CO_2 from fuel combustion, is intended to reduce 8.45 equivalent to 33.8% of the diesel currently used, when you know that above the goal number of 10 %, a third part of necessity, demanding strong economic and political organization and efforts around the biomass.

[1] * General Relation Industry/Petrochemical in Bahia/BR, place X, [8]

6. Conclusion and Restrictions

Work with energy efficiency is simple when Industry management gives importance to utilities as: steam (generated by water and heat from combustible), direct heat to furnace (generated by heat from combustible burning), and cooling water (that depends of cooling tower work). The difficulties are to change managers' decision model that analyze short term problems and does not work to increase human and operational reliability. One other concern is about the necessity to change design criteria preparing factories in smaller size.

Despite the great potential of Brazil to the wide use of biomass, it is not still efficient to process and distribute products in biomass segment; it depends of governments' infrastructure in logistics area. Although there are many searches for new technologies in which the fuel is biomass, it does have large-scale policies or actions that make the distribution of this form of biomass for industry, already ready for use. Therefore, it is necessary to analyze the economics chain in the vertical form, including all activities in the life cycle of different biomasses. For the energetic matrix change to renewable one, some multi-attributes assessment (environment, economic, ethical, policy, social) to choice biomass must be done. The criteria for choice of matrix must be analyzed in biomass to prevent, for lack of planning, the projects unviable after long-term, development policy for biomass, availability of materials, supply guarantees, social and environmental benefits.

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Integration of biogas plants in the building materials industry

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Abstract: The paper quantifies the synergy-effects of an areal combination of biogas-plants with plants of the building materials industry (e.g. cement plants) from the energetic and economical point of view. Therefore a model biogas and cement plant are defined and the effects of a combination of both plants in terms of energetic efficiency, investment and operating costs, greenhouse gas emission reduction and overall energy production costs are quantified. The main benefits of this combination are the utilisation of low temperature excess heat sources from the cement plant for fermenter heating and the direct thermal utilisation of unprocessed biogas as a valuable, CO_2-neutral fuel for combustion processes for instance clinker burning. Due to the combination, the energetic efficiency of the biogas plant, defined as utilisable energy output in relation to the energy content of the produced biogas, significantly increases from 63.0% to 83.8%. Concurrently the energy production costs are reduced, turning biogas into a competitive source of energy without the need for federal sponsorship. Calculations show, that from a plant size of around 90 m^3_{STP}/h biogas production costs in combined plants are even lower than the actual market prize of natural gas.

Keywords: *biogas, cement plant, thermal utilisation, excess heat recovery*

Nomenclature

volumetric flow rate (standard temperature and pressure) .... m^3_{STP}/h
energy (general) .... *kWh*
electrical energy .... kWh_{el}
thermal energy .... kWh_{th}
European currency .... *€, ct*

1. Introduction

The anaerobic fermentation of biogenic material presents a well known technology in waste treatment and agriculture. Furthermore the specific production of biogas out of renewable resources provides an opportunity to integrate CO_2-neutral energy sources in the power supply chain. Nevertheless state of the art concepts of biogas utilisation like electricity generation in combined heat and power plants (CHPs) or processing of the raw biogas to inject it in existing gas supply systems are still in need of improvement. Energy losses due to processing and compression steps or the production of a significant amount of excess heat reduce the percentage of useable energy from the raw biogas.

In view of this problem, an alternative way of gas utilisation would be desirable. The combination of biogas plants with plants of the building materials industry especially cement plants, presents a unique opportunity to meet these demands [1]. The main benefits are:

- utilisation of excess heat from the cement plant for fermenter heating
- raw biogas as CO_2-neutral fuel without the need of processing
- ammonia recovery from the digestate and use as reducing agent in DeNOx-processes

High temperature processes in the cement, lime and magnesia industry are a source of waste heat at various temperature levels. The use of this energy for heating a mesophillic biogas fermenter (~35°C) allows the utilisation of excess heat at temperature levels beyond 100°C, which presents a problem for other state-of-the-art solutions.

The average calorific value of biogas with 21 MJ/m³ (60% methane, [2]) is sufficient for a direct use as fuel in cement and clinker burning. Primary fuel combustion in the rotary kiln and secondary combustion in the precalciner can be adjusted to work with natural gas as well as biogas [3]. The demands in terms of gas composition for direct burning are not that strict as for CHP plants or injection in natural gas supply systems. Compression of the gas to the pipeline pressure (30 to 80 bar) is not necessary. Hence, raw biogas can be used directly for burning without processing steps like desulphurisation and NH_3-removal. H_2S in the biogas is oxidised to SO_2 during combustion, which reacts to alkalisulphates with the clinker in the preheating and calcining system [4]. The fate of NH_3 has to be investigated.

The application of biogas reduces the greenhouse-gas emissions of the cement plant due to the substitution of fossil fuels. On the other hand the combination offers the possibility to improve the partially negative ecobalance of some biogas production ways [5].

The third benefit is the potential recovery of ammonia from the digestate. The output of digestate as a fertiliser for agricultural areas is limited to certain times of the year due to ammonia emissions. Processing of digestate and ammonia recovery can solve the problem of temporal dependency with the concurrent benefit of producing a NO_x-reducing agent for cement plants. By decreasing the ammonium concentration in the effluent for example by steam-stripping, the recycling of the liquid phase into the fermenter might be possible.

2. Methodology

To quantify the synergy effects of the areal combination of biogas and cement plants, an Excel-model was developed, in which conventional biogas plants with CHP are compared to the corresponding combined plant in regard to energetic efficiency, CO_2-savings, energy production costs and plant feasibility. The biogas plant scale can be adjusted by varying the amount of substrates. For the actual calculations a substrate mix with 90% manure and 10% co-substrates (4% food leftovers, 3% glycerine and 3% flotate sludge) was chosen.

The energy balances and costs of combining a conventional biogas plant with a production of 250 m^3_{STP}/h respectively 550 kW_{el} installed electrical power with a cement plant with a production capacity of 440 000 $t_{clinker}$/a are presented in detail. Both plants represent a mean plant size in Austria derived from overall production data divided by the number of plants [6, 7]. In biogas production the trend goes to larger plant sizes, wherefore the mean biogas plant size derived from literature data (270 kW_{el}/plant) was doubled. Based on averaged data of numerous existing biogas-plants [8, 9] in combination with data from CHP evaluations [10] a basic energy balance for a model biogas-plant was determined. To quantify the main excess heat sources of a model cement plant, the mean thermal energy balance was calculated from averaged literature data for Austrian cement plants [11].

Investment and operating costs of the conventional plant were calculated with four different literature models [2, 9, 12, 13] to prove consistency. The estimations were converted to actual costs on the basis of 2009 by correction with the harmonised index of consumer prices in Austria. The most suited model due to its modular configuration (FNR, 2008) was chosen for the economical comparison of conventional and combined plants. Based on the published FNR-data, compensating curves for specific investment and operating costs were implemented to calculate the scale dependent energy production costs. Investment and operating costs of the combined plant do not comprise expenses for CHP and desulphurisation units but an additional cost factor for the combination (burner, gas pipeline, excess heat utilisation). This factor is made up of fixed costs and scale dependent additional costs (investment costs combination in € = 30000 + (actual plant size [m^3_{STP}/h] / 500) * 100000). It is assumed that substrate and digestate processing costs are the same for both plants, wherefore these expenses remain unaccounted for.

The determined operating costs together with the depreciation charges result in mean energy production costs in ct/kWh, when divided by the useable energy output. Depreciation charges were calculated on the basis of an annuity factor for 16 years deprication period and an imputed interest rate of 6%. The income of the conventional biogas plant comprises the sale of electricity and thermal energy according to the renewable energy feed-in tariff of the ÖSVO 2010 [14]. In case of the combined plants, the income is considered to result from cost savings for fossil fuels (natural gas and fuel oil) [15] and CO_2-savings valuated with an actual emission certificate price of 15 €/t CO_2. Electrical energy to cover the internal demand of the combined plant has to be bought on the market [16]. Based on these data the ROI and payback-period for the conventional and combined plant can be calculated.

The determination of the CO_2-savings is based on a representative mixture of cement plant fuels from literature [6]. It is assumed, that first natural gas and then fuel oil are replaced by biogas, as far as the produced amount of biogas can cover the demands of these fuels. Mean CO_2-savings were calculated from literature data for CO_2-emission rates of fossil fuels [17]. The electrical energy demand of the combined plant is covered by electricity from national power networks, which decreases the CO_2-savings due to emission of greenhouse gases during the production of conventional electrical energy [18].

3. Results

The basic energy balance of a 250 m^3_{STP}/h model biogas plant is visualised in figure 1.

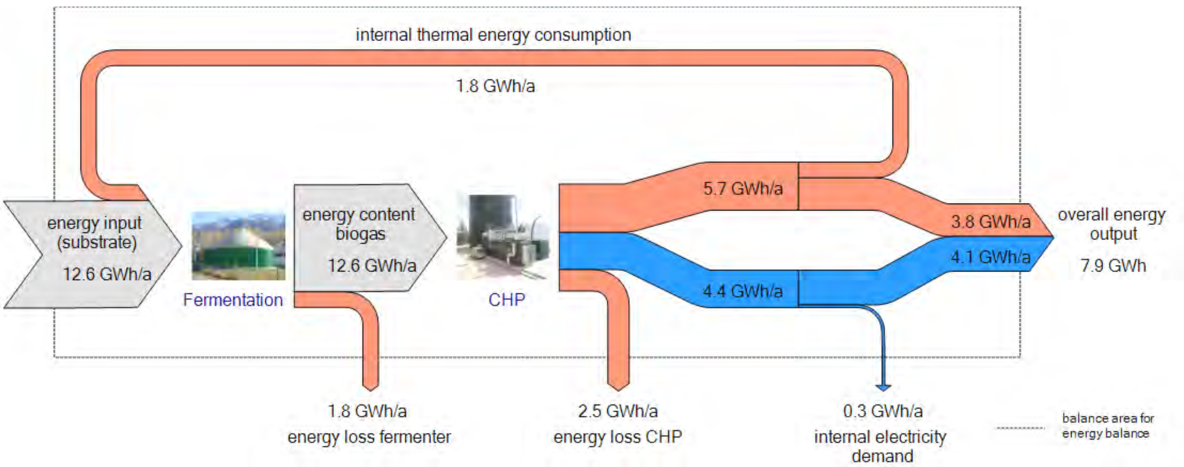

Fig. 1. Energy balance of a conventional biogas plant (250 m^3_{STP}/h) with combined heat and power unit (CHP, 550 kWh_{el} installed electrical power); for detailed data see table 2.

Figure 1 shows that only 35% of the input energy of 12.6 GWh/a can be converted to electrical energy with 45% low temperature excess heat from the CHP. After deduction of the internal electrical and thermal energy demand, 30.5% thermal energy and 32.5% electrical energy remain, giving an overall energetic plant efficiency of 63%. The high amounts of energy needed for fermenter heating and a CHP efficiency of 80% significantly decrease the overall plant efficiency. Moreover, this calculation represents the ideal case, where 100% of the available thermal energy is utilised for example for drying processes or district heating.

The thermal energy balance of the model cement plant (440 000 $t_{clinker}$/a) is visualised in figure 2.

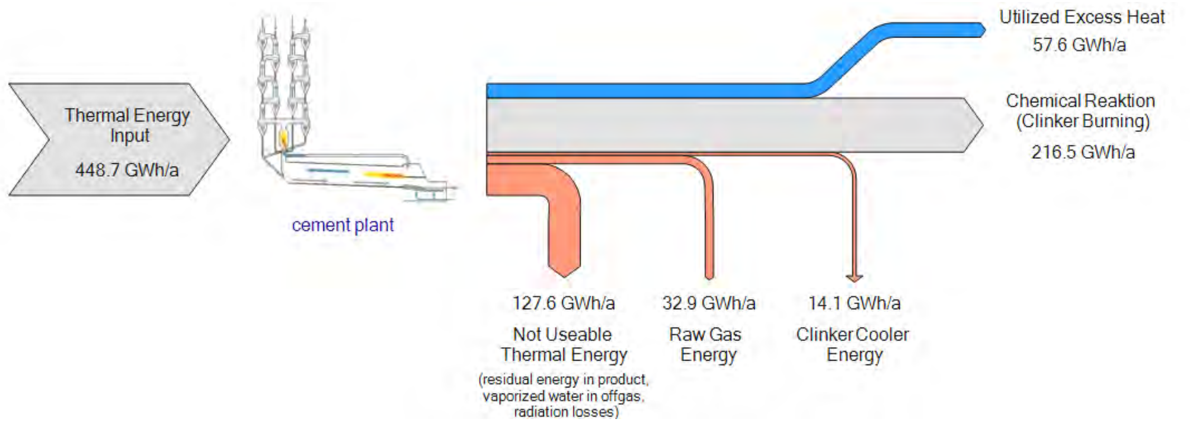

Fig. 2. Thermal energy balance of a conventional cement plant (440 000 $t_{clinker}$ /a)

Not useable thermal energy like the remaining energy content in the product, vaporised water in the offgas and thermal radiation turn out to be the main excess heat sources. The residual energy in the cooling air after the clinker cooler and the energy in the raw gas after the raw mill can easily be utilised for fermenter heating by adequate heat recovery concepts, for example the installation of gas/fluid heat exchangers as shown in figure 3.

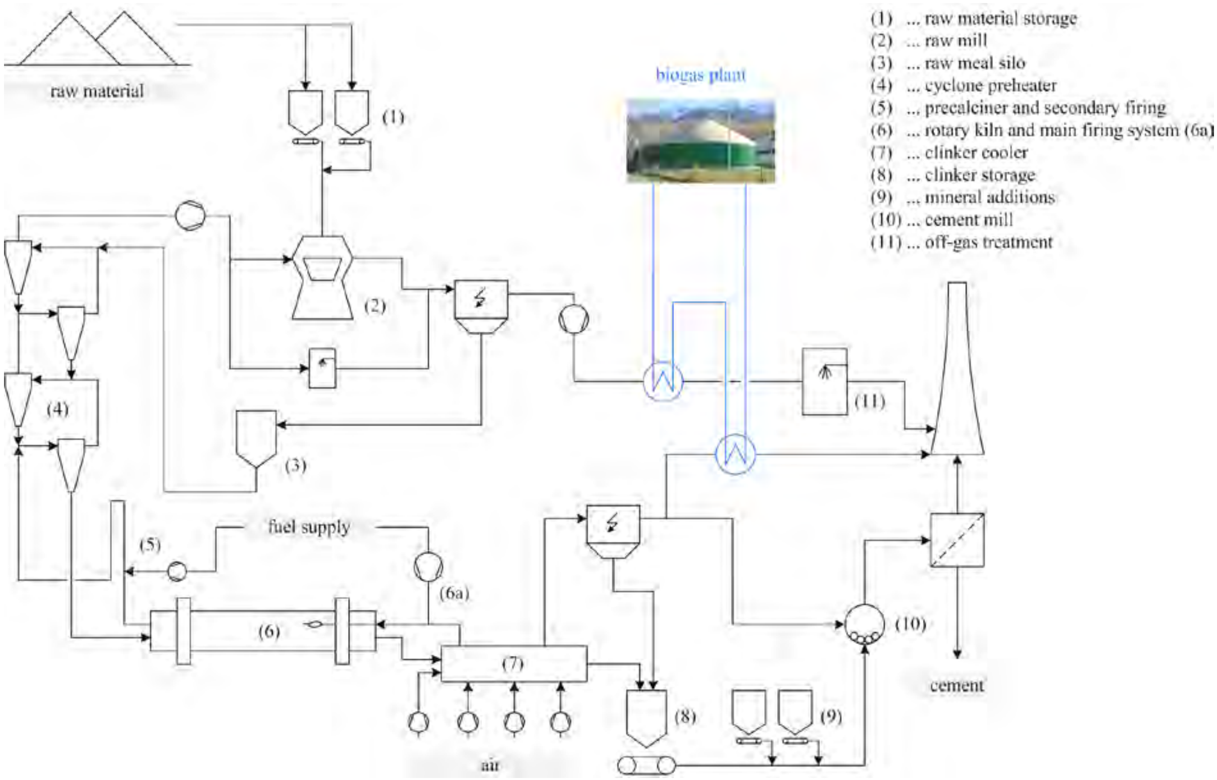

Fig. 3. Process flowchart of a combined biogas and cement plant.

Figure 4 illustrates the effects of this combination on the energy balance of a 250 m^3_{STP}/h biogas plant. Clinker cooler and raw gas excess energy together offer nearly the 27-fold amount of energy needed for fermenter heating. Electrical energy has to be bought in addition. The direct use of raw biogas enhances the utilisable energy of the biogas plant, leading to a major increase from 63.0 to 83.8% in the overall plant efficiency (cf. table 2). The thermal efficiency of the cement plant only slightly increases from 61.3 to 61.5% due to its large excess heat production compared to the energy demand of the biogas plant. On the basis of the above defined plants scales, 2.7% of the thermal energy consumption of the cement plant can be replaced by raw biogas, resulting in a decrease in greenhouse gas emissions of around 2860 t CO_2/a or 0.8% of the annual CO_2-emissions of the cement plant.

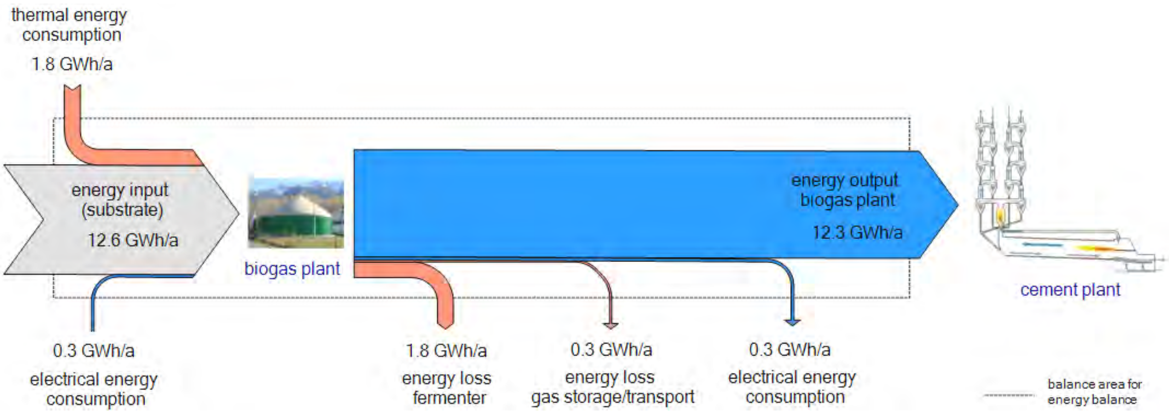

Fig. 4. Energy balance of a combined plant; biogas plant (250 m^3_{STP}/h) coupled with a cement plant (440 000 $t_{clinker}$/a)

Table 1 comprises the estimated investment costs for a conventional biogas plant (250 m^3_{STP}/h) with biogas utilisation via a CHP. The results of the models generally fit together, with the FNR model being the closest to the mean investment costs of 1,750,819€ derived from all models.

Table 1. Investment costs for a conventional biogas plant (250 m^3_{STP}/h) based on different models

		FNR [12]	KTBL [9]	LfU Bayern [2]	Hornbacher* [13]
plant investment costs	[€]	1,172,538	943,757	-	1,578,733
CHP investment costs	[€]	493,729	626,819	-	336,284
total investment costs	**[€]**	**1,666,267**	**1,570,577**	**1,851,414**	**1,915,017**

* estimation excl. CHP, CHP costs estimated with different model (ASUE [10])

Table 2 shows the results of the energy balance as well as the energy production costs and plant feasibility calculations of a conventional plant compared with the combined alternative.

Investment and operating costs of the combined plant are considerably lower because of the missing CHP plant. Together with the higher amount of energy output in terms of fuel, the production costs of energy in a combined plant are around 3.2 ct/kWh compared to 7.0 ct/kWh for a conventional plant, in which 100% of the thermal energy output of the CHP are utilised. Electricity production costs without thermal energy utilisation are 13.5 ct/kWh_{el}. The ROI of the combined plant is somewhat higher and the payback period shorter because of the lower investment and operating costs compared to the conventional plant.

Table 2. Base data of a conventional biogas plant compared with an equally scaled combined plant

		FNR conventional plant	FNR combined plants
biogas production	[m^3_{STP}/h]	250	250
plant energy input	[kWh/a]	12,580,295	14,718,946
electrical energy output	[kWh_{el}/a]	4,088,596	0
thermal energy output	[kWh_{th}/a]	3,836,990	0
utilisable energy output	[kWh/a]	7,925,586	12,328,,689
overall plant efficiency	**[%]**	**63.0**	**83.8**
total investment costs	[€]	1,666,267	1,175,732
operating costs	[€/a]	387,181	281,055
annual depreciation	[€/a]	164,881	116,341
total variable costs	[€/a]	552,062	397,396
energy production costs*	**[ct/kWh]**	**7.0**	**3.2**
electrical energy costs	[ct/kWh_{el}]	13.5	-
cost savings fossil fuels	[€/a]	0	471,895
cost savings CO_2-emissions	[€/a]	0	45,598
electrical energy income	[€/a]	506,986	0
thermal energy income	[€/a]	92,088	0
total income	[€/a]	599,074	517,494
total profit	[€/a]	47,012	120,098
ROI (profit/investment)	[%]	2.8	10.2
payback period (debt-repayment method)	[a]	11.0	6.1

* 100% utilisation of thermal energy

The depiction of the energy production costs of the conventional and combined plant over the plant scale shows the typical decrease in production costs with increasing plant size (figure 5).

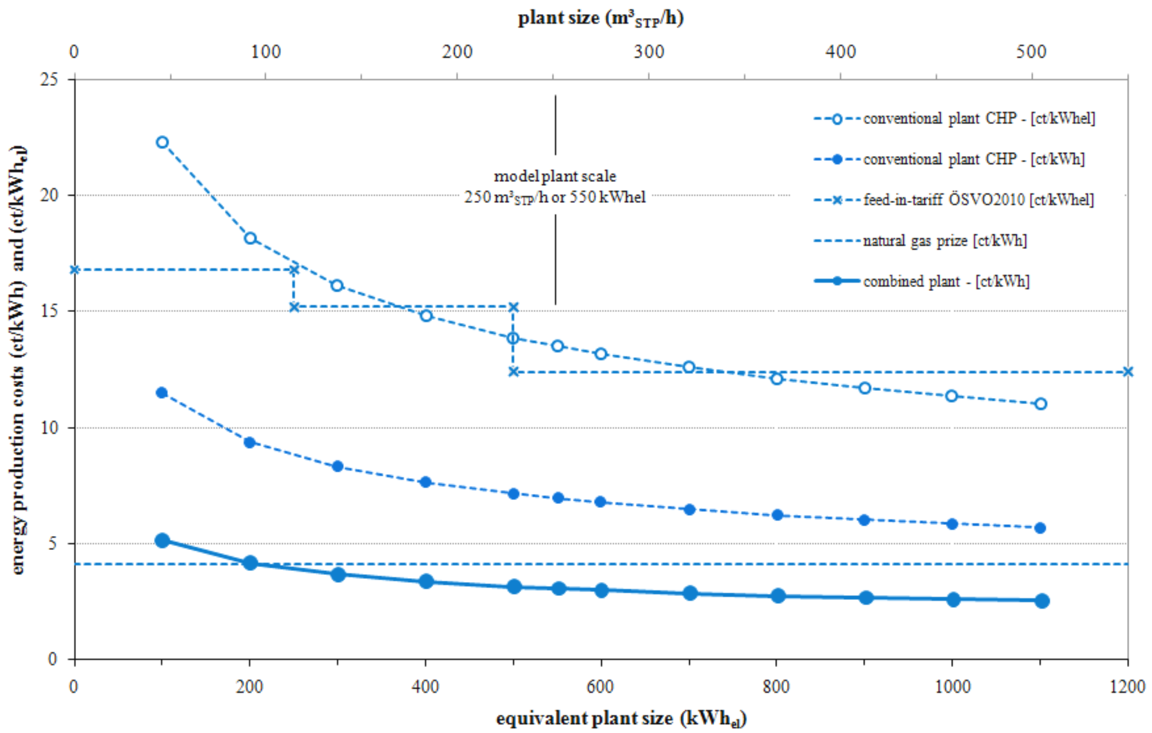

Fig. 5. Energy production costs (electrical and thermal energy) for various plant sizes.

Conventional biogas plants without thermal energy utilisation have electrical energy production costs from 20 to 12 ct/kWh$_{el}$. The simultaneous use of 100% of the CHPs thermal energy output can decrease the energy production costs to values between 11 and 6 ct/kWh but is difficult to implement. Compared to the feed-in-tariff in accordance with the ÖSVO 2010 [14] one can see, that the combined use of thermal energy is essential for the feasibility of a conventional biogas plant. The energy production costs of combined plants (~ 5 and 2.5 ct/kWh) are well below conventional plants due to the higher amount of energy utilised as fuel for clinker burning. From a plant size of 200 kWh$_{el}$ (~ 90 m^3_{STP}/h) the production costs of biogas in combined plants actually fall below the costs for natural gas [20].

4. Conclusions

The combination of a biogas plant with a cement plant is a possibility to significantly increase the overall efficiency of a biogas plant. The use of unprocessed biogas as a fuel for clinker burning and the utilisation of excess heat from the cement plant enables biogas costs to be competitive to natural gas costs even without federal sponsorship.

Nevertheless, there are still points that have to be investigated, first and foremost the fate of H_2S and NH_3 in the clinker burning process and their contribution to NOx and SO_2 emissions of the cement plant. Moreover, solutions for the gas utilisation during maintenance periods of the cement plant have to be found. Whereas these periods might also be used for servicing the biogas plant, concepts must be developed for a controlled diminishing of the biogas production rate by reducing or altering the substrate feed and concurrent burning of biogas. Thereby, the internal thermal energy demand of the biogas plant can be covered temporarily.

The recovery of ammonia from the digestate for DeNOx-processes would be a major benefit for the cement plant. Potential technical solutions like steam-stripping of liquid digestate have to be investigated. Especially substrates with the potential to cause ammonia inhibition of the fermentation process might be processed in combined plants, if ammonia recovery is feasible. The practicability also strongly depends on the type of substrates, which have to be suited for fermentation but not for direct burning. Important parameters for waste fuels in cement plants are calorific value along with the content of water, ash, sulphur, chlorine and heavy metals as well as the suitability for the burners [3]. Examples for substrates with limited applicability are liquid manure and brewery and agricultural residues due to the high water content. The inhomogeneity of food residues as well as slaughterhouse waste and similar materials impede direct burning, but otherwise present wastes high in biogas production.

Due to sufficiently available waste heat energy and the huge fuel consumption of cement plants, the share of fuel provided by biogas can be increased almost arbitrarily, resulting in cheaper biogas production costs and significant CO_2-savings. One 2 MW biogas plant can substitute over 10% of the energy consumption of a 440 000 $t_{clinker}$/a cement plant and save around 13 000 t CO_2/a. The substitution is only limited by the available amount of substrates for the biogas plant. Nevertheless, also small scale options are possible, because any industrial plant with high temperature processes and utilisable excess heat, high fossil fuel consumption and the need of a denitrification system is a potential site where biogas plants can be installed. In many cases this combination would be the better alternative compared to biogas plants in the open countryside. With the developed model, site specific questions like maximum substrate and transport costs for economical plant operation can be estimated. Thereby, the number of potential biogas plant sites increases and the role of biogas as CO_2-neutral fuel in power supply can be strenghtened due to the installation of sustainable energy systems.

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Improvement of energy utilization in natural gas liquid plant through using self-refrigeration system

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Abstract: In recent years, there has been great incentive to improve the energy utilization with which the existing capital in offshore and onshore surface facilities is utilized. One of the most energy intensive processes in oil upstream industry is natural gas liquid or NGL recovery plant. The main gorge of energy consumption in conventional NGL plants is propane refrigeration. Hence, more attention should be focused on the effective utilization of propane chillers in a NGL plant. In this study, a novel process configuration for recovery of natural gas liquids in NGL plant is purposed. The required refrigeration in this configuration is obtained by a self-refrigeration system. In summary, the novel scheme generates refrigeration internally, decreasing cooling load of propane chiller and providing additional refrigeration for inlet gas cooling due to plant capacity increase. Besides, the recycled stripping gas also eliminates the need for external reboiler heat. The warmer the stripping gas, the less demand is placed upon the bottom reboiler, thereby saving fuel and energy cost. In this investigation, a simulation model has been developed on the basis of using novel configuration in Gachsaran NGL1200 in south of Iran. The model has been applied for evaluating of energy utilization in this plant. Results of the model show decreasing in total electricity demand of the plant from 268 kWh/t_{NGL} to 175 kWh/t_{NGL} by decreasing cooling load and electricity consumption in propane chiller. Also, the need for reboiler heat is satisfied and efficacy of demethanizer column is improved from 72% to 84% by more NGL recovery. Finally, economical analysis of the new retrofit has been studied.

Keywords: *NGL plant, self-refrigeration, SGR, energy utilization*

1. Introduction

Natural Liquid gas factories which produce NGL are one of the important and energy intensive units of offshore industries. In these units, natural gas liquids are separated from the sweet gas which has been sweetened in gas sweetening units before. Recovery of natural gas liquids (NGL) components in gas not only may be required for hydrocarbon dew point control in a natural gas stream, but also yields a source of revenue, e.g., natural gas may include up to about fifty percent by volume of heavier hydrocarbons recovered as NGL [1].

Most of the NGL plants in operation today use conventional single-stage turbo expander technology for moderately high ethane recovery. Based on this technology, after the inlet gas is treated to remove water and other contaminants, it’s cooled by cold residue gas in gas/gas exchangers. Propane refrigeration is often required to help in condensing the heavy components for a rich gas. Then, liquid condensed from the inlet gas is separated and fed to the tower for further fractionation after being flashed to the tower pressure. The remaining non-condensed vapor portion is subject to turbo-expansion to the top section of the demethanizer column, with the cold liquids acting as the top reflux to enhance recovery of heavier hydrocarbon components.

The growing economic opportunities offered by the markets associated with natural gas liquids determined the development of using different technologies in NGL recovery units. The difference between the various technologies lays in the energy recovery strategies that each of them utilizes [2].

One of the most attractive technologies for reducing energy intensity in NGL recovery unit is Stripping Gas Refrigeration (SGR) method. SGR is a self-refrigeration system is widely applicable not only for new, grass-root plants but for revamping old, existing plants. This technology utilizes a slipstream from the demethanizer bottom. This stream is totally or partially vaporized, providing additional refrigeration for inlet gas cooling. The flashed vapor generated from the self-refrigeration cycle is recycled back to the column, where it serves as stripping gas. Stripping gas increases the critical pressure thus enhancing the relative volatility.

This paper focuses on revamping existing plants using the stripping gas refrigeration scheme. To this aim, factory of NGL 1200 in south of Iran is selected as case study. The results show the economic return on retrofit investment is much more attractive and also, there are opportunities for upgrading the performance of the plant, e.g., plant capacity increases and energy intensity decreases over the time [3].

2. NGL recovery process

The process flow diagram of a NGL plant based on the simulation of NGL1200 by HYSYS software is depicted in figure (1). According to this figure, inlet sweet gas flows into the two stages of gas to gas heat exchanging process (E_1 and E_3) and exchanges its heat with separated gas stream form the three phases separator (E_6) and therefore, its temperature is decreased from 65^{0C} to 25^{0C}. Then, outflow stream from second heat exchanger enters into two stages of propane chilling system (E_4 and E_5) and it is cooled to temperature lower than -29 centigrade degrees to condense out the liquids. At the exit point of chilling system, gas has two phases condition and therefore liquid and vapor phases should be separated by separator (E_6). The vapor phase returns to the heat exchanger (E_3) and the liquid phase is then fed into the demethanizer column which has 9 trays to stabilize gas liquids and separate light compounds. Demethanizer column also has a kettle reboiler for providing required heat in the bottom section of the column for vaporizing heavy product and recycling it to the column. Overhead flow of column which has more methane and ethane will be recompressed by compressor (E_{11}) and will be returned to the gas injection unit; propane, butane and condensates are separated as bottom product and sent to the pressurized refrigerated storage vessels to await transportation to market [4].

Table (1) represents physical properties of streams which have been approximated by the Peng-Robinson equation of state formula through developing simulation model by HYSYS software. The aforementioned simulation model has been applied for analysis of performance of the factory of NGL1200 and estimation total energy intensity and efficiency of this plant [5].

According to results of simulation, total performance and energy intensity of NGL1200 are represented in table (2). Also, major energy intensive equipments of NGL1200 are reported in table (3).

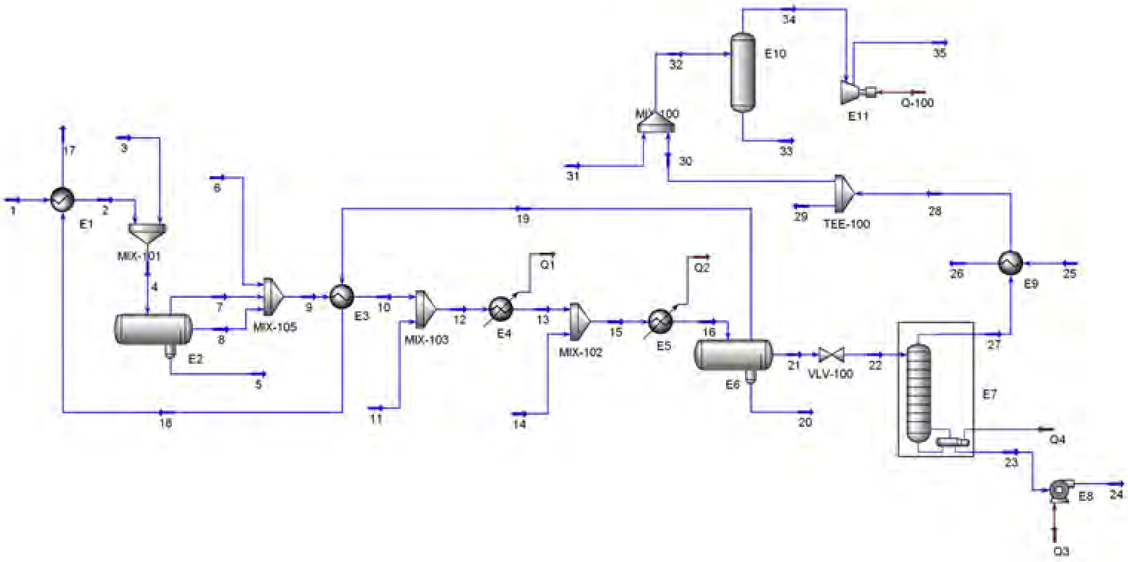

Fig. 1 Process flow diagram of NGL1200

3. Self-refrigeration method

Self- refrigeration method is a modern method to increase NGL plant capacity, to decrease plant electricity consumption and to eliminate the need for external reboiler load. Also, application of this method increases critical pressure and volatility of demethanizer column and therefore, efficacy of column will be improved. This method is known as Stripping Gas Refrigeration (SGR) method [6].

SGR method generates internal refrigeration by expanding a liquid stream from the bottom of the demethanizer column. Simulated process of SGR method and its application in NGL1200 is represented in figure (2)**.** According to this figure, liquid stream from the bottom of the column (stream 39) is then heated by indirect heat exchange with inlet sweet gas to generate a two-phase stream. The two-phase stream (stream 42) is flashed in a separator. The flashed vapor (stream 44) is compressed and recycled to the demethanizer as a stripping gas, which increases the ethane and propane concentration in the column. The flashed liquid stream (stream 43) is pumped and mixed with other NGL product streams.

Three major advantages of using SGR method in a NGL plant may be concluded by following items [7]:

1) Increasing production level up to 20%.
2) Increasing recovery of ethane. Concentration of ethane and propane will be increased in the column and heat profile on the trays will be decreased significantly.
3) Increasing operational pressure of the column is one of the other advantages of this method which increases volatility of propane and ethane and then separation efficacy of column will be increased.

Modification of physical properties of streams after using SGR method in NGL1300 is represented in table (4) [8].

Table1. Physical properties and flow rate of streams

Stream line	1	2	3	4	5	6	7
Temperature (C)	60.5	37	62.1	38.3	38.3	25	38.3
Pressure (kPa)	3690	3680	3770	3680	3680	4300	3680
Mass flow (t/h)	200.6	200.6	12.8	213.4	0.47	2.3	211.5
Stream line	8	9	10	11	12	13	14
Temperature (C)	38.3	38.3	24	25	24	-5	25
Pressure (kPa)	3680	3680	3670	4300	4300	3655	4300
Mass flow (t/h)	1.4	215.2	215.2	2.2	217.4	217.4	2.2
Stream line	15	16	17	18	19	20	21
Temperature (C)	-5	-29	47	-10	-29	-29	-29
Pressure (kPa)	3655	3640	3510	3640	3640	3640	3640
Mass flow (t/h)	219.6	219.6	113	113	113	7	99.6
Stream line	22	23	24	27			
Temperature (C)	-38	33.3	35	-38			
Pressure (kPa)	2000	2000	3910	2000			
Mass flow (t/h)	99.6	78	78	21.6			

Table2. Performance and energy intensity of NGL1300

Inlet gas flow rate	206 t/h
NGL production	78 t/h
Lean gas production	128 t/h
Electricity intensity	268.5 kWh/t
Thermal heat intensity	56.4 kWh/t
Demethanizer Efficacy	72%

Table3. Specification of energy intensive equipments of NGL1200

	Electrical power (kW)	Heat load (kW)
Propane pre chiller (E_4)	3673	7014
Propane main chiller(E_5)	3673	6153
Reboiler	-	4411
Lean Gas Compressor	531×2	-

Table4. Physical properties of main streams after using SGR

Stream line	Flow rate t/h	Pressure kPa	Temperature C
External gas line from two phase heat exchanger (15)	9	3650	7.7
The last external line from two phase heat exchanger (42)	104	1900	16
The last internal line to two phase heat exchanger (39)	104	2000	-26
External line from compressor to demethanizer column(45)	9	1900	16

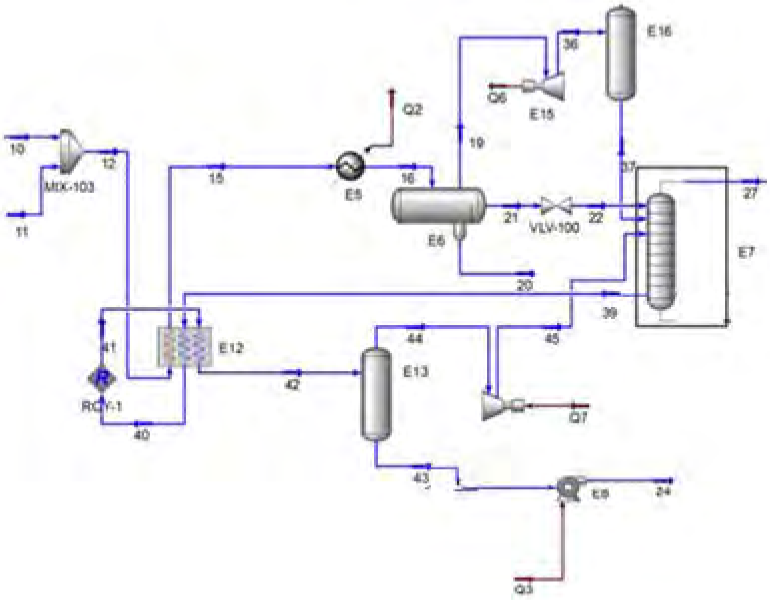

Fig. 2 Using SGR method in NGL1200

4. Results and Discussions

Comparison between results of simulation of NGL1200 before and after using SGR method is represented by table (5).

Table5. Comparison between obtained results before and after using SGR method

	Before	After
NGL production rate (t/h)	78 t/h	92.8
Electricity intensity (kWh/t_{NGL})	268.5	175
Thermal energy intensity (kWh/t_{NGL})	56.4	0
Demethanizer efficacy (%)	72	84

The results indicate that, application of self-refrigeration method reduces electricity intensity of the plant up to 34.7 % and also eliminates the need for reboiler heat load completely. Decreasing in electricity intensity is obtained directly from replacing cooling load of propane per-chiller by heat exchanging of liquid stream from the bottom of demethanizer column with inlet sweet gas. Required capital investment for improving this novel configuration in Gachsaran NGL1200 is represented in table (6).

Table6. Capital investment of SGR method

Item	Capital Investment (10^3 \$)
Expander	256
Separators	21.6
Compressor	25.6
Pump	15
Two phase heat exchanger	336
Installation	182

The results of feasibility study show payback period of total investment of project will be lower than 2 years when the unit price of electricity and NGL is considered consequently, 4 cent per kWh and 500 cent per kg [10].

5. Conclusion

The objective of this research work has been to introduce a novel configuration in NGL plants which is obtained by a self-refrigeration system name as Stripping Gas Refrigeration (SGR). SGR scheme provides overall energy integration and replaces propane refrigeration system. The main results of using this configuration may be concluded as decreasing propane refrigeration, eliminating external heat source of reboiler, decreasing compression hoarse power of the plant. Also, using this method is accompanied with lower capital and operating cost with less impact to the existing equipment of the plant. With purposing total capital investment around 836 thousands dollars including, net present value (NPV) of project may be estimated at 5.6 millions dollars through 15 years operation of the system and its economical feasibility will be supported [11].

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Analysis of optimal application for exhaust gas in thermal oxidizers with case studies

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Abstract: There is potential for optimizing thermal oxidizer plants to increase industrial energy efficiency results in environmental and economic dimension of sustainability. In the present work, genetic algorithm is implemented for three thermal oxidizer cases in three different petrochemical plants to optimize the fuel cost for the three Heat Recovery Steam Generators (HRSG's) which are going to be used for the recovery of the heat from the outlet of the thermal oxidizer units. Generally, thermal oxidizers are used in petrochemical plants to burn waste gases in the plant to reduce the environmental impact of the off-gases of plant and normally the waste heat are released to the atmosphere via a stack. The optimization results have been compared for three cases. Five decision variables have been selected and the objective function was optimized. By increasing the fuel price, the values of thermo-economical decision variables tend to those thermodynamically optimal designs.

Keywords: *Heat Recovery Steam Generator (HRSG), thermo-economics, Optimization, Thermal Oxidizer, Genetic Algorithm, Low Density Polyethylene (LDPE) Plant.*

Nomenclatures

c	*Cost per exergy unit…………..* $\$.MJ^{-1}$
c	*Cost of fuel per energy unit…* $\$.MJ^{-1}$
$\dot{c}$	*Cost flow rate………………..* $\$.sec^{-1}$
c_p	*Specific heat at constant Pressure………………* $KJ.Kg^{-1}.K^{-1}$
CRF	*Capital recovery factor*
h	*Enthalpy……………………..* $KJ.Kg^{-1}$
LHV	*Lower heating value…………* $KJ.Kg^{-1}$
$\dot{m}$	*Mass flow rate…………………* $Kg.s^{-1}$
r_c	*Compressor pressure ratio*
T	*Temperature……………………………..K*
Z	*Capital cost of a component……………$*
$\dot{Z}$	*Capital cost rate………………* $\$.sec^{-1}$
ΔP	*Pressure loss*
η_{ac}	*Compressor isentropic efficiency*
η_{cc}	*Combustion chamber first law efficiency*
γ	*Specific heat ratio*
φ	*Maintenance factor*
EA	*Evolutionary algorithm*
GA	*Genetic algorithm*
P,/Pr,	*pressure ratio of compressor*
r_{ih}	*Inlet humidity percent*
η_{to}	Thermal efficiency of thermal oxidizer
$\dot{W}$	Work……………………..KW

Subscripts

ac	*Air compressor*
a	*Air*
cc	*Combustion chamber*
ev	*Evaporator*
ec	*Economizer*
f	*Fuel*
F	*Fuel for a component*
g	*Combustion gasses*
j	*Stream*
k	*Component*
s	*Steam*
P	*Product of a component*
Pinch	*Pinch point*

1. Introduction

One of the important ways to reduce the effects of environmental impacts of industrial plants is increasing energy efficiency of the plants. Developing techniques for designing efficient and cost-effective energy systems is one of the foremost challenges of energy engineering face. In a world with finite natural resources and increasing energy demand by developing countries, it becomes increasingly important to understand the mechanisms which degrade energy and resources and to develop systematic approaches for improving the design of energy systems and reducing the impact on t he environment. The second law of thermodynamics combined with economics represents a very powerful tool for the systematic study and optimization of energy systems. This combination forms the basis of the relatively new field of thermo-economics.

Ethylene is the main feed of LDPE (Low density polyethylene) plant to produce LDPE product(s) in high pressure. By using a compressor system, excess ethylene in different units of the plant, some traced gases like Methane and Propane, small quantity of water and air are forced to a multi channel combustion chamber of thermal oxidizer unit to burn and diminish the concentration of pollutant, as consequences of imposed environmental limitations that exist for the petrochemical off-gases. After burning the off-gases in the combustion chamber, the considerable medium quality waste gas is released to atmosphere via vent stack. In practise, in most of the petrochemical plants the thermal oxidizer units work continuously as a matter of excess amount of ethylene and other mentioned substances.

For a medium LDPE plant, maximum volume off gases reaches 55000 kg/h with constant steady state pressure. This flow produces an average thermal caloric value of 45000 KJ/kg with average 300 °C flue gas.

The structure of a common thermal oxidizer is illustrated in figure 1. The installation consists of two compressor systems, multi channel combustion chambers, fuel supply and burner systems. In current models for the environmental condition the following are considered (T = 298.15 K and P = 1.013 bar). The operating fuel for the total plant is natural gas (taken as methane) with a lower heating value (LHV) equal to 50000 kJ/kg.

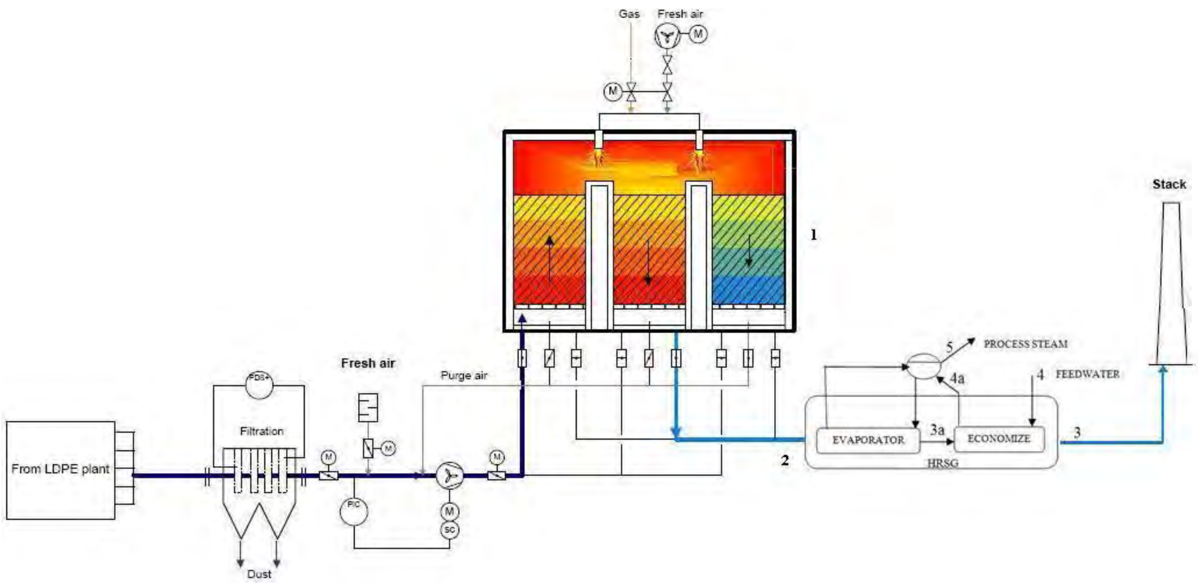

Fig. 1. Schematic sketch of thermal oxidizer with HRSG

In the current research, a part of waste heat energy system (thermal oxidizer) in LDPE (Low Density Polyethylene) plant is optimized according to some decision variables. The hot gases from the combustion chamber are conducted to a HRSG (Heat Recovery Steam Generator) to be utilized for producing steam and hot water. This steam and/or hot water can be used in different ways in this plant (LDPE Plant) or other adjacent industrial plants. Moreover, in this investigation three different thermal oxidizers units were studied and data obtained are analysed for research validation. The models used in this paper are realistic but incomplete from an engineering point of view since the object of this study is to present distinct models of thermoeconomic optimization. Therefore, it would be unreasonable to use an excessively complicated mathematical model to describe the performance of the plant.

2. Methodology

For modelling the system three categories of equations have been considered, the equations which describe the behaviour of the system (physical model), the equations for calculating the capital costs of the components (economic model) and the equations which has been used to calculate the thermodynamic properties (thermodynamic model) [1,2]. The decision variables selected for the optimization are the compressor pressure ratio P,/Pr, the isentropic efficiencies of the compressor (η_c), inlet humidity percent (r_{ih}), the temperature of the combustion gas at the HRSG inlet (T_2) and thermal efficiency of thermal oxidizer (η_{to}).

The following models are formulated as a function of these decision variables. To simplify these models without loss of methodological generality, the following assumptions are made: (1) The air and the combustion gases behave as ideal gases with constant specific heats. (2) For combustion calculations, the fuel is taken to be methane CH4 (3) All components, except the combustion chamber, are adiabatic. (4) Reasonable values are chosen for the pressure loss of the air and gas flows in the combustion chamber and recuperate boiler.

Our optimization program that is based on evolutionary algorithm has good convergence and better results due to using three input category data from three different petrochemical plants. As we know the optimization procedure is so crucial in engineering fields, especially mechanical engineering. Among the various techniques evolutionary algorithms (EAs) are of the greatest importance because of their convergence rate. Among EA algorithms, the Genetic Algorithm is the best option due to its less time consuming for iteration time as well as satisfying the several constraints. Besides, at the end of this study the influence of alteration in the demanded steam on the design parameters has been also studied.

In this paper, after thermodynamic modelling of the system and formation of the objective function, a cogeneration unit with thermal characteristics of well known problem [1,3,4,5] are simulated, optimized, and its results are compared to the results of other cases; in order to ensure the validity of our physical modelling and optimization procedure. Subsequently, parameters of problem are modified to match the conditions and requirements of the present work.

2.1. Thermodynamic modeling of thermal oxidizer with HRSG

Having known the values of decision variables (r_c, η_c, η_{to}, T2 and r_{ih}) for a set of fixed demands of process steam, the values of temperature and pressure in all lines of system was computed. Consequently, the value of fuel mass flow rate $\dot{m}_f$, which should be expressed in terms of decision variables, is determined. The relations of thermodynamic modelling are as follows:

Air compressor

$$T_{out} = T_{in}\left\{1+\frac{1}{\eta_{AC}}\left[r_c^{\frac{\gamma_a-1}{\gamma_a}}-1\right]\right\}, \qquad (1)$$

$$\dot{W}_{ac} = \dot{m}_a . c_{p,a}(T_{out}-T_{in}) \qquad (2)$$

Combustion chamber

$$\dot{m}_a h_1 + \dot{m}_f \, LHV = \dot{m}_g h_2 + (1-\eta_{cc})\,\dot{m}_f \, LHV \tag{3}$$

$$\frac{P_2}{P_1} = (1-\Delta P_{cc}) \tag{4}$$

Heat recovery steam generator

$$\dot{m}_s (h_5 - h_4) = \dot{m}_g (h_2 - h_3) \tag{5}$$

$$\dot{m}_s (h_5 - h_{4a}) = \dot{m}_g (h_2 - h_{3a}) \tag{6}$$

2.2. Objective function

The objective function is defined as the sum of two parts; the operational cost rate, which is related to the fuel expense, the rate of capital cost which stands for the capital investment and maintenance expenses. Therefore, the objective function represents total cost rate of the plant in terms of dollar per unit of time.

$$Obj.Func. = c_f \dot{m}_f LHV + \sum \dot{Z}_k \tag{7}$$

Since the amounts of ultimate products (process steam) are fixed, the objective function is to be minimized so that the values of optimal design parameters would be obtained. For calculating the rate of operating cost equation, we have:

$$\dot{c}_f = c_f \dot{m}_f LHV \tag{8}$$

In which c_f = 0.003 \$/MJ is the regional cost of fuel per unit of energy,$\dot{m}_f$ is the fuel mass flow rate, and LHV = 50000 kJ/kg is the lower heating value of Methane.

For expressing the purchase cost of equipment in terms of design parameters, several method have been suggested [2, 7-11]. In this paper, we used the cost functions mentioned in ref [2]. However, some modifications were made to tailor these results to the regional conditions in Iran and taking into account the inflammation rate. For converting the capital investment into cost per time unit:

$$\dot{Z}_k = Z_k.CRF.\varphi/(N \times 3600) \tag{9}$$

Where, Z_k is the purchase cost of component in dollar, CRF (18%) is the capital recovery factor, N is the annual number of the operation hours of the unit (7500 hr), and φ (1.06) is the maintenance factor.

2.3. Optimization Procedure

Minimizing the objective function Eq.7 is a nonlinear optimization problem. In order to achieve feasible design parameters some physical constraints should be considered seriously. The list of these constraints and their reasons are briefed in table 1. Moreover, the following inequality constraints should be satisfied in heat exchangers (air pre-heater and heat recovery steam generator).

$$T_2 > T_1, \quad T_2 > T_5, \quad T_{3a} > T_5 + \Delta T_{pinch,\, min} \tag{10}$$

In the present work a genetic algorithm code is developed in Matlab Software Programming.

Table1. The list of constraints

Constraints	Reason
$T_2 \le 1600^\circ K$	Material limitation
$r_c \le 16$	Commercial availability
$\eta_{ac} \le 0.9$	Commercial availability
$\eta_{to} \le 0.96$	Commercial availability
$T_3 \ge 400^\circ K$	To avoid formation of sulfuric acid in exhaust gases
$T_{4a} = T_5 - 15^\circ K$	To avoid evaporation of water in HRSG economizer

2.4. Evolutionary algorithm (Genetic Algorithm)

Such algorithms simulate an evolutionary process where the goal is to evolve solutions by means of cross over, mutation, and selection based on their quality (fitness) with respect to the optimization problem at hand. Evolutionary algorithms (EAs) are highly relevant for industrial applications, because they are capable of handling problems with non-linear constraints, multiple objectives and dynamic components properties that frequently appear in real-world problems. Moreover the input and output values for Genetic Algorithm method used in this study are shown in tables 2, 3.

Table 2. Genetic algorithm input

Tuning Parameters	Value
Population size	500
Maximum number of generation	1000
PC(Probability of Crossover) %	70
Pm (Probability of mutation) %	1
Number of crossover	2
Selection in process	Tournament
Tournament size	2

3. Discussion and result

The numerical values of the optimum design parameters of the thermal oxidizer with HRSG are listed in table 3. Moreover, the constraints of the problem are listed in table 1. These results are compared with other case's results. Figure 2 depicts the changes in the objective function versus generation in the developed genetic algorithm code.

Table 3. The comparison of simulation and optimization numerical output for three mentioned cases.

Decision variable	Optimum design	Optimum design	Optimum design
r_c	8.597	8.523	8.504
η_C	0.8465	0.8468	0.83292
η_{to}	94.5	95	95.4
T_2 (K)	504	573	642.3
r_{ih} (K)	80	70	65
Objective Function	0.362 ($/s)	0.3617 ($/s)	0.3294 ($/s)

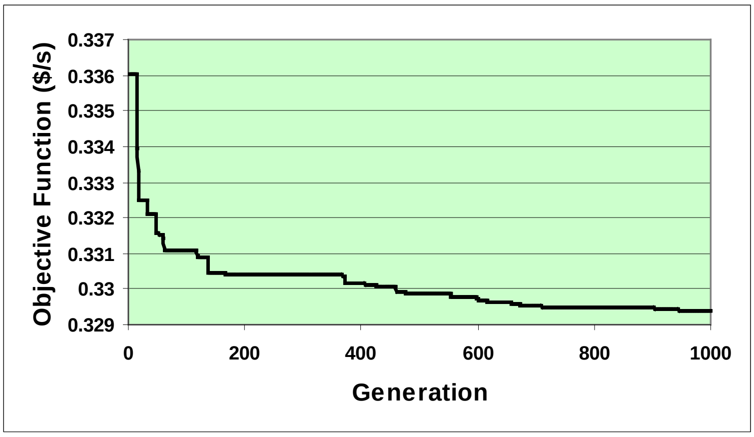

Fig. 2. Variation of Objective Function of the system with Generation (CE=.003$/MJ).

Study of the variation of the optimal decision variables versus fuel unit cost reveals that by increasing the fuel cost optimal decision variables generally shift to thermodynamically more efficient design. As it can be clearly seen the values of decision variables r_p, η_{ac}, and HRSG inlet temperature (T_2) increase with increasing fuel unit cost. It is worthy to mention that while increasing combustion inlet temperature (T_1) reduces the exergy destruction in combustion chamber and heat exchangers (HRSG), due to the exhaust gases constraint ($T_3 >$ 400K); it decreases with increasing the fuel unit cost. It should be noted that for each T_2 there exists a T_1 in which the best thermodynamical efficiency may be achieved. Moreover, an increase in HRSG inlet temperature reduces the exergy destruction in combustion chamber; and since increasing T_2 results in higher exhaust temperature of exhaust gases, the constraint T_3 > 400K does not cause any limitation for rising T_2. Due the fact that any increase in T_2 will dramatically affects the HRSG investment cost, figures 3-5 show the influence of the unit cost of fuel on the values of some the optimal decision variables. Figure 5 shows that when the fuel price increased the combustion chamber fuel mass flow rate decrease for minimizing the objective function. Due to uncertainty of capital investment data, it is imperative to study the results of capital expense variation on the optimal values of decision variables.

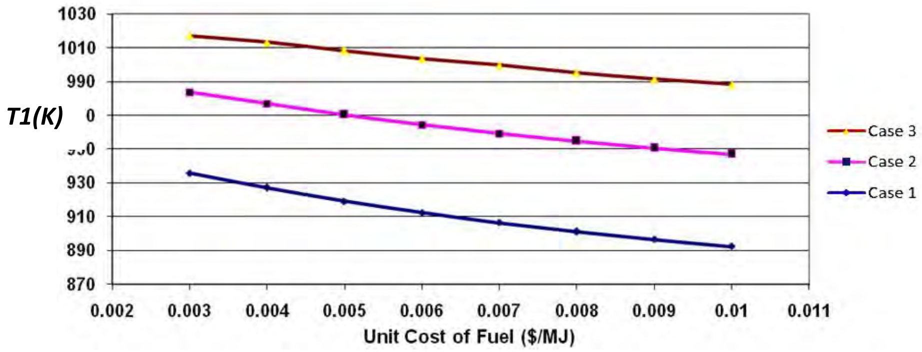

Fig. 3. The effects of fuel unit cost on the optimal value of combustion chamber inlet temperature, T1

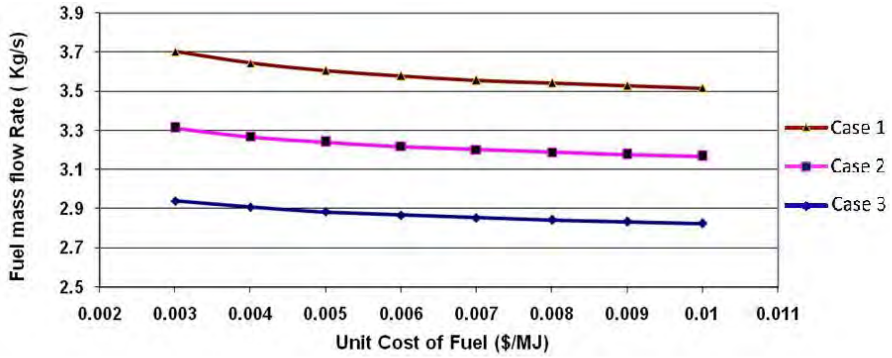

Fig. 4. The effects of fuel unit cost on the optimal value of Fuel Mass Flow Rate, mf

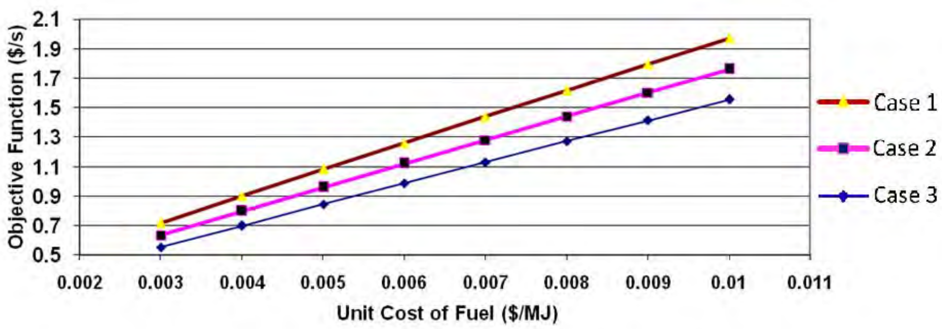

Fig. 5. The effects of fuel unit cost on the optimal value of Objective Function ($/s)

4. Conclusion

The determined optimum design parameters for thermal oxidizer with HRSG apparently show a trade-off between thermodynamically and economically optimal designs. For example, from thermodynamic point of view, the decision variable η_c should be selected as high as possible while this leads to an increase in capital cost. It should be noted that any change in the numerical values of a decision variable not only affects the performance of the related equipment but also all the performance of other equipments as well. It can be deduced from the figures 3-5 that by increasing the fuel price the values of decision variable in thermo-economically optimal design tend to those of thermodynamically optimal design.

Using heat recovery, thermal oxidizers cause more energy efficiency and decrease the level of green house gases accordingly. In spite of the fact that utilizing these types of technologies categorized as an end-of-pipe solution, nevertheless according to the three pillars of sustainability it contribute to both environmental dimension and economic dimension of sustainability.

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Evaluation of repowering in a gas fired steam power plant based on exergy and exergoeconomic analysis

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Abstract: Increased competition among power generating companies, changes in generating system load requirements, lower allowable plant emissions, and changes in fuel availability and cost accentuate the need to closely assess the economics and performance of older electric generating units. Generally, decisions must be made as to whether these units should be retired and replaced with new generation capacity, whether capacity should be purchased from other generation companies, or if these existing units should be repowered. These decisions usually require the evaluation of many factors. The analysis is usually complicated due to the interaction of all the factors involved. In this paper, evaluation of a 156MW steam power plant and proposed repowered scenario has been performed. The exergy and exergoeconomic analysis method was applied in order to evaluate the proposed repowered plant. Simulation of each case has been performed in Thermoflow software. Also, computer code has been developed for exergy and exergoeconomic analysis. It is anticipated that the results provide insights useful to designers into the relations between the thermodynamic losses and capital costs, it also helps to demonstrate the merits of second law analysis over the more conventional first law analysis techniques.

Keywords: *Repowering; Combined cycles; Gas turbines; Steam injection*

Nomenclature

c cost per unit exergy ($/MW) ....($/MW)
C cost flow rate ....($/hr)
e exergy rate per mass.....................(MW/kg)
E specific exergy ....(MW)
Z capital cost rate of unit......................($/hr)
GT ……………………………….gas turbine
CRF …………………….capital recovery factor
PWF ……………………..Present worth factor
LHV………………….....Lower heating value
PW…………………………………..Present worth

1. Introduction

Deregulation and competition are further fueling the demand for new power generation equipment worldwide. Due to the availability and cleanliness of gas, and the ease of consent, gas turbine applications have increased over the last few years. This development is driven by the addition of capacity, but also by major replacement programs.[1] Almost all industrialized countries are now facing some degree of electric power shortage. The major problem is probably the lack of suitable sites for building new power plants of whatever type or size. Moreover, increasing environmental awareness has resulted in more demanding requirements in terms of preliminary analysis, prolonging and complicating the plant commissioning process. All these problems have led many utilities to consider extending the life of existing plants by repowering. Basically, these interventions have been done on gas fired steam plants by addition of a natural gas fired turbine. This reduces specific emissions of the existing steam plant while maintaining or even slightly improving its efficiency. As a rule, a repowered plant can be expected to give a lower cost per kW h produced as well as per kW installed repowering of steam plants can be achieved in two ways: feed water repowering and boiler repowering. The first option uses heat from the turbine exhaust to raise the feed water temperature instead of bleeding steam. This means that increased steam flow has to be managed by the low pressure section of the original steam turbine, requiring either extensive modification of the steam turbine or impairing the repowered plant performance. The other option, boiler repowering, entails major steam generator redesign[2]. Energy systems involve a large number and various types of interactions with the world outside their physical boundaries. The designer must, therefore, face many issues, which deal primarily with the energetic and economic aspects of the system. Thermodynamic laws govern energy conversion processes, costs are involved in obtaining the final products (expenses for the purchase of equipment and input energy resources, operation and maintenance costs), and the effects of undesired fluxes to the ambient must be evaluated in order to answer environmental concerns. Second law analysis has been widely used in the last several decades by many researchers. Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy-generation of the components [3]. Furthermore, exergoeconomic analysis estimates the unit cost of products such as electricity, steam and quantifies monetary loss due to irreversibility. Also, this analysis provides a tool for the optimum design and operation of complex thermal systems [3], [4], [5].

In this study, exergetic, thermoeconomic and exergy analyses have been performed for 156MW steam cycle and repowered gas fired steam power plants. In these analyses, mass and energy conservation laws were applied to each component. Quantitative balance of the exergies and exergy costs for each component and for the whole system was carefully considered. The exergy-balance equation developed by Oh et al. [6] and the corresponding exergy cost-balance equations developed by Kimet al. [7] were used in these analyses. In this regard, computer program has been developed for energy, exergy, exergoeconomic and exergy analysis of both of cases in different load conditions. Furthermore, it can also used to study plant characteristics, namely, thermodynamic performance and sensitivity to changes in process and/or component design variables. In this paper, the authors evaluate and compare repowered power planet and steam power plants in view of exergy and thermoeconomic analysis.

2 Process description

In this paper, GHAZVIN steam cycle power plant has repowered and compared with old steam cycle. The steam cycle power plant encompasses three turbines, that work with three different pressures and 6 feed water heaters. The Steam cycle has been modeled by MATLAB code and STEAM PRO (THERMOFLOW). Results of modeling steam cycle have been introduced and compared with real data in table.1.

Table1. Compare result of modeling steam cycle

	THERMOFLOW	Simulation code	Real
Plant Gross power(kW)	156300	156305	156294
Plant Gross Heat Rate(kJ/kWh)	9010	9120	8976
Plant Gross Efficiency (LHV)	39.9%	39.4%	40.1%
Superheater Capacity(kg/s)	133	130	136
Reheater Capacity(kg/s)	115	114	117

3. Repowering

There are several alternatives to combine and integrate a gas turbine into an existing steam power plant. For 156MW steam power plant unit in Iran, the best alternative is full repowering because its boiler is very old and boiler life time is concluded. Full repowering is defined as complete replacement of the original boiler with a combination of one or more gas turbines (GT) and heat-recovery steam generators (HRSG), and is widely used with very old

plants with boilers at the end of their lifetime. It is considered as one of the simplest ways of repowering for existing plant.
For this power plant, Full Repowering with SGT5-4000F (formerly known as CC 2.V94.3A) with triple pressure reheat cycle was found to be the most economic approach.
Schematic flow diagram of combined cycle with the components is shown in Fig. 2. The gas cycle is selected as a topping cycle. The heating devices in the HRSG are arranged from the high temperature (HT) to the low temperature (LT) exchangers in the flue gas path to get the minimum temperature difference between the flue gas and the water/steam.

4. Exergoeconomic Analysis

All costs due to owning and operating a plant depend on the type of financing, the required capital, the expected life of a component, and so on. The annualized (levelized) cost method of Moran [9] was used to estimate the capital cost of system components in this study. The amortization cost for a particular plant component may be written as:

$$PW = C_i - S_n PWF(i,n) \tag{1}$$

$$\dot{C}(\$/year) = PW \times CRF(i,n) \tag{2}$$

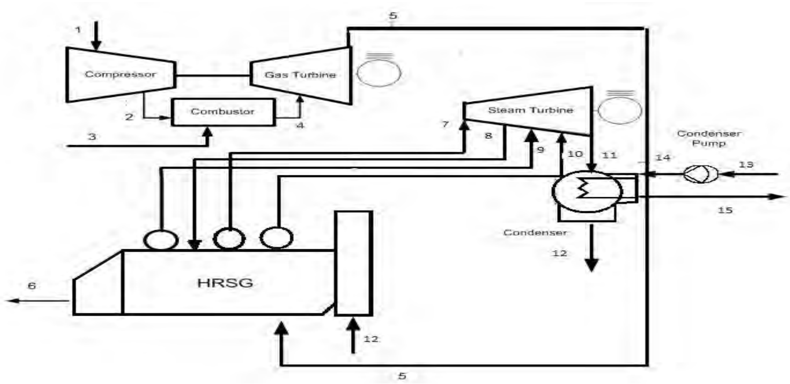

Fig 1.- combined cycle power plant

The present worth of the component is converted to annualized cost by using the capital recovery factor CRF(*i*,*n*), i.e [4]. Dividing the levelized cost by 8000 annual operating hours, we obtain the following capital cost for the *k*th component of the plant.

$$Z_k = \Phi_k \dot{C}_k / (3600 \times 8000) \tag{3}$$

The maintenance cost is taken into consideration through the factor $\Phi_k = 1.06$ for each plant component whose expected life is assumed to be 15 years [6].

4.1 Thermoeconomic Modeling

The results from an exergy analysis constitute a unique base for exergoeconomics, an exergy-aided cost reduction method. A general exergy-balance equation, applicable to any component of a thermal system may be formulated by utilizing the first and second law of thermodynamics [4].
The cost balance expresses that the cost rate associated with the product of the system (C_P), the cost rates equals the total rate of expenditure made to generate the product, namely the fuel cost rate (C_F), the cost rates associated with capital investment (Z^{CI}), operating and

maintenance (Z^{OM}) [12].In a conventional economic analysis, a cost balance is usually formulated for the overall system (subscript tot) operating at steady state [11]:

$$C_{P,tot} = C_{F,tot} + Z_{tot}$$
(4)

Accordingly, for a component receiving a heat transfer and generating power, we would write [4]:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} - \sum_i \dot{C}_{i,k} + Z_k$$
(5)

To solve for the unknown variables, it is necessary to develop a system of equations applying Eq. (5) to each component, and it some cases we need to apply some additional equations, to fit the number of unknown variables with the number of equations [12]. A general exergy-balance equation, able to any component of a thermal system may be formulated by utilizing the first and second law of thermodynamics. In a conventional economic analysis a cost balance is usually formulated for the overall system operating at steady state. To derive the cost balance equation for each component, we assigned a unit cost to the principal product for each component. Depending on the type of fuel consumed in the production process different unit cost of product should be assigned [13].

Table2. Combined cycle results

	Repowering
Gas Turbine(kW)	278041
Steam Turbine(kW)	125655
Plant Total (kW)	403695
Plant net LHV efficiency (%)	55.27
Plant net LHV heat rate(kJ/kWh)	6514
Gas turbine LHV efficiency (%)	39.05
Steam turbine efficiency (%)	34.59

5. Results and discussion

In this paper, computer codes have been developed for thermodynamic simulation and analysis of 156-MW old steam cycle and 400-MW repowered combined power plants. The enthalpy and entropy of non-interacting gas species were calculated by using appropriate polynomials fitted to the thermophysical data in the JANAF Tables [14]. Also the values of physical properties such as enthalpy and entropy for water and steam were evaluated by using equations suggested by the International Association for the Properties of Water and Steam IAPWS-IF97) [14].
Table 2 indicates specification of repowered plant. It shows that, 68% of total power is produced by gas turbine cycle with 39% efficiency, in addition remained power are produced by steam cycle with 34% overall efficiency. Repowered cycle produces 250MW more than old power plant. Heat rate in repowering power plant is 6500(KJ/KWh) and 1500(KJ/KWh) more than old power plant. As a result of repowering, overall efficiency rises 15% and new power plant produce net power with less reduction of energy. The combined cycle results have been developed for gas turbine partial load. Load condition varied from 30% to 100% of full load and figure 2 presents load variation and net power of cycles. Further, entire rate of

exergy destruction has been shown in this figure. However full load has the most exergy destruction, ratio of exregy destruction to supplied energy is less than partial load. In figure 3 efficiency of combined cycle accompaniment gas turbine cycle and steam cycle exhibited. Gas turbine efficiency severely depends on design load and it is decreased when works at partial load states. Since supplied energy for steam cycle depends on exit flow stream of gas turbine, steam cycle efficiency is just independent of load condition. Combined cycle efficiency varied from 40% to 55% and deteriorates with variation from design load.

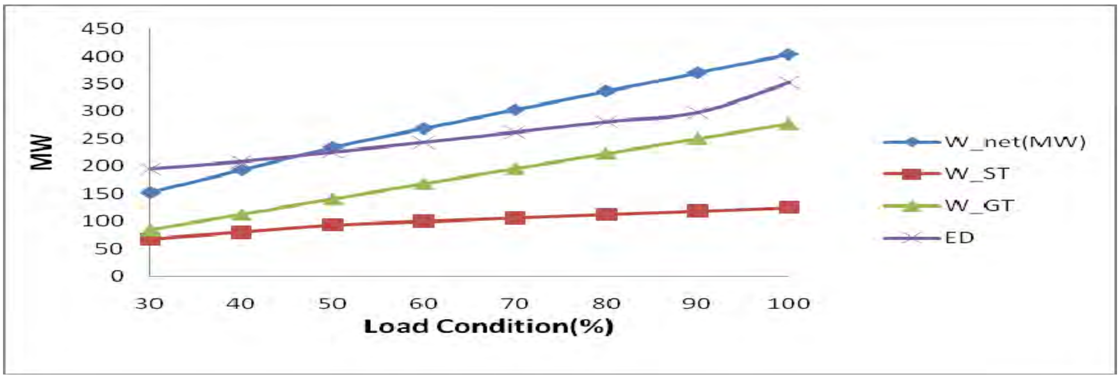

Fig 2. Variation of output power

In this regard, exergy flow and cost flow rates of exergy with and without considering capital investment for each stream in old power plant and repowering plant have been calculated. Also, Table 3 and 4 show Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in old and repowered power plants. These results represent that boiler in old steam power plant and that combustion chamber and heat recovery steam generator in repowered combined cycle has most exergy and exergy cost destruction due to nature of combustion; however combustor in gas fired combined cycle plant shares about 51% TED, 44% TCD0 and 43% TCD. In next steps, compressor and steam generator of repowered have most exergy and exergy cost destruction. Cost product of steam turbine and gas turbine for combined cycle with and without considering capital investment at various load conditions has been presented in figure 4. As results shown, CP_0 and CP increase when load condition reduces because the thermal efficiency decreases. Therefore full load has the best and minimum cost product. In figure 5 rate of total cost exergy destruction has been shown at different load. As results shown, TCD0 and TCD0 reduce when load condition decreases and vice versa because the fuel consumption decreases when load condition reduces and vice versa, so TCD0 and TCD have direct relation with load conditions. In steam cycle power plant 430 MW exergy is destructed and more than 85% of exergy destruction happened in boiler. However combined cycle produced 250 MW net power more than steam cycle, Total exergy destruction in combined cycle is 296 MW and 70% of steam cycle exergy destruction. Since cost product of gas turbine in combined cycle is less than steam turbine and majority of output power produced with gas turbine, combined cycle cost product is reasonable. Therefore repowered power plant generated more power than old power plant with recuperated efficiency and more reasonable cost product.

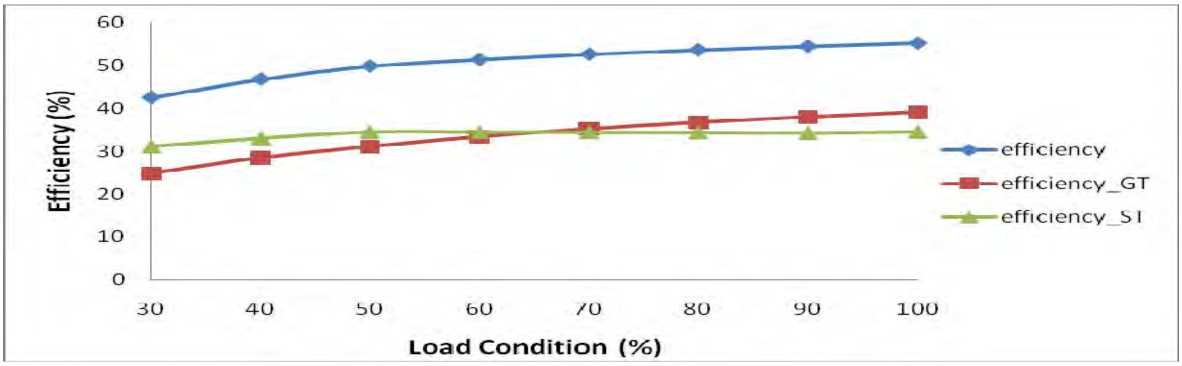

Fig 3. Partial load efficiency

Table 3. Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in steam cycle power plant

Component	Exergy Destruction	CF0 ($/MW)	CP0 ($/M	CD0 ($.s)	CF ($/MW)	CP ($/MW	CD ($/s)
FWH1	1.2437	0.0054	0.0086	0.0067	0.0056	0.009	0.0069
FWH2	0.3984	0.0054	0.0059	0.0021	0.0056	0.0062	0.0022
FWH3	0.3295	0.0054	0.0399	0.0017	0.0056	0.0414	0.0018
FWH4	0.5141	0.0187	0.0193	0.0096	0.0196	0.0203	0.0100
FWH5	0.539	0.0055	0.0062	0.0029	0.0057	0.0065	0.0030
FWH6	0.5659	0.0057	0.006	0.0032	0.0059	0.0064	0.0033
CONDENSER	6.0506	0.0054	0.0103	0.0326	0.0056	0.0109	0.0338
LP St Turbine	9.1386	0.0057	0.0068	0.0520	0.0059	0.0072	0.0539
IP St Turbine	2.4625	0.0054	0.0056	0.0132	0.0056	0.0059	0.0137
HP St Turbine	18.5699	0.0054	0.0061	0.1002	0.0056	0.0064	0.1039
Boiler	388.9632	0.0014	0.0043	0.5445	0.0014	0.0044	0.5445
CP	0.3484	0.003	0.0038	0.0010	0.0031	0.004	0.0010
FPT	1.3422	0.003	0.0042	0.0040	0.0032	0.0045	0.0042

6. Conclusion

In this paper, an exergy-costing method has been applied to both cases to estimate the unit costs of electricity produced from steam turbines. The computer program that was developed which shows that the exergy and the thermoeconomic analysis presented here can be applied to any energy system systematically and elegantly. If correct information on the initial investments, salvage values and maintenance costs for each component can be supplied, the unit cost of products can be evaluated.

Table 4. Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in repowered power plant

Component	Exergy Destruction(MW)	CF0 ($/MW)	CP0 ($/MW)	CD0 ($.s)	CF ($/MW)	CP ($/MW)	CD ($/s)
COMP	46.2489	0.0061	0.0073	0.2821	0.0064	0.0078	0.2959
COMB	152.5663	0.0049	0.0059	0.7475	0.0051	0.0061	0.7780
GT	17.0101	0.0059	0.0061	0.1003	0.0061	0.0064	0.1037
ST	36.2881	0.0083	0.0092	0.3011	0.0089	0.0101	0.3229
HRSG	38.6824	0.0063	0.0073	0.2436	0.0065	0.0078	0.2514
COND	4.8385	0.0083	0.2376	0.0401	0.0083	0.2603	0.0401
FWP	0.0236	0.0064	0.0113	0.0001	0.0064	0.0177	0.0001
CWP	0.6226	0.0064	0.0006	0.0039	0.0064	0.0007	0.0039

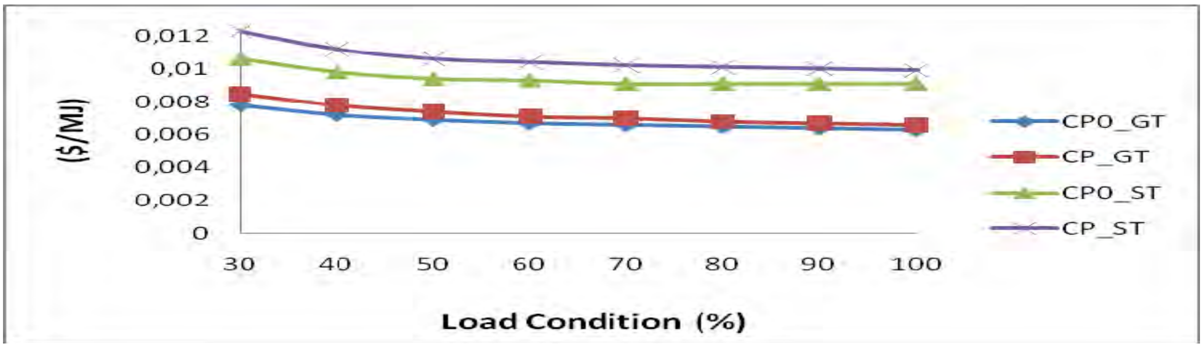

Fig4. C_p and C_{P0} of repowered power plants at different loads

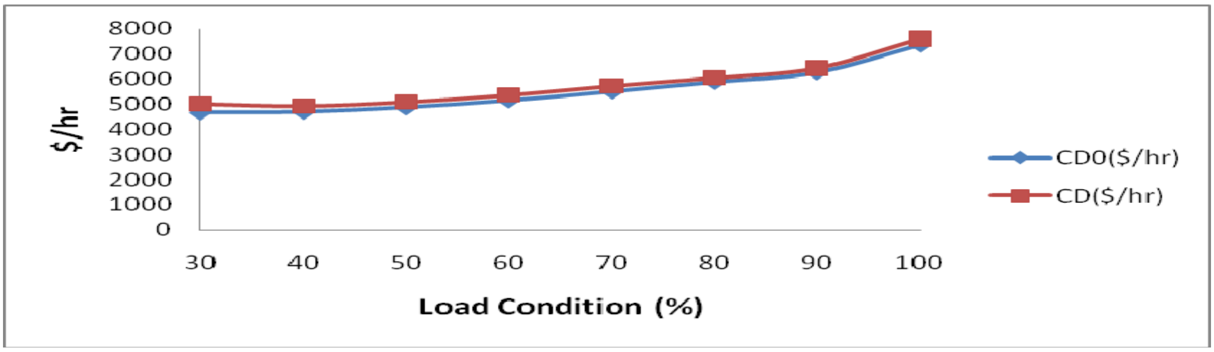

Fig 5.CD, CD_0 of repowered power plants at different load

Although the overall picture of a system can be shown and major directions for improving the system performance can be identified from the above two levels of analysis, the maximum potential or the limit of improvement for individual units and processes are still uncertain, since the exergy loss analysis so far is based on the concept of total exergy loss. In some cases, the suggestions for promising modifications based on the total exergy loss may be misleading, since they do not consider the minimum exergy loss which is required to operate a process.

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An Inquiry into the Sources of Change in Industrial Energy Use in the Japanese Economy: Multiple Calibration Decomposition Analysis

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Abstract: Decomposition methodologies are necessary to examine the causal factors of energy use trends in an economy. This paper suggests a new approach -the Multiple Calibration Decomposition Analysis (MCDA)- to investigate the sources of change in industrial energy use in the Japanese economy. The multiple calibration technique is utilized for an *ex post* decomposition analysis of structural change between periods, enabling distinction between price substitution and technological change for each sector. This paper explains the theoretical properties of MCDA and applies it to an empirical case -the change in energy use in Japanese industry from 1970 to 1990. This paper clarifies how industrial energy use was affected by price substitution or technological change through the experience of the two oil crises, focusing on energy-intensive industry. The paper shows that technological change played an important role in reducing industrial energy use in the Japanese economy. Remarkably, oil-saving technological change advanced by 60% or more in energy-intensive industry during the 1980s.

Keywords: *calibration, decomposition, industrial energy efficiency, price substitution, technological change*

1. Introduction

New interest has arisen in energy demand analysis, reflecting the rapid fluctuation of oil prices, and by the same token the problem of climate change (e.g., Dowlatabadi and Oravetz [1], Metcalf [2], Sue Wing [3]). From a historical point of view, discussions of energy demand analysis have been lively since the oil crises of the 1970s. A vast amount of literature has been devoted to such analyses, including classic works by Hudson and Jorgenson [4] Berndt and Wood [5], Manne [6], Borges and Goulder [7], and Solow [8].

Change in energy use is caused by various factors, including price substitution and autonomous technological development. Determining the contribution of these factors to energy use trends is a difficult but necessary quest, for which decomposition techniques are required. In this context, many decomposition methodologies have been accepted for the quantification of causal factors: for example, Index Decomposition (ID; see, e.g., Ang and Zhang [9], Hoekstra [10]) and Structural Decomposition Analysis (SDA; see, e.g., Rose and Casler [11], Rose [12], Hoekstra [10]), which are well-established decomposition methodologies for this purpose.

This paper proposes a new approach -the Multiple Calibration Decomposition Analysis (MCDA)- to investigate the driving forces of change in industrial energy use in the Japanese economy. The MCDA methodology was originally proposed by Okushima and Tamura [13]. The multiple calibration technique is applied to an *ex post* decomposition analysis of structural change between periods, enabling distinction between price substitution and technological change for each sector. This approach has sounder microtheoretical foundations than conventional methods.

In this paper, the MCDA methodology is applied to the decomposition analysis of change in industrial energy use following the oil crises of 1970-1990, focusing on energy-intensive industry. This period includes two oil crises, during which a rise in oil prices influenced the

Japanese economy to an enormous extent. Moreover, energy use by industry, especially energy-intensive industry, is a key factor of change in energy use in the economy. This is an appropriate area to apply this method to evaluate the extent to which industrial energy use was affected by price substitution or technological change. Besides that, this kind of analysis may add to our stock of information for future Japanese energy or environmental policy.

The remainder of the paper is structured as follows. Section 2 explains the MCDA methodology. Section 3 applies the method to an empirical case, energy use in Japanese industry from 1970 to 1990. The final section provides concluding remarks.

2. Methodology

This section outlines a new decomposition methodology -the Multiple Calibration Decomposition Analysis (MCDA)- originally proposed by Okushima and Tamura [13]. The method explicitly defines two-tier constant elasticity of substitution (CES) production functions as an underlying model to separate price substitution effects from other types of technological change. For more information on CES functions, see, e.g., Shoven and Whalley [14]. The MCDA decomposes structural change in the economy, shown by the change in factor inputs per unit of output between periods (CFI), into two parts: one attributable to price substitution (PS) and the other attributable to technological change (TC).

This paper assumes the model structure in the MCDA to be as shown in Fig. 1. The two models which are identical except for the number of sectors are employed in the following section. The production functions are given by two-tier constant-returns-to-scale CES functions. The model comprises capital *K*, labor *L*, energy aggregate *E*, and material aggregate *M*, as well as energy and material inputs. Capital *K* and labor *L* are the primary factors of production.

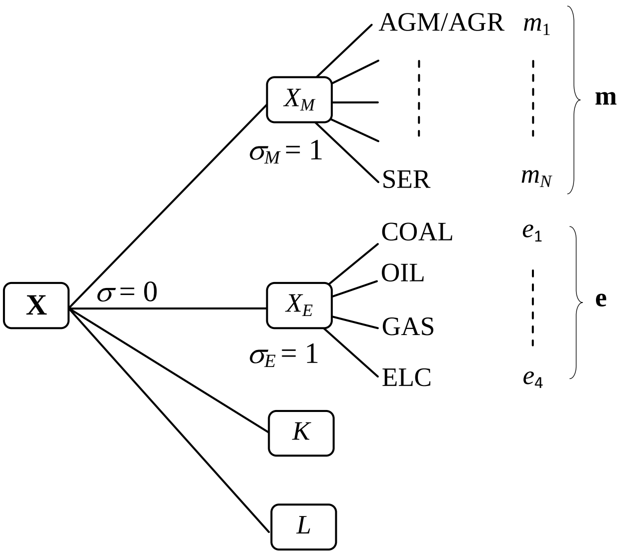

Fig. 1. The model (N = 5 in the 9-sector model and N=14 in the 18-sector model)

Fig. 2 illustrates the MCDA methodology. The MCDA can exactly decompose the CFI into PS and TC. PS, which depends upon the elasticity of substitution (σ) and the change in relative prices between the periods ($p^{t-1} \rightarrow p^t$), represents the price substitution effects, while TC represents those portions of the factor input change that cannot be interpreted by the price substitution effects ($\lambda^{t-1} \rightarrow \lambda^t$), including autonomous technological development. The counterfactual points of the MCDA mean the junctures into which the effects of the relative price change between the initial and terminal periods are incorporated. From a theoretical perspective, PS means a change in factor inputs along the production function, while TC refers to shifts in the production function. Therefore, the decomposition of the MCDA is consistent with production theory in microeconomics. The method has clear microtheoretical foundations; then, the decomposition components can be interpreted in a theoretically meaningful way. For more details of the MCDA methodology, see Okushima and Tamura [13].

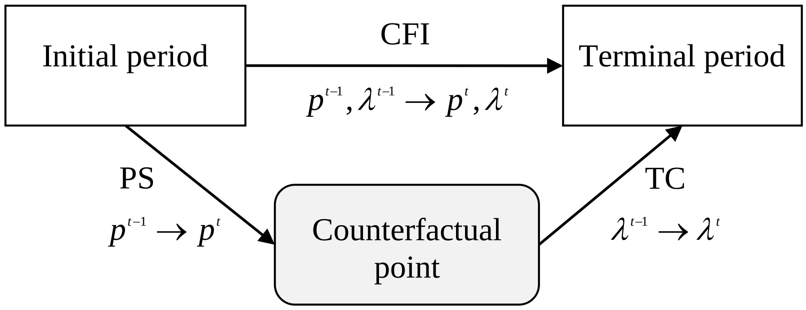

Fig. 2. The methodology

3. Empirical results

This paper applies the Multiple Calibration Decomposition Analysis (MCDA) to investigate the sources of change in industrial energy use in Japan. While Okushima and Tamura [13] is a comprehensive study of changes in energy use and carbon dioxide emissions in the Japanese economy from 1970 to 1995, this paper centers on the change in industrial energy use, especially energy-intensive industry, in the 1970-1990 period. This period includes two oil crises: one in 1973 and a second in 1979. It is widely recognized that skyrocketing oil prices had a huge influence on the Japanese economy during this time, and that the structural changes had a great impact on manufacturing energy use (see, e.g., IEA [15]). This situation presents a typical context in which to apply the method, which can provide a detailed analysis of how change in industrial energy use was caused by price substitution or technological change.

This section analyzes the change in industrial energy use, using data from 1970 to 1990. Nominal outputs (factor inputs) are obtained from the 1970-75-80 and 1985-90-95 Linked Input-Output Tables (Management and Coordination Agency). Real outputs (factor inputs) are obtained by deflating the nominal values by the corresponding prices. Prices of goods and services are from the Domestic Wholesale Price Index (Bank of Japan) or Deflators on Outputs of National Accounts (Economic Planning Agency). Capital and labor prices are estimated following Ito and Murota [16]. In the MCDA, these prices are normalized such that the prices in the initial period are at unity. This units convention, originally proposed by Harberger [17] and widely adopted since (Shoven and Whalley[14], [18], Dawkins et al. [19]), permits the analysis of consistent units across time. The elasticities of substitution are assumed, for the purposes of simplicity, to be $\sigma = 0$ and $\sigma_E, \sigma_M = 1$ as in Fig. 1; nevertheless, these estimates are not significantly different from those in the previous literature that econometrically estimates these elasticities for the Japanese economy (see, e.g., Okushima and Goto [20]).

As in Fig. 1, the sectors are classified into five industries and four energy inputs in the 9-sector model. On the other hand, the sectors are classified into fourteen industries and four energy inputs in the 18-sector model. Please see the notes accompanying Table 1 and Table 2 for the sector classification.

First, Fig. 3 is a summary of the trends in Japan's energy use (see, e.g., IEA[15]). Energy use in the Japanese economy has continuously increased in volume since the 1970s. However, the growth rate in the early 1980s after the oil crises was lower than in other periods. It is recognized that Japan succeeded in the field of energy conservation and substitution from oil as a result of the lessons of the oil crises (see, e.g., Gregory [21]). The proportion of oil in both primary supply and final consumption has decreased after the oil crises, while the proportions of gas and electricity have increased, mainly owing to the use of natural gas and nuclear power. The primary supply of coal, such as for power generation, is gradually increasing while final consumption has remained almost unchanged, and its share of final consumption is diminishing. Following the trend of final energy consumption, the changes in factor inputs (CFIs) also reflect this experience. Table 1 shows that the CFIs for coal and oil are mostly negative while those for gas and electricity are the opposite. The CFIs should be caused by various effects such as price substitution or technological change.

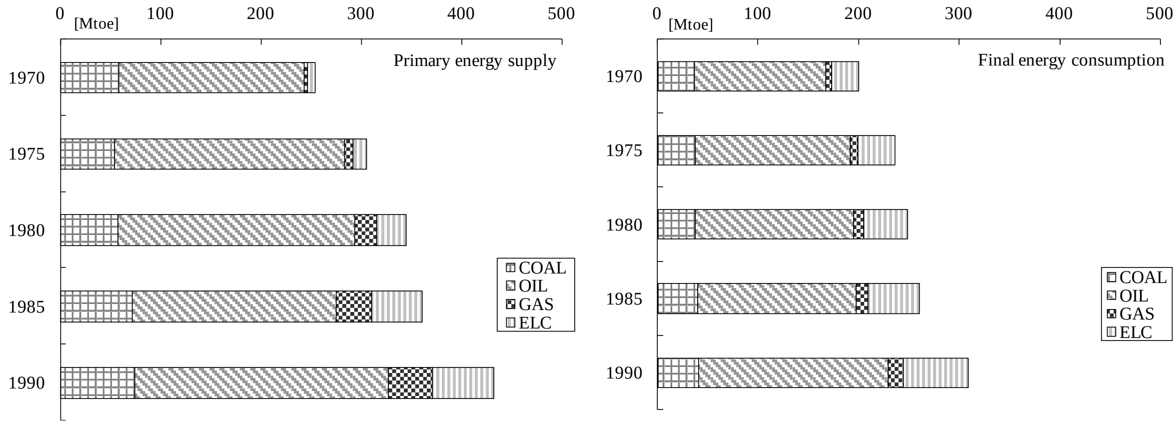

Fig. 3. Primary energy supply and final energy consumption in Japan (Source: IEA[22])

Table 1 illustrates the decomposition of the CFIs by the MCDA with the 9-sector model. The MCDA decomposes the CFI into technological change (TC) and price substitution (PS). The advantage of the method is that it can evaluate these causal factors in terms of types of energy, sectors, or periods, respectively. Table 1 demonstrates that in the 1970s the PSs for oil are negative in all sectors while those for the other types of energy are mostly positive. This means that the rise in oil prices decreased the factor inputs of oil while the demand for coal, gas, and electricity increased because of relatively low prices. Conversely, the PSs for oil become positive in the 1980s, reflecting the fall in oil prices, while those for other types of energy, coal and electricity, become negative. It is remarkable that the PSs for coal form a sharp contrast with those for oil. The PSs for gas are mostly positive. This indicates that the industries had expanded their use of gas because of its price advantage. Thus, the MCDA can clearly show the price substitution effect consistent with the production theory; that is, substitution from inputs with higher prices to those with lower prices.

Table 1 also reveals that the TCs for oil are largely negative in the 1980s. Theoretically, this means that the CFIs for oil had decreased to a greater degree than was expected from the price substitution effect (PS). This is consistent with other empirical studies, such as Han and Lakshmanan [23] and Unander et al. [24], which suggest that improvements in energy efficiency took place in the period even without higher prices. The result indicates that oil-saving technological change had occurred primarily in the 1980s rather than in the 1970s. In addition, the TCs for coal are almost all negative throughout the periods. The result shows the importance of technological change in reducing industrial energy use.

Table 1. Decomposition of the changes in energy inputs

	Sector														
Input/	AGM			EII			MAC			OMF			SER		
Period	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS
COAL															
(i)	-59.5	-89.7	30.2	29.6	22.9	6.7	-70.1	-77.6	7.5	-43.6	-50.8	7.1	-5.2	-22.6	17.4
(ii)	-23.6	-67.4	43.8	-31.7	-54.3	22.6	-19.2	-52.6	33.4	-14.1	-49.1	35.0	-0.3	-36.4	36.0
(iii)	-68.5	-59.4	-9.1	-36.1	-29.9	-6.2	-60.1	-52.7	-7.4	-36.8	-29.4	-7.4	-32.7	-24.8	-7.8
(iv)	32.2	57.8	-25.6	-25.4	-6.4	-19.0	-3.6	18.1	-21.7	-22.5	-0.4	-22.1	-19.3	3.9	-23.2
OIL															
(i)	-9.2	-5.2	-4.0	0.6	21.9	-21.3	-51.0	-30.3	-20.7	-6.6	14.4	-21.0	-22.0	-8.5	-13.4
(ii)	-1.5	-0.5	-1.1	-8.2	7.4	-15.7	-36.8	-28.6	-8.2	7.6	14.8	-7.1	-23.2	-16.8	-6.4
(iii)	-43.2	-43.6	0.3	-23.9	-27.5	3.5	-28.0	-30.2	2.2	-38.8	-41.0	2.1	-15.2	-16.9	1.7
(iv)	-4.1	-5.2	1.1	-32.0	-41.9	9.9	-41.8	-48.2	6.3	-31.1	-36.9	5.8	-22.9	-27.2	4.4
GAS															
(i)	14.3	-33.0	47.3	2.8	-17.9	20.7	-36.3	-57.9	21.6	-13.2	-34.4	21.2	49.1	16.3	32.8
(ii)	30.6	2.6	27.9	34.0	25.0	9.0	-13.4	-32.0	18.7	62.0	41.9	20.1	15.4	-5.6	21.0
(iii)	-24.7	-23.8	-0.9	-51.0	-53.3	2.3	-42.8	-43.8	1.0	84.7	83.8	0.9	-17.8	-18.3	0.5
(iv)	-40.2	-43.6	3.4	88.3	75.8	12.4	-41.9	-50.6	8.8	19.0	10.8	8.2	-15.5	-22.2	6.7
ELC															
(i)	7.5	-32.8	40.3	12.9	-2.1	15.0	-17.9	-33.8	15.9	20.9	5.5	15.5	21.0	-5.5	26.5
(ii)	23.3	12.4	10.9	-9.1	-3.6	-5.4	-16.4	-19.3	2.9	19.2	15.1	4.1	1.3	-3.6	4.9
(iii)	-24.5	-21.2	-3.2	-7.7	-7.5	-0.1	37.0	38.4	-1.4	-6.3	-4.9	-1.5	-2.9	-1.0	-1.9
(iv)	25.8	33.0	-7.2	0.5	-0.4	0.9	-24.0	-21.7	-2.4	-6.1	-3.3	-2.8	8.3	12.5	-4.2

Note: (1) The values are percentage changes.
(2) Classifications are as follows.
AGM: Agriculture, forestry, fishery, and mining; EII: Energy-intensive industry (paper and pulp, chemical, ceramics, and iron and steel); MAC: Machinery; OMF: Other manufacturing; SER: Services and others (including construction); COAL: Coal and coal products; OIL: Oil and oil products; GAS: Gas; ELC: Electricity.
(3) Periods are as follows. (i): 1970-75; (ii): 1975-80; (iii): 1980-85; (iv): 1985-90.

Next, this paper investigates the details of energy use in energy-intensive industry (EII), using the 18-sector model. Here, EII represents the following four industries: paper and pulp (PAP), chemical (CHM), ceramics (CRM), and iron and steel (IAS). These industries account for a large proportion -i.e., about seventy percent- of the industrial energy use in the Japanese economy. It is widely known that EII contributed greatly to the reduction of energy consumption in the period. METI [25] shows that energy efficiency rose dramatically by 42% in PAP, 34% in CHM, 26% in CRM, and 17% in IAS between 1973 and 1990 (see also, e.g., Toichi [26]). Unander et al. [24] examines such improvements in energy efficiency and implies that both price change and other factors induce it. The MCDA has the advantage of enabling the decomposition of CFI, i.e., the change in energy efficiency, into PS and TC. Hence, this section examines the energy use of EII more closely using the MCDA.

Table 2 illustrates the decomposition result. The PSs for oil are negative in all sectors in the 1970s, while they all become positive in the 1980s. Among the other types of energy, coal shows a clear contrast in terms of PSs during these periods. This shows an offsetting effect of a demand for coal as a substitute for oil, because of its price advantage. The trend in PSs nearly corresponds with that of the EII total in Table 1.

Table 2 also shows that the TCs for oil are strongly negative in the 1980s. Corresponding with the above result in Table 1, oil-saving technological change was primarily developed in the 1980s for those industries. These results are supported by engineering studies indicating that energy conservation was attained by means of an improvement in operations in the 1970s, while full-scale energy conservation was advanced by the introduction of various kinds of energy-saving technology in the 1980s after the second oil crisis (see, e.g., the Study Group on Energy and Industry [27]). In fact, multifarious technological innovations took place during that period; specifically, the continuous casting or waste heat recovery in IAS, and the waste heat recovery equipment of plants in CHM (see, e.g., METI [25]).

There is a point of contrast regarding PAP and CRM: the TCs for coal in these industries from 1975 to 1985 are sizably positive, although those in other EIIs are mostly negative. At this point, engineering studies indicate that PAP and CRM increased the use of coal by installing new combustion equipment in that period (see, e.g., the Study Group on Energy and Industry [27], METI [25]). The trend is reflected in these backgrounds. As a result, the CFIs for coal in PAP and CRM greatly increased; the TCs also increased without regard to the trend of PSs. The results in this section indicate that technological change is important for diminishing industrial energy use.

Table 2. Decomposition of the changes in energy inputs in energy-intensive industry

	Sector											
Input/	PAP			CHM			CRM			IAS		
Period	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS	CFI	TC	PS
COAL												
(i)	-89.4	-92.6	3.2	-20.0	-34.9	14.9	-51.9	-65.2	13.3	25.2	23.9	1.3
(ii)	158.6	125.6	33.1	-13.3	-51.2	37.9	333.6	295.5	38.1	-31.1	-42.4	11.3
(iii)	277.7	285.3	-7.6	-4.1	4.2	-8.3	10.4	17.9	-7.5	-32.6	-29.1	-3.6
(iv)	-14.5	8.4	-22.9	-26.1	-2.7	-23.4	-24.6	-3.3	-21.4	-16.5	-4.8	-11.6
OIL												
(i)	-28.8	-4.8	-23.9	2.6	17.9	-15.3	17.8	34.3	-16.5	-5.1	20.2	-25.3
(ii)	81.5	90.0	-8.4	-12.2	-7.1	-5.1	-25.6	-20.7	-5.0	-28.6	-5.2	-23.4
(iii)	4.7	2.7	2.0	-31.4	-32.6	1.2	-28.0	-30.1	2.1	-47.4	-53.9	6.4
(iv)	-59.1	-63.8	4.7	-31.2	-35.3	4.1	-40.5	-47.3	6.8	-40.4	-60.4	20.0
GAS												
(i)	1.7	-15.0	16.7	6.8	-23.2	30.0	-11.5	-39.6	28.2	16.1	1.5	14.6
(ii)	-16.7	-35.0	18.4	-5.0	-27.7	22.7	-3.8	-26.7	22.9	181.2	182.2	-1.0
(iii)	21.6	20.8	0.7	-66.0	-65.9	-0.1	6.5	5.6	0.9	-62.3	-67.4	5.1
(iv)	7.8	0.7	7.1	71.6	65.1	6.4	78.2	69.0	9.2	173.7	150.9	22.8
ELC												
(i)	17.8	6.6	11.2	2.7	-21.1	23.8	26.9	4.8	22.1	13.4	4.3	9.2
(ii)	-14.1	-16.8	2.7	-24.2	-30.6	6.4	5.4	-1.2	6.6	-5.4	8.7	-14.1
(iii)	-15.0	-13.4	-1.6	7.0	9.4	-2.4	-26.5	-25.0	-1.5	-6.6	-9.3	2.7
(iv)	9.2	13.1	-3.9	-14.3	-9.8	-4.5	-6.8	-4.8	-1.9	15.8	5.6	10.2

Note: (1) The values are percentage changes.
(2) Classifications are as follows.
PAP: Paper and pulp; CHM: Chemical; CRM: Ceramics; IAS: Iron and steel.
(3) Periods are as follows. (i): 1970-75; (ii): 1975-80; (iii): 1980-85; (iv): 1985-90.

4. Conclusions

This paper suggests a new approach -the Multiple Calibration Decomposition Analysis (MCDA)- to investigate the sources of change in industrial energy use in the Japanese economy during the 1970-1990 period. The primary contribution of this paper is to use the new methodology to examine the causal factors of energy use change in energy-intensive industry (EII) following the oil crises. The MCDA can decompose the change in factor inputs per unit of output (CFI) into price substitution (PS) and technological change (TC) in a multisector general equilibrium framework. The empirical result in Section 3 shows how industrial energy use was influenced by price substitution or technological change through the experience of the two oil crises. It illustrates that price substitution from oil to other types of energy occurred in the 1970s, while the reverse occurred in the 1980s. Nevertheless, factor inputs of oil decreased in the 1980s, because oil-saving technological change primarily occurred in that period. Notably, oil-saving technological change in EII advanced by 60% or more in the 1980s. This paper casts light on EII and investigates the details of its contribution. The results show the important role of technological change in curtailing industrial energy use in the Japanese economy.

This study presents the MCDA, which could serve as a practical tool for energy analysis. Finally, it clarifies the assumptions upon which the MCDA depends. It is notable that the method employs a deterministic procedure, and the reliability of empirical results depends on the empirical validity of elasticity parameters. Hence, the MCDA has similar defects to applied general equilibrium analysis. In practice, there are still problems in acquiring reliable elasticity parameters. Nevertheless, the method would be a great help in energy analysis with the support of other conventional methods.

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Simulation of energy recovery system for power generation form coal bed gas of Tabas coal mine of Iran

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Abstract: Coal mine methane is a general description for all methane released prior to, during and after mining operations. As such, there is considerable variability in flow rate and composition of the various gas emissions during mining operations. It would be highly desirable to recover energy from emitted methane of coal mine to generate electricity. Hence, more attention should be focused on the effective utilization of emitted methane in coal mines. The energy recovery system, as one of the promising technologies, has been attracting increased attention to generate electricity from emitted methane in Tabas mine. Some energy recovery systems with different configurations may be proposed such as gas turbine and gas engines. In this investigation, a simulation model has been developed in Hysys software environment to predict generated power from combination of ventilation air and drainage gas (mixture with 1.6 % methane concentration) form Tabas mine by using a lean-burn gas turbine.

Keywords: *Coal bed gas, energy recovery system, lean-burn gas turbine, simulation*

1. Introduction

New natural gas reserves are vital to guaranteeing a steady supply of affordable fuel to generate electricity and preserve quality of life. Coal bed gas is a form of natural gas reserve which is extracted from coal beds. In recent decades it has become an important source of energy in many countries of the world. It is mainly composed of methane with variable amounts of ethane, nitrogen, and carbon dioxide [1].

A large portion of the methane emitted from coal mines comes from gob areas (collapsed rock over mined-out coal). Coal mines frequently do not use medium-quality gas from gob wells and instead vent the gas to the atmosphere, contributing to global warming. However, gas with a methane concentration exceeding 35% can in fact be used as a fuel for on-site power generation [2]. Given their large energy requirements, coal mines can recover methane and generate electricity with energy recovery systems to realize significant economic savings and reduce greenhouse gas emissions. Generating electricity is an attractive option because most coal mines have significant electricity loads. Electricity is required to run nearly every piece of equipment including mining machines, conveyor belts, desalination plants, coal preparation plants, and ventilation fans [3].

Coal bed gas methane is emitted in two streams: (1) mine ventilation air (0.1–1% CH_4) and (2) gas drained from the seam before and after mining (60–95%) CH_4. Drainage gas can be utilized to generate electricity directly [4]. For example, internal combustion engines, such as compression fired diesel engines and compression ignition engines modified to be spark-fired engines commonly use drainage gas to generate electricity[5]. The main problem of using drainage gas is related to its periodic extraction from the mine. Also, ventilation air methane is the most difficult source of methane to use as an energy source, as the air volume is large and the methane resource is dilute and variable in concentration and flow rate. Because of low concentration of methane in mine ventilation air, effective technology will be required to utilize it and generate electricity. As brilliant idea, it will be possible to combine ventilation air and drainage gas and produce mixture with sufficient concentration of methane. The

mixture then can be used as fuel in low concentration methane combustion process such as lean-burn gas turbine for on-site power generation in the mine location [6].
In this investigation, a simulation model has been developed in Hysys software environment to predict generated power from combination of ventilation air and drainage methane in an energy recovery system. To this aim, Tabas mine is considered as case study. The results of the simulation model show that the large portion of total electricity demand of the Tabas coal mine can be supplied from the coal bed gas.

2. Materials and Methods

2.1. System description

There are several technologies that can be used for stationary power generation by directly using drainage gas, namely conventional gas turbines and gas engines or every internal combustion engine. However, it would be expected that variation of methane concentration and amount of the drainage gas should affect the continuous and stable operation of the power generation units.
The mechanism for generation power from ventilation air may be considered in two categories: 1) Catalytic oxidation 2) Thermal oxidation. In general, catalytic combustion is a multi-step process involving diffusion methane to the catalyst surface, adsorption onto the catalyst, reaction, and release of the product species from the catalyst surface and diffusion back into the bulk [7].

Thermal oxidation can be occurred in combustion chamber of lean-burn gas turbine. The lean-burn gas turbine is a recuperative gas turbine, which uses heat from the combustion process to preheat the air containing methane to the auto-ignition temperature (in the range 700–1000 C), with the combusted gas being used to drive a turbine. This gas turbine can operate continuously when the methane concentration in air is above 1.6%, which leads to the air being preheated to 700 C before combustion. Therefore, it requires the addition of substantial quantities of methane to the ventilation air to reach adequate methane concentrations from drainage methane. The mixture is preheated by a recuperator to 450 C. Then a recuperative combustion chamber uses the hot combustion products to further heat the fuel–air mixture to a point where ignition occurs. The fuel and air mixture is injected through stainless steel tubes into the combustion region. The burnt gas then passes up the outside of the stainless steel tubes to heat incoming air, and then enters into the turbine inlet to drive the turbine. This heat exchange reduces the exit temperature of air to 850 C, which is the same as the standard Centaur turbine. With this design, there is a need to use a turbine that has a low combustion temperature [8].

In this paper, Tabas mine is considered as a case study. Tabas mine is located in Yazd Province, 80 km south of Tabas City of Iran. This mine is the first mechanized coal mine of Iran that is designed by room and pillar method. Overall specifications of the mine are represented in table (1).

Table1. Overall specifications of Tabas Mine

Total production per year (2009)	1.2 Millions tones
Ventilation air flow rate (0.18 % CH4 by volume)	360000 Nm^3/h
Drainage gas flow rate (76.5% CH4 by volume)	2271 Nm^3/h
Total installed electricity demand	10.8 MW

Concentration of methane in ventilation air is available by on site measuring system. Figure (1) shows the variation of methane concentration in ventilation air flow during 7 months.

According to this figure, the higher peak and average value of methane concentration are measured around 0.25% and 0.18% respectively. It is clear that, the concentration of methane in ventilation air is not sufficient for burning in combustion chamber of lean-burn gas turbine. Therefore, mixing of certain amount of drainage gas will be required to improve the level of methane concentration up to 1.6%.

Schematic of energy recovery system which may be used for methane recovery in Tabas coal mine is depicted in figure (2). According to this figure, ventilation air and drainage gas are mixed together in the mixer storage and with suitable concentration will be fed into the lean-burn gas turbine. It may be possible to use remainder amount of drainage gas in a gas engine for generating excess electricity.

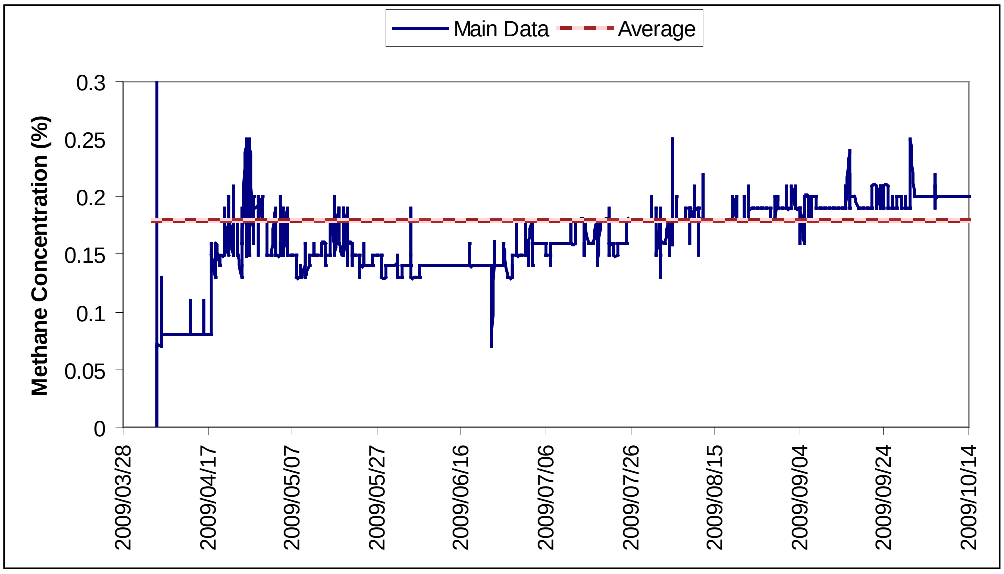

Fig. 1 Variation of methane concentration of ventilation air in Tabas mine

2.2. Methodology

The simulation model has been found on the theoretical principles of first and second lows of thermodynamics and it has been tailored to identify the design condition of specified energy recovery system for power generation in Tabas coal mine. To this aim, HYSYS simulator is used. Simulated framework of the energy recovery system in Tabas coal mine is represented in figure (3). While, the methane concentration of ventilation air of Tabas mine is very low, total amount of drainage gas should be consumed for generating power in lean-burn gas turbine cycle. Therefore, no gas engine will be required for excess power generation. Physical properties of streams are approximated by the Peng-Robinson equation of state formula through developing simulation model by HYSYS software [9].

3. Results and Discussions

The aforementioned simulation model has been applied for performance analysis of the energy recovery system and estimation total generated power form the energy recovery system in Tabas coal mine. According to represented results in table (2), 6.193 MW power can be generated by the energy recovery system. The thermal efficiency of the cycle is obtained at 24.74% because of low concentration of methane in the inlet feed of combustion chamber of lean-burn gas turbine.

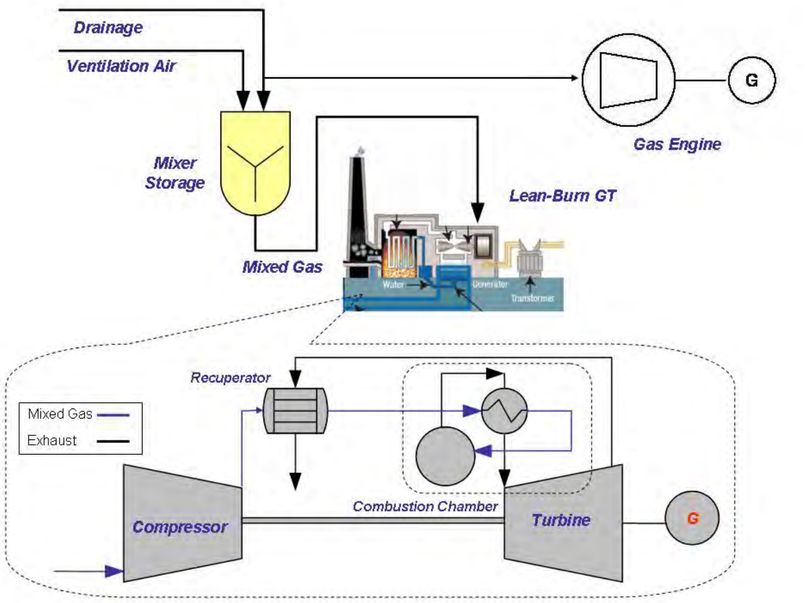

Fig. 2 schematic of energy recovery system in coal mine

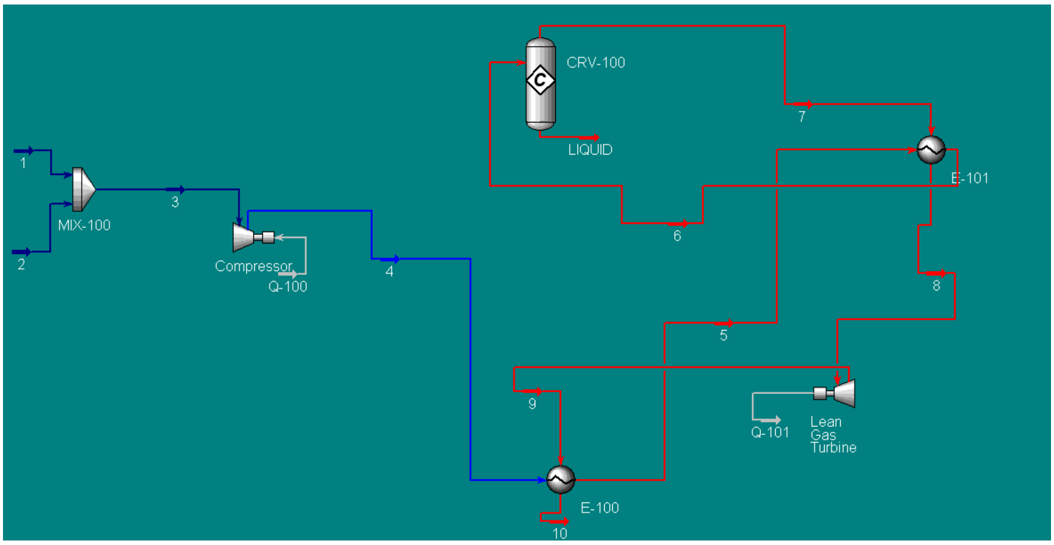

Fig. 3 Simulated frame work of energy recovery system in HYSYS simulator

Table2. Simulation results

Turbine power generated (MW)	12.60
Compressor power consumed (MW)	6.407
Net power generated by cycle (MW)	6.193
Thermal efficiency of cycle (%)	24.74
Usage percentage of ventilation air (%)	54
Usage percentage of drainage gas (%)	100

According to simulation results, physical properties and flow rate of streams are represented in table (3). Also, compositions of main streams are reported in table (4).

Table3. Physical properties and flow rate of streams

Line	1	2	3	4	5
Temperature(C)	50	25	25.57	139.3	352
Pressure(kPa)	150	150	150	400	350
Flow(kg/h)	2503	194000	196503	196503	196503
Line	6	7	8	9	10
Temperature(C)	773.5	1137	738.1	538.5	334.5
Pressure(kPa)	300	300	297	106	100
Flow(kg/h)	196503	196503	196503	196503	196503

Table4. Composition of main streams

(Mole Fraction)	**1**	**2**	**3**	**7**	**8**	**10**
Oxygen	0.006	0.2116	0.2078	0.176	0.176	0.177
Nitrogen	0.16	0.7766	0.7651	0.7651	0.7651	0.764
Ethane	0.020	0	0.0004	0.0004	0.0004	0.0003
H_2O	0	0	0	0.0317	0.0317	0.0317
CO_2	0.048	0.010	0.0107	0.0266	0.0266	0.0263
CH_4	0.765	0.0018	0.0160	0.0002	0.0002	0.0002

Figure (4-a) shows variation of the thermal efficiency with the compression ratio. It is clear that the thermal efficiency will be increased with increasing of compression ratio in compressor. It can be observed in this figure that, the thermal efficiency of cycle reaches to its maximum point at each selected value of compression ratio by increasing methane concentration in inlet fuel mixture of lean-burn gas turbine. As shown in figure (4-b), increasing of the compression ratio is accompanied with increasing of the methane concentration in the intake feed at each turbine inlet temperature (TIT). However, it can be observed from combination of figure (4-a) and (4-b), at the same pressure ratio, higher thermal efficiency may be obtained at higher TIT and higher concentration of methane.

4. Conclusion

The objective of this research work has been to introduce an energy recovery system for power generation from coal bed gas of Tabas coal mine of Iran. With the aim of developing more efficient, cost-effective technologies for mitigating and utilizing the diluted coal mine, this paper studied a novel energy recovery system, which can be powered with about 1.6 % methane (volume) in intake mixture. The results indicate that, the methane concentration of ventilation air and also temporal availability of drainage gas should be considered as main factors for developing any power generation system in a coal mine. Based on the obtained results from simulation, 6.193 MW power may be generated from coal bed gas recovery in Tabas coal mine. Therefore, 57% of total electricity demand of the mine can be supplied by the on-site power generation in this mine. If electricity unit price is considered as 0.09 \$/kWh and with purposing total capital investment around 6.7 millions dollars including lean-burn gas turbine, ventilation fan, drainage fan, mixer and piping, internal rate of ratio (IRR) and net present value (NPV) of project may be estimated at 41% and 14.6 millions dollars respectively and its economical feasibility will be supported.

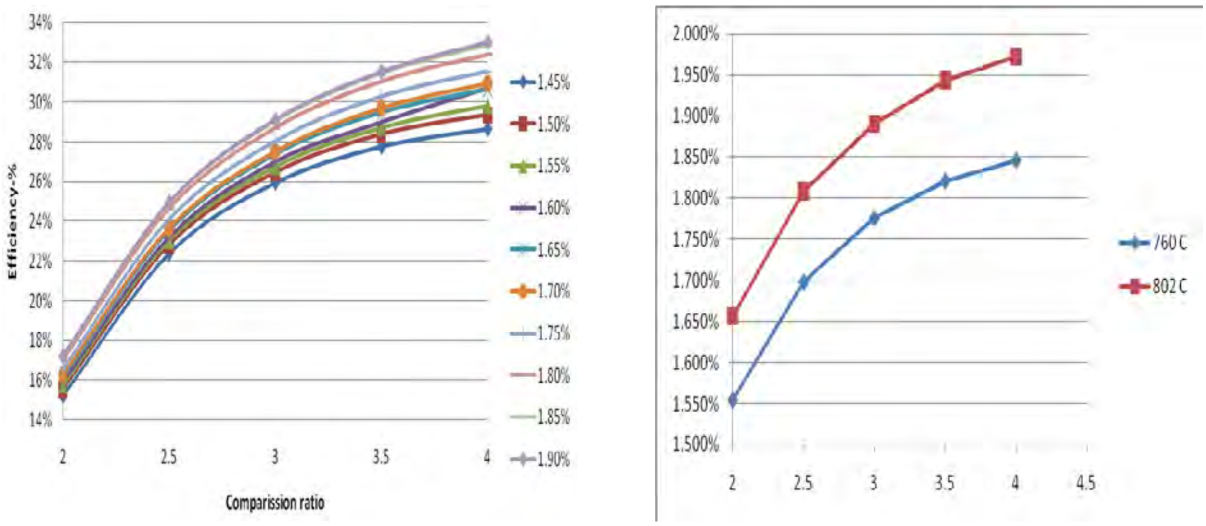

Fig. 4: a) Variation of thermal efficiency with compression ratio b) variation of TIT with compression ratio and different methane concentration

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Possibilities and problems in using exergy expressions in process integration

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Abstract: Industrial energy systems are complicated networks, where changes in one process influence its neighboring processes. Saving energy in one unit does not necessarily lead to energy savings for the total system. A study has been carried out on the possibility to use the exergy concept in the analysis of industrial energy systems. The exergy concept defines the quality of an amount of energy in relation to its surrounding, expressing the part that could be converted into work. The study consists of literature studies and general evaluations, an extensive case study and an interview study. In the latter it was found that non technical factors are major obstacles to the introduction of exergy.

Keywords: *Energy efficiency, Exergy, Process integration, User acceptance, Industrial energy system*

1. Introduction

1.1. The need and development of process integration in Swedish industry

Energy use in Swedish industry amounts to more than 40% of the national energy use. The three most energy-intensive industrial branches in Sweden, pulp and paper, iron and steel and chemical industries use more than two thirds of industrial energy use. Over the years a large effort has been made to increase industrial energy efficiency. This includes measures to increase energy efficiency as well as increased use of excess energy in other branches, e.g. for heat and electricity generation.

One problem is that industrial energy systems are complicated networks where changes in one process, influence its neighboring processes. Thus saving energy in one unit does not necessarily lead to an energy saving for the whole system. A system approach is needed to avoid sub optimization. One early attempt to make a more systematic analysis of this type of problems, the Pinch analysis, was made at Manchester University [1] during the 1970s. A method, pinch analysis, was developed, where the heat-carrying media are categorized as either cold streams (media that are heated during the process) or hot streams (media that are cooled down during the process). They are then added to one hot and one cold stream. The system could be characterized by the point where the composite streams are closest to each other, the pinch point. Exergy analysis [2] and mathematical programming, e.g. the MIND method [3], have been developed for industrial energy system studies starting in the 1980s. A national program to support research, development and use of process integration in Sweden was initiated and financed in cooperation between the Swedish Energy Agency and the Swedish energy-intensive industry [4],[5]. It started 1997 and ended in 2010.

The energy systems of the steel industry are characterized by large high temperature flows of molten solid and gaseous materials, as well as energy intensive chemical reactions. Mathematical programming was considered most suitable for that type of system. A methodology, reMIND, was developed and implemented for practical steel plant use (ref [6]-

[9]). Based on successful industrial applications three research supporting agencies and a group of Scandinavian steel- and mining companies decided to start and finance an excellence center for process integration in the steel industry, PRISMA which is located at Swerea MEFOS AB in Luleå.

The national program focused on three process integration technologies: Pinch analysis, mathematical programming and exergy analysis. When the work was summarized, it was seen that the main part of research was on mathematical programming and pinch analysis, whereas only a very limited work was made on exergy studies. Considering this, the Process Integration Program of the Swedish Energy Agency has supported a special study on the usefulness of the exergy concept, as well as its limitations and obstacles to future use.

1.2. What is exergy?

Energy balances are a common tool in technical energy studies. In these balances energy input equals energy output. This is based on the first law of thermodynamics: energy can neither be destroyed nor be created. The balances also include energy losses. The lost energy has not disappeared; it is converted into a practically useless flow of low-value energy, e.g. used cooling water or waste gas. This indicates the need of a way to describe also the quality of energy flows. The exergy concept defines the quality of an amount of energy in relation to its surrounding, expressing the part that can be converted into work. It is based on the second law of thermodynamics: the entropy of an isolated system never decreases. A certain media can produce work only if there is a difference e.g. in temperature and pressure versus the surrounding. The exergy expression describes the theoretically possible production of work as a function of that difference:

$$E = \Delta H - T_0 * \Delta S \tag{1}$$

Where E = exergy, H = enthalpy, S = entropy, ΔH and ΔS are differences from the reference state (the surroundings) and T_0 = the absolute temperature at the reference state.

For a non compressible liquid or solid with constant specific heat the entropy difference can be calculated as

$$\Delta S = m * c_p * \ln\left(\frac{T}{T_0}\right) \tag{2}$$

And for an ideal gas as

$$\Delta S = m * \left(c_p * \ln\left(\frac{T}{T_0}\right) + R * \ln\left(\frac{p_0}{p}\right)\right) \tag{3}$$

Where m and c_p are mass and specific heat, T and p are absolute temperature and pressure of the substance and T_0 and p_0 are temperature and pressure at the reference state.

1.3. Scope of paper

The main scope is to improve the knowledge of when and how exergy analysis is useful on its own or in combination with other methods and methodologies, as well as on the improvements needed to increase the use of exergy analysis in process integration projects. It was considered important to cover both technical and nontechnical limitations to an improved use. The work was structured in the following parts: literature study, analysis, interview study, case study and synthesis.

2. Methodology

The study was carried out in five steps

Step 1. A literature study with the aim to provide an overview on the utilization and advantages of the exergy analysis method in several systems, especially in industrial ones.

Step 2. An analysis where literature data and experience of the project partners were used to define subsystems where exergy can be used as well as identifying problems and unanswered questions.

Step 3. An interview study with the aim to find the reasons why Exergy was used or not used by different actors. The method was based on a combination of in-depth, semi-structured interviews and a more straight-forward questionnaire [10]. Both technical and non-technical aspects were studied. The questions were formulated using the results of the analysis study

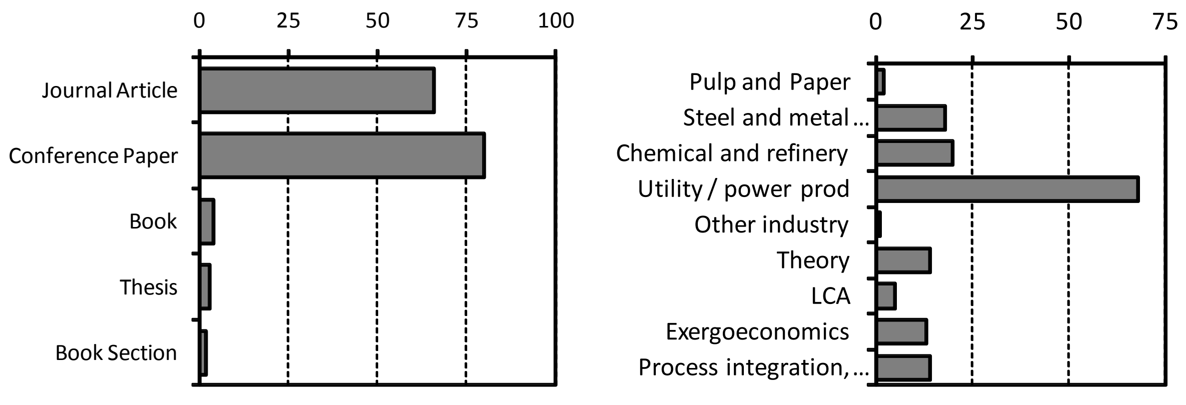
Step 4. A case study to demonstrate the practical application on an industrial system. The case chosen was the Luleå Energy: The SSAB steel plant, CHP (combined heat and power plant) and district heating. Collected production data were used for exergy calculations both for the total system and some subsystems

Step 5. A synthesis based on the results from step 1-4 with the aim to answer the following questions: Which criteria for comparison should be used? Should the methodology be used in combination with other methods? Should there be increased dissemination? When should the exergy concept be used? Is exergy research worthwhile? Could the formulation of the exergy concept be explained in a better way? When should the exergy concept and exergy studies be used? Is there a need for exergy research

3. Results

3.1. Literature study

155 references were included, and 115 of these were described in some detail. The distribution between publication categories is illustrated in Fig. 1 a. The main part of material is distributed almost evenly between journal and conference publications.



a) Category of publication *b) Subject of publication*

Fig. 1 Distribution of literature references between publication types and subjects. The diagrams show the number of references per category

The collected references described the use in different industrial branches and for specific equipment, some more sophisticated uses, e.g. in LCA or exergoecoonomics, as well as some general studies. The distribution between these subjects is illustrated

The use is relatively small in the pulp and paper industry. The reason is probably that the transport and exchange of thermal energy is a dominant part of the energy system, which gives a preference for pinch analysis. A higher frequency of references is shown for steel and chemical industry where chemical reactions and energies are important. The power industry and utilities show the highest frequency in Fig. 1 b. A reason can be that components like boilers, turbines, valves and heat exchangers usually entail large exergy destruction rates. The solutions proposed to minimize these losses are often to change operation parameters or to install new equipment with different operating characteristics. The most common action proposed to increase exergy efficiency is to decrease the temperature difference in heat transfer equipment. Since this decreases the driving force, investment costs are likely to increase.

In a system of nodes and streams, exergy analysis is applied to the efficiency of nodes. This can lead to more capital-intensive suggestions e.g. change of process technology.

Several authors suggest using combined pinch and exergy analysis to achieve better results. Pinch analysis could be used to determine minimum cooling and heating demands, thereafter exergy analysis could be used to detect inefficiencies. Finally, the design capabilities of pinch analysis could be used to synthesize a heat exchanger network.

3.2. Analysis

The usefulness of the Exergy concept was analyzed separately in pulp and paper, steel industry, mining industry, cement industry, use for electricity generation and for regional cooperation. The result varied between branches. Two interesting uses can be: energy quality to compare subsystems and recovering excess energies. Presently there is a lack of comparison data. Creating a BAT (Best Available Technology) database for energy efficiency and exergy destruction could be interesting. This study also produced parameters for the interview study

3.3. Interview study

The aim was to observe the effect of technical and non-technical factors which were of great importance for the introduction of exergy studies as well as for failure or success in the application. The interview form consisted of an interview part where questions were answered in words and a short questionnaire part, where the respondents could rank different obstacles to each other. Fig. 2 illustrates the weighted summary of important obstacles in the questionnaire part. The most important factor seems to be the lack of strategy. Points like lack of time, priorities, lack of capital and slim organization got a low priority. A comment when these points were discussed was: “When we get the job to make an energy analysis the priority is always very high, so those limitations (to the use of exergy analysis, author’s remark) are not relevant”.

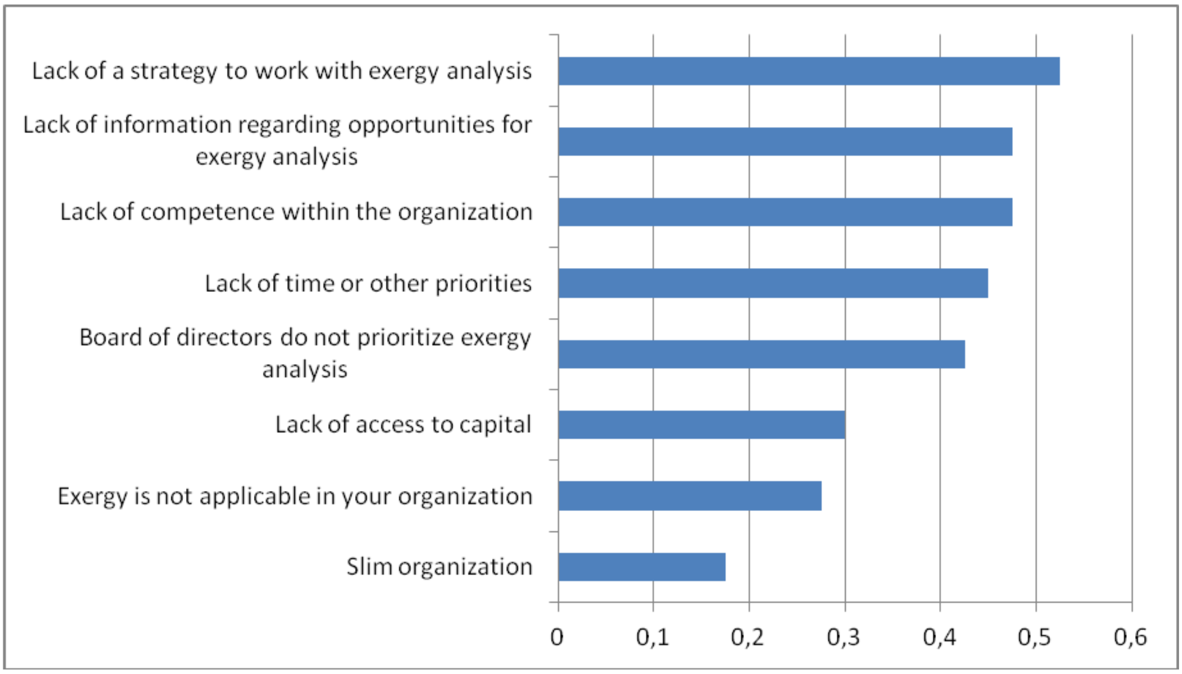


Fig. 2 Weighted summary of obstacles for exergy analysis. Often important =1, sometimes important =0.5, seldom Important = 0.

The answers to the in-depth interview questions indicated that one reason for the low rate of applications of exergy analysis is that most missions in the industry, according to respondents, do not require this type of tool, e.g. studies for small and medium-sized businesses. Only about 600 of 59 000 manufacturing companies in Sweden are defined as energy-intensive. This can be linked to the obstacles heterogeneity, i.e. the method is not considered by respondents to be applicable in most industries. One reason for the low level of potential applications, however, seems to be that several respondents felt that exergy was difficult to use. One conclusion from this is that the development of software for exergy could promote its use. The major obstacle to exergy analysis that was detected in the interview study was heterogeneity in the technical system level and information imperfections and asymmetries in the socio-technical systems level. (The heterogeneity refers to the fact that different companies have differing conditions for the use of exergy. Imperfections refer to lack of sufficient information and asymmetry to differences in information between different actors.) The highest ranked obstacle to the use of exergy analysis was a lack of strategy. This can be linked to one respondent who indicated that exergy often competes with cost analysis. One conclusion from this is that the tool should be competitive in the analysis of large technical systems where it can be used as decision support for industries or society.

3.4. Case study

The case study was made for the Luleå energy system. Existing data for the steel plant site, see ref [11] were extended by data collected from the CHP plant and District heating network.

An example of Sankey diagrams showing energy and exergy flows from the SSAB study 2005 is shown in Fig. 3. In the energy diagram for the blast furnace there is an energy input of 100%, whereas the output is 86.7 % export and 13.3 % losses. The sum of input flows is equal to the sum of the output flows because energy is indestructible according to the first law of thermodynamics. If we instead look at the exergy diagram, both the export and the heat loss flows are lower because the energy consists of energy forms of lower exergy value. Also the output exergy is lower than the input exergy. The difference is irreversibly destroyed and corresponds to the entropy increase.

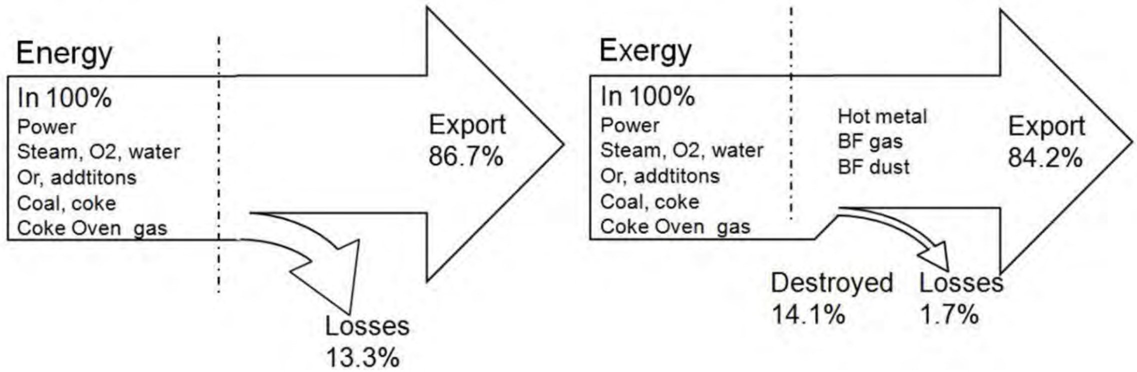


Fig. 3 SSAB Study 2005, Example on Energy-Exergy Diagrams for the blast furnace [12].

The destroyed exergy is a measure of the inefficiency of the unit in question. The heat loss exergy is a measure on the energy that could possibly be recovered.

Fig. 4 shows similar values for the heat and power plant. There are comparatively small heat loss flows, but a relatively high amount of destroyed exergy. The destruction rate is quite different between the units in Fig. 4. It is highest for the boiler and more moderate for the heat exchanger and turbine.

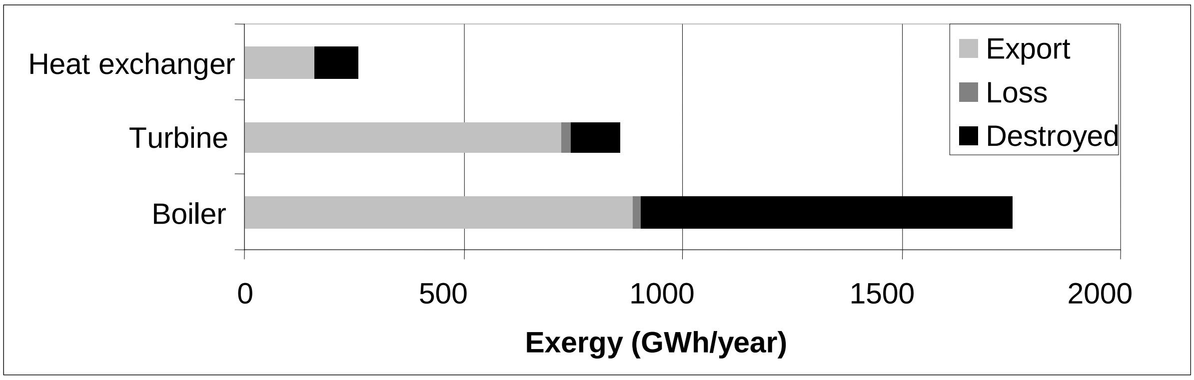


Fig. 4 Example on Exergy balances for the heat and power plant.

The reason for the higher destruction rate in the boiler is that it converts fuel energy (in principle 100% exergy) into high pressure steam with an exergy content that is roughly 50% of the enthalpy. It does not indicate a problem with the boiler; the boiler simply has a function where exergy destruction is inevitable. An important conclusion of this is that exergy destruction rate (or exergy efficiency) can be a tool to find out where to look. However, if it is to be used to judge bad or good function a reference value is needed. This could be previous data from the unit or published data. A catalogue for reference exergy data could perhaps be of interest.

Fig. 5 shows a Sankey diagram for the total system: Steel plant – Heat and power plant – District heating. The exergy in heat loss flows was relatively small in Fig. 3 but has increased when all steel plant units are increased. This flow represents energy that theoretically could be recovered as higher forms. These results have initiated quantitative studies on recovery e.g. by ORC turbine It can be seen that the exergy is destroyed stepwise through the system. The low amount of exergy in the district heating indicates that a large amount of energy sent to users with a low exergy demand. This can be a potential use for energy recovery from the steel plant. This can be expected to produce media flows with low or moderate exergy content.

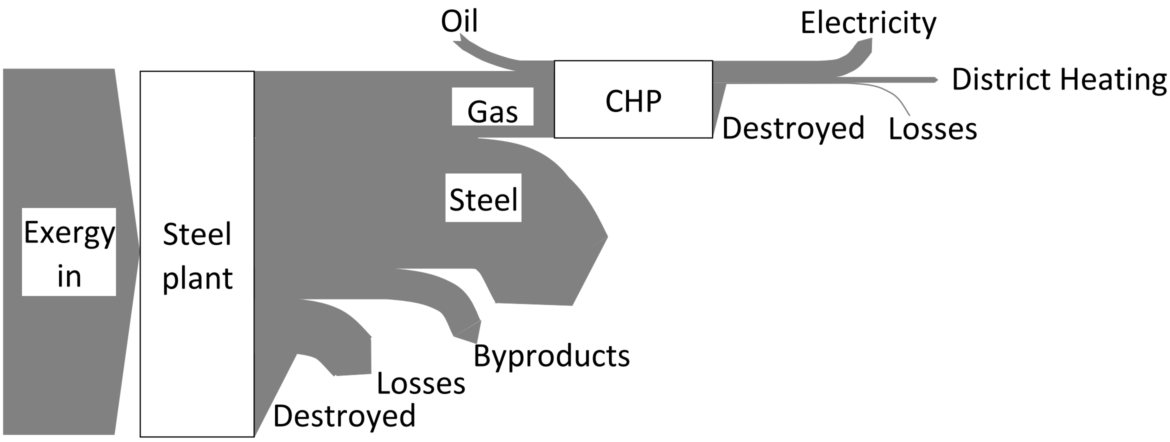


Fig. 5 Exergy flows through the total system

4. Synthesis, Discussion and Conclusions

In the project it was shown that:

- Exergy analysis is most competitive for industrial systems dominated by chemical conversions and energies other than thermal energies, e.g. chemical energy. Good examples are the steel industry and the chemical industry, especially refineries. Another important use is systems with different pressures and where production of electricity is of interest.
- Exergy expressions can be used to study process efficiency, possible modifications and mapping possibilities for excess energy recovery.
- Relatively much exergy is used for heating with a low need for exergy, compare Fig. 5. A study to decrease the imbalance using a modified system temperature is planned. Variations in the hot water balance for district heating are also influencing the energy efficiency.
- It is probably better to use a combination of Process integration methods than to only focus on one.
- Inclusion of exergy calculations in the mathematical programming tool reMIND was explored in the case study [15]. Continued work is interesting.
- Non-technical factors are responsible for the slow adoption of exergy analysis, e.g. lack of strategy, heterogeneity, information imperfections and asymmetries.
- The interview study has given an insight into the effect of non-technical parameters. The present technique has a relatively broad spectrum of questions which gives a good result even with a limited amount of respondents.
- Exergy studies are becoming established for system studies in the steel industry. Extension to further sites is being planned.
- A catalogue of reference data would be of interest for better interpretation of results

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Exergy Analysis applied to a Mexican flavor industry that uses liquefied petroleum gas as a primary energy source

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Abstract: An exergy analysis to a Mexican flavor industry, which uses liquefied petroleum gas as a primary energy fuel in their process equipment was carried out. .
The analysis used a proposed method that quantifies efficiency by means of exergetic indicators. To apply it to this case study equipment, the system or process was assumed to be a block that interacts with the surroundings in three ways: heat, work and mass transfer. The analyzed blocks were boilers, a thermal oxidizer, dryers, a distillation tower and extractors. Work and heat needs were covered by liquefied petroleum gas.
The exergy indicators quantify the degradation of energy by determinining the difference between the actual operation efficiency of the block and the maximum operation, both of them obtained from second law point of view. These indicators were exergy loss, efficiency, effectiveness, performance and potential of improvement.
Following the exergetic method application, it was found that the indicators of the effectiveness and performance in all blocks analyzed are near zero. This means that the process equipments are using a high exergy source to perform their function and also in large quantity. The results show that the oxidizer presented the major irreversibilities, and it is the equipment with the greatest potential for improvement and the key to reducing fuel consumption.

Keywords: *Optimization, Efficiency, Indicators, Block, Quantify*

Nomenclature

Latin Symbols

Efl *effluents exergy losses* .... *kJ/kg*
Ex *exergy* .... *kJ/kg*
H *enthalpy* .... *kJ/kg*
Irr *Irreversible exergy losses* .... *kJ/kg*
S *entropy* .... *kJ/kg K*
Pot *Improvement potential* .... *kJ/kg*

Greek symbols

ε *Effectiveness* ....
ζ *Performance* ....
η *Efficiency* ....
Δ *difference*

Subscripts

ntp *net produced* ....
nts *net supplied* ....
tte *total input* ....
tts *total output*
uts *useful outlet exergy*
0 *reference, dead state*

1. Introduction

The industry sector is sensitive to the variability of the energy prices; as a result it adjusts the production priority to an efficient energy consumption to obtain advantages in cost. The economic factor is not the only reason to reach an efficient energy consumption in a country. The environmental negative impact as a result of an inefficient use of an energy resource is important as well [1,2].

Efficient energy use in the industry sector is possible with energy consumption analysis. Two problems promptly arise: the scarce information about an optimum use of energy in the industrial processes and the use of inefficient technology. [3,4].

The exergy analysis is especially useful when it is necessary to detect equipment, systems or processes that use a high quality energy source that is unnecessary for the objective, because in this case important exergy losses arise [3]. Exergy analysis has been applied since the early 1970's with the aim of finding the most rational use of energy, which means at the same time reducing fossil fuel consumption, applying energy efficiency and matching the quality levels of the energy supplied and demanded [5]. The exergy method is useful for improving the efficiency of energy-resource use, for it quantifies the locations, types and magnitudes of wastes and losses. Also it is useful in identifying the causes, locations and magnitudes of process inefficiencies [6].

This paper discusses an exergy analysis of a flavoring industry plant (FIP) located in Morelos, Mexico. The monitoring of energy utilization of different equipments used in the process was necessary in order to investigate, analyze, verify and compare the data so as to try to understand the actual condition. The monitoring and data collection lasted from March to December, 2009. Table 1 shows the analyzed equipment:

Table 1. Identify and capacity of the analyzed equipment.

Identification	Capacity	Units
Distillation column A-001	700	l
Distillation column A-002	700	l
Distillation column A-004	70	l
Distillation column A-009	1900	l
Extractor A-103	2734	l
Extractor A-104	2734	l
Extractor A-106	7570	l
Extractor A-107	7570	l
Dryer S-01	30	kg/h
Dryer S-02	40	kg/h
Dryer S-03	150	kg/h
Dryer S-05	100	kg/h
Boiler CA-01	250	hp(S)
Boiler CA-02	100	hp(S)
Oxidizer		

l: liters, kg/h: kilograms per hour, hp(S) Boiler horsepower

These five kinds of equipments have the following function in the FIP:

- *Distillation column*: To separate mixtures based on differences in their volatilities in a boiling liquid mixture.
- *Extractor*: To separate a substance from a matrix. In the case of the FIP we refer to solid phase extraction.
- *Dryers*: To eliminate the liquid in a substance. The powder production starts by atomizing the emulsion in a hot air stream inside the dryer chamber in which the liquids evaporate instantly. The active material in the emulsion is encapsulated inside the film material.
- *Boiler*: To generate steam with the liquefied petroleum gas (LPG) combustion. The liquid water changes to vapor phase due to the high temperatures obtained.

2. Methodology of exergetic analysis

Exergy is defined as the maximum theoretical work obtainable from the interaction of a system with its environment until the equilibrium state between both is reached [7], it can also be seen as the departure state of one system from that of the reference environment [8]. Therefore, exergy is a thermodynamic potential dependent on the state of the system under analysis and its surrounding environment, so called “reference state”. The environment is regarded as a part of the system surroundings, large in extent so that no changes in its intensive properties, pressure P_0 and temperature T_0 mainly, occur as a result of the interaction with the system considered.

The exergy method quantifies the energy degradation using six different indicators. We assume the equipment, system or process to be a block that is interacting with the surroundings through heat, work and mass transfer. The work and the heat refer to the energy such as electricity solar radiation, mechanic work, etc. The mass transfer is the inflow and outflow of chemical substance, flows like vapor and fuel [9]. In the analyzer equipments in the flavor industry, the required work and heat are provided by LPG.

The exergy is the quality of energy in the block and is defined as:

$$Ex = (H - H_0) - [T_0(S - S_0)] \tag{1}$$

In Eq (1), the first term is the total enthalpy of the system that includes the thermal, mechanical, chemiscal, kinetic and potential energy. The second term, on the right -hand side, is the total entropy. The enthalpy (H_0) and entropy (S_0) of the reference state are defined by its pressure, composition, velocity, position and temperature.

2.1. Exergetic indicators

In order to quantify the energy degradation of the block, a series of exergy indicators were used. These indicators were: exergy losses (Irr), efficiency (*η*), effectiveness (*ε*), performance (*ζ*), potential of improvement (*Pot*). These are the relationship between the reality and the ideality expressed by fraction or percentage [4]. Table 2 shows the corresponding indicators:

Table2. Exergetic indicators to quantify the energy.

Exergy indicator	Equation
Exergy losses	$Irr = \sum(Ex_{tte} - Ex_{tts})$
Efficiency	$\eta = \frac{\sum Ex_{tts}}{\sum Ex_{tte}}$
Effectiveness	$\varepsilon = \frac{Ex_{ntp}}{Ex_{nts}}$
Performance	$\zeta = \frac{Ex_{uts}}{Ex_{tte}}$
Potential improvement	$Pot = Irr(1-\varepsilon) + Efl$

Below is a brief explanation of each indicator:

- *Exergy losses.* The measure of the total exergy provided by the inflow such as fuel and raw material, and the total exergy at the outlet such as products and effluents.
- *Efficiency.* The ratio of the total exergy at the outlet of the block in relation to the total exergy of the inlet.
- *Effectiveness.* It evaluates if the analyzed block satisfies its function, considering the term “net” means difference (Δ). The net exergy produced is the one obtained by the products and the net exergy supplied is provided by the energy resource, for instance LPG.
- *Performance.* Relation of the useful outlet exergy and total entrance exergy.

- *Potential improvement.* It is the measurement of block improvement. The equation has been obtained through the combination by exergy losses and the system effectiveness. The exergy losses are due to two different sources, the first one derives from the internal use of the block and is referred to as irreversibilities (Irr) and the last one arises from the effluents (Efl), that are released into the environment like wastes.

To obtain the reference temperature, the actual hourly temperature in the process plant was registered for a week. The value was 29.3 ºC±1.9°C. The pressure was considered constant at 101.325 kPa.

2.2. Blocks

As mentioned in the introduction, five different equipments were analyzed. The exergetic balance of each equipment was different and depended on the way that it operated, the energy quantities they require, and the energy wasted in irreversibilities, so it was necessary to consider an exergetic balance for each case.

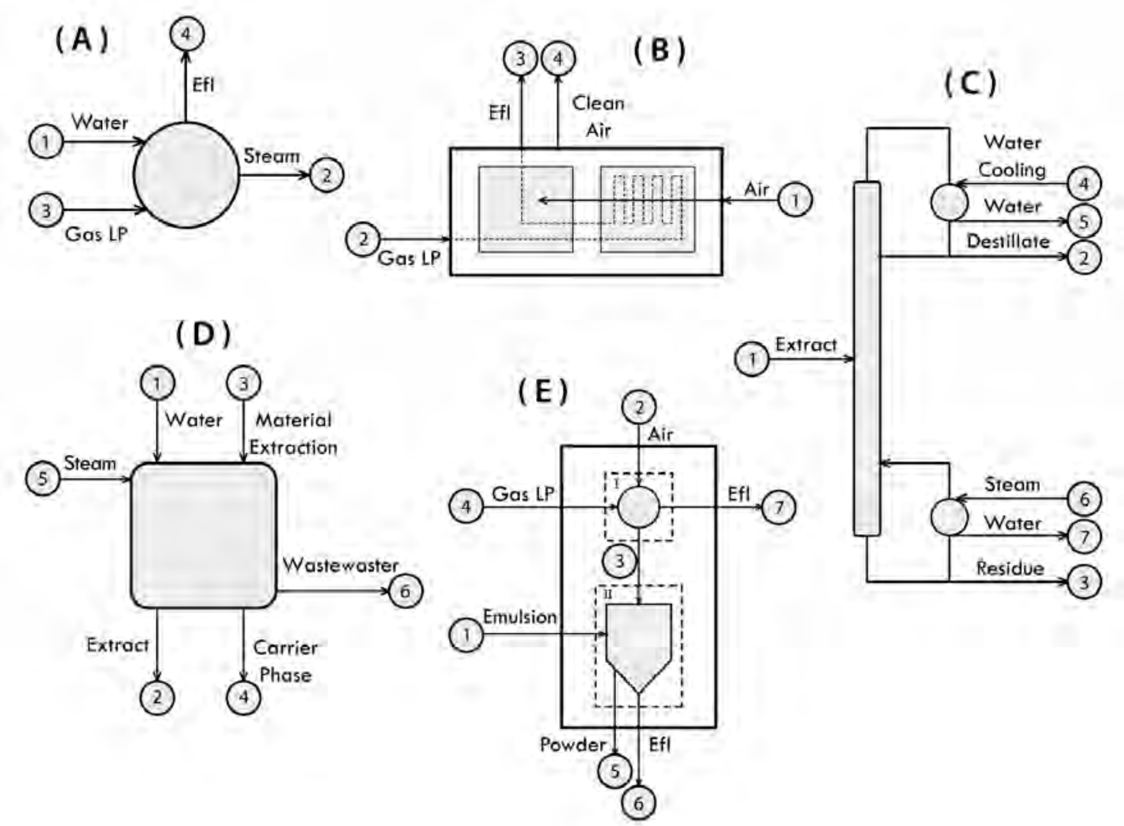

Fig. 1. Diagrams of the blocks. Boiler (A), Oxidizer (B), Distillation tower (C), Extractor (D) and Dryer (E)

Figure 1 shows the diagrams of the different blocks to be analyzed. The numbers represent the process streams of each case. When the arrows point inwards, it refers to the stream with the exergy that enters the equipment; it could be fuel, vapor or fluid. Conversely, when the arrow points outwards, it refers to the stream with the exergy that goes to the environment, such as products, effluents or wastes. Table 3 shows all the exergetic balances obtained for the blocks.

Table 3. Exergetic balance

Block	Ex_{tte}	Ex_{tts}	Ex_{nts}	Ex_{ntp}
Distillation tower	$Ex_1 + Ex_4 + Ex_6$	$Ex_2 + Ex_3 + Ex_5 + Ex_7$	$(Ex_6 - Ex_7) + [Ex_1 - (Ex_2 + Ex_3)] + (Ex_4 - Ex_5)$	$(Ex_2 + Ex_3) - Ex_1$
Extractor	$Ex_1 + Ex_3 + Ex_5$	$Ex_5 + Ex_4 + Ex_6$	$Ex_5 - Ex_6$	$(Ex_2 + Ex_4) - (Ex_1 + Ex_3)$
Dryer	$Ex_1 + Ex_2 + Ex_4$	$Ex_5 + Ex_6 + Ex_7$	$Ex_4 - Ex_7$	$Ex_5 - Ex_1$
Boiler	$Ex_1 + Ex_3$	$Ex_2 + Ex_4$	$Ex_3 - Ex_4$	$Ex_2 - Ex_1$
Oxidizer	$Ex_1 + Ex_2$	$Ex_3 + Ex_4$	$Ex_2 - Ex_3$	$Ex_4 - Ex_1$

Finally, with the exergy balance of each block it is necessary to calculate the exergetic indicators with the equations presented in Table 2.

3. Results

The values of the indicators in all the equipments studied were plotted with the objective of analyzing and comparing the behavior in the FIP.

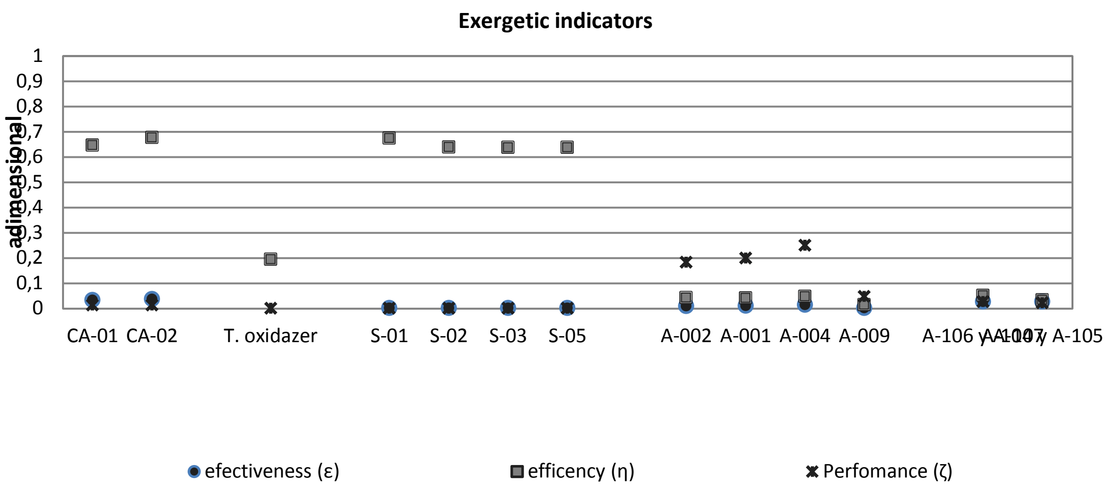

Fig. 2. Effectiveness, efficiency, performance of the analyzer blocks in the FIP

Figure 2 presents the dimensionless indicators: the effectiveness, efficiency and performance. The effectiveness is near a zero value in all the blocks as a consequence of the important quantity of exergy required to carry out their objective. This happens commonly with old equipment where the design does not have priority on saving fuel. The performance is larger in the distillation columns 0,2 to 0,3 because they do not require high temperatures for their function and the effluents are smaller than in others blocks. The efficiency of the combustion equipment is estimated at 0.7 which shows a large amount of effluent in the total output exergy, with up to 65% of exergy provided by the LPG thrown into the atmosphere as combustion gases.

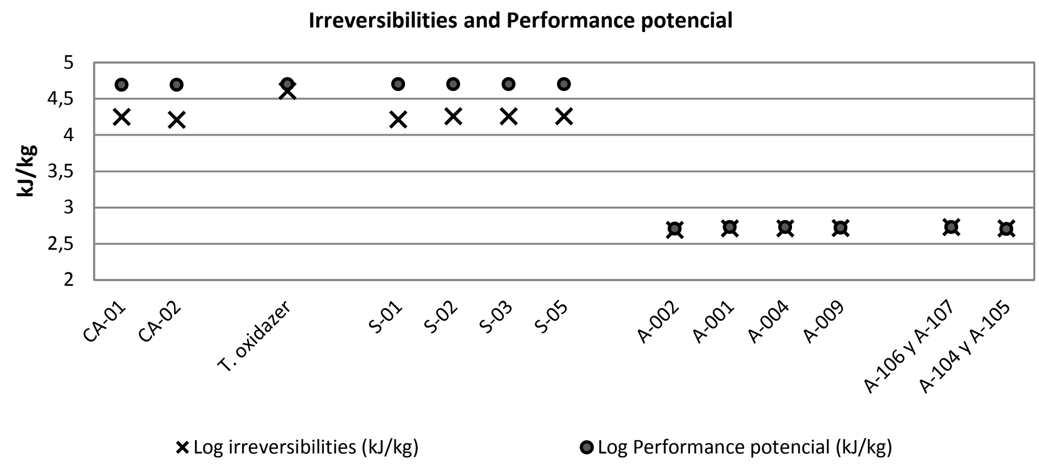

Fig. 3. Irreversibility and improvement potential of the analyzer blocks in the FIP

In Figure 3, the distillations columns and extractors present similar improvement potential values and irreversibilities due to the fact that the effluents are insignificant, a slight flow of water between 60°C to 80°C from the steam used to obtain the process temperature circulating in the insulation of the equipments. In contrast in the combustion equipment their improvement potential is higher than the irreversibbilities because of the large quantity of effluents, 33000 kJ/kg. These blocks have an important feasibility of optimization, by recovering heat from the effluents to preheat the water used in the boiler.

As a result of the method, the global exergy flow of the plant can be represented with a Sankey diagram; this diagram is a summary of the exergy analysis of all equipments of the FIP. The width of the arrow gives the flow, specifies the effluents (arrows pointing upwards), irreversibilities (arrows pointing downwards) and the net exergy produced (arrows pointing to the right), the numbers outside the arrows in parenthesis describe the percentage of the total exergy in the FIP, and the numbers inside the blocks in parenthesis describe the quantity of equipment that represents each block. The indicators represent a specific aspect of the equipment and the Sankey diagram the interaction of all the blocks in the FIP. In Figure 4, an expansion in scale from the steam of the oulet of the boilers to the inlet of the extractors and distillation tower was necessary, because only the 0.35% is the net produced exergy as steam.

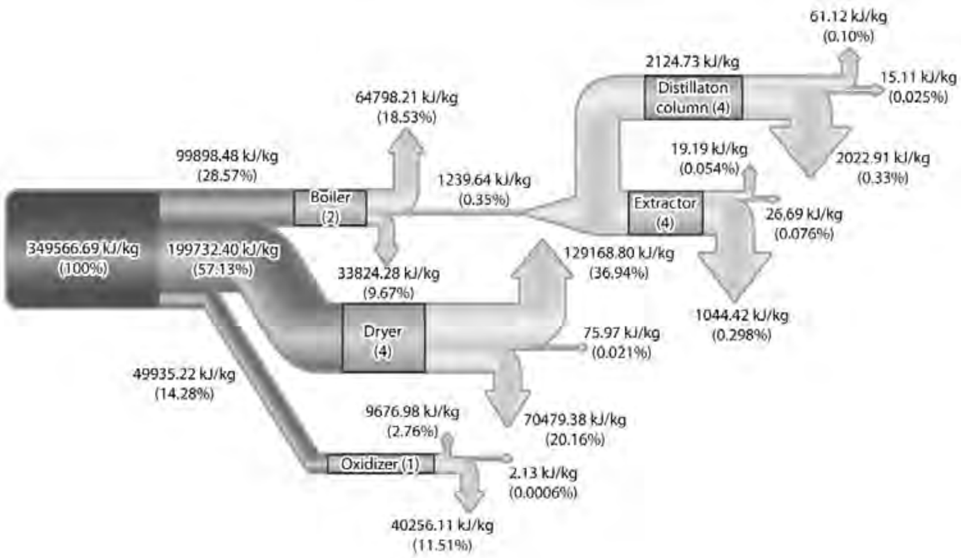

Fig. 4. Sankey diagram for the global exergy flow in a FIP

The diagram shows that the exergy provided by the LPG energy source is 349,566 kJ/kg, and is distributed to the process blocks. Over half of the exergy 57.1% is used for the driying process in which only 0.021% of the net exergy produced is obtained as powder.

The distillation columns and extractors have small effluents of approximately 20 kJ/kg per equipment, compared with the combustions blocks with 33000 kJ/kg. On the other hand. they have more important irreversibilities, as compared to the combustion blocks. To optimize these equipments it is necessary to analyze how they operate and find an improvement in their design. [10].

4. Conclusions

In this paper a second law analysis in a flavor industry was carried out. The process blocks with higher efficiency, close to 0.7, were the boilers and the dryers. This is to the fact that the total output exergy includes the effluents, that represent 90% of the total of the exergy that is provided by the fuel.

The thermal oxidizer does not present important losses in effluents (9,676.98 kJ/kg), but its irreversibilities are the largest with 40,256.11 kJ/kg and an effectiveness close to zero. As a result, this block has the highest performance potential 49,933.6 kJ/kg and is the main equipment in which to focus in order to achieve a low fuel consumption. It is possible to use other kind of equipment for the same objective (eliminates unpleasant odor) without using combustion.

The distillation towers and extractors present low effluents (20 kJ/kg) per equipment approximately as compare with combustion blocks (33,000 kJ/kg). This means that the energy is degraded in the distillation columns due to the presence of significant irreversibilities. To optimize these equipments it is necessary analyze their performance and find a design improvement, owing to the fact that they are more than 30 years old with no technological improvements. The best solution is to upgrade the equipments.

The indicators in all equipments such as efficiency, effectiveness, and performance are close to zero. This means that the FIP requires a high exergy source and a large quantity forcarried out its objective, approximately 350,000 kJ/kg. This consumption decrease at least 68% applying waste heat recovery of the effluents of the combustion equipments, like boilers, dryers and oxidizer, to warm currents in other processes such as in the extractors where the optimal temperature is 60 °C. [10].

5. Acknowledges

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Thermal cooling basin exploration for thermal calculations

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Abstract: There are a number of cooling systems known across the world. For decades they have undergone development, changing coolants and their chemical composition, but water has, thanks to its universal properties, remained an undying presence in this technology. Water is used as a carrier heat or cold for cooling spaces and some cooling equipment itself, for accumulating and radiating heat to an environment with lower heat potential, for heat evaporation, and as a solvent which is great at dissolving substances we know as cooling agents.

Pools are an especially practical and aesthetically appealing execution of a co oling system – provided appropriate temperature modes and external air temperature during the operational season. In centralised heat supply conditions, heat production companies choose to install cogeneration engines to increase energy production efficiency and profitability, allowing both electricity and heat to be produced from one type of fuel. However, the world at large has also seen trigeneration systems: such large urban areas as New York and Tokyo have long been using one type of fuel to produce electricity and, adjusting to weather patterns, either heat or cold energy. Of course, these enormous cities and their energy delivery patterns cannot be compared to those of small cities and rural towns which are common in the Baltic and CIS countries. Conversion of heat into cold energy takes place at heat absorption cooling facilities. Heat absorption facilities require a fluid overcooling cycle to store a concentrated fluid. The temperature modes of this cycle (which vary between producers) produce low-potential heat which cannot be reused to produce heat energy, e.g. 35-29*C. To support such a temperature schedule, producers generally recommend installing heat evaporation towers, but they are expensive and will often clash visually with the landscape. A cooling pool may be used instead for both practical and aesthetic reasons, using water sprayers to promote evaporation. Water spraying is necessary to increase the surface area of water-to-air contact: this way, the surface area is equal to the combined areas of all water droplets. The depth of a pool must be no less than 1.5 m, preventing heating by sun rays. Pool cooling properties improve with finer droplet size, although this carries higher electricity expenses to produce adequately high pressure before pulverisation. Such pools may use fountains which serve both as a cooling facility and an attractive landscaping piece. An evaporation pool is also significantly cheaper to build than an evaporation tower, although water loss may be higher.

In consideration of the facts described above, a pool with a water spraying device was built for this research project. With appropriate air temperature, pressure and relative humidity, heat yield and yield changes were measured.

The goal of this study was to compare the research and experimental parts of the project to similar studies performed previously, in order to determine the practical viability of using heat evaporation pools as well as to develop a complete prototype which may be used as the basis for building similar structures.

Keywords: *cooling systems, heat evaporation pools*

1. Introduction

Latvia is located in a climate region where heat is necessary not only for improving quality of life, but also as a prerequisite for survival during the winter, which lasts for about 200 calendar days. Therefore, heat supply is a particularly important part of Latvia's power industry, as evident from the fact that over 60% of the country's energy resource consumption goes into heating. Increasing the efficiency of heat supply, especially centralised heat supply, which provides 30% of the heat required within the country by households and technological facilities (the proportion of centralised heat supply in the housing sector exceeds 45%). Increasing the efficiency of centralised heat supply systems also has a d eciding role in ensuring the competitive ability of heat supply companies, which in turn is a requirement for using the possibilities and advantages of centralised heat supply systems. In the large part of country (one-third of the primary energy consumption) as the raw material for the energy production (including centralized heating) is used natural gas. It increases the dependence of the energy import and the energy purchase price. There is as a large potential of renewable energy in Latvia, it could be used in energy production, but in many cases necessary investment for communication shift are hardly to attract, that's way there musts be done everything to improve current centralised heat supply, to make maximum benefit for the energy supplier ad it's user.

2.1. Purpose of Introducing a Trigeneration System

One of the solutions for improving the efficiency of the centralised heat supply system might be introducing a trigeneration system in the centralised municipal heat supply system. Traditional producers of electricity produce electricity from fuel, such as fuel oil, diesel or natural gas, however this process is inefficient: it produces waste heat, which may be converted into various types of energy and put to use. At cogeneration facilities, this heat is used to supply nearby household or industrial demand. In case of trigeneration, fuel is used to produce electricity, heat, and, if necessary, convert the heat into cold energy, to be used for household or industrial cooling; additional heat is removed from smoke and gas before they are emitted into the atmosphere, producing additional heat for heating or cooling of spaces. Trigeneration systems in large urban areas as New York and Tokyo have long been using one type of fuel to produce electricity and, adjusting to weather patterns, either heat or cold energy, but it is a great challenge to adjust this system in areas that do not requires such great energy consumption.
Purpose of introducing a trigeneration system:

- Consumption of heat load during the summer period
- Economically advantageous conditions for using the heat source
- Constant loading of the cogeneration facility year-round
- Potential for reducing heat energy tariffs

The centralised heat supply system works according to a specific temperature schedule adapted to changes in external air temperature. The city boiler house works according to such a temperature schedule. The boiler house generally services not only tenement and private houses, but also office spaces, utility consumers and often production facilities interested in heat absorption capacities for their cooling equipment during the summer. There is no need for heating inside the city's residential spaces; the heat supply system works according to a 65-40°C temperature schedule (not Riga). The heat producer considers the issue of profitable heat carrier temperature during summer months – it is well known that with increased heat carrier temperature, heat carrier surface heat loss increases as well (the temperature schedule for trigeneration heat absorption equipment is 95-70°C). Here, one must consider the usefulness of maintaining adequate heat carrier temperature for heat absorption equipment, while at the same time providing the same temperature to tenement houses, which only use hot water. On the other hand, it is useful because cogeneration facilities may be operated at higher loads during the summer period. An assessment of issues related to introducing a trigeneration system must consider the possibility of dividing the heat supply network into primary and secondary circuits. This means that a heat source would produce heat both for delivering hot water to consumers during the summer period and for cooling spaces. The principal layout of a trigeneration system is shown in Figure No. 1. However, the following obstacles complicate the introduction of a trigeneration system:

- Heating network configuration must be adjusted
- A heat supply and temperature schedule must be specified for consumers
- Daily heat consumption patterns must be analysed
- Strategic choice of absorption equipment (centralised, decentralised)
- **Building an evaporation tower**

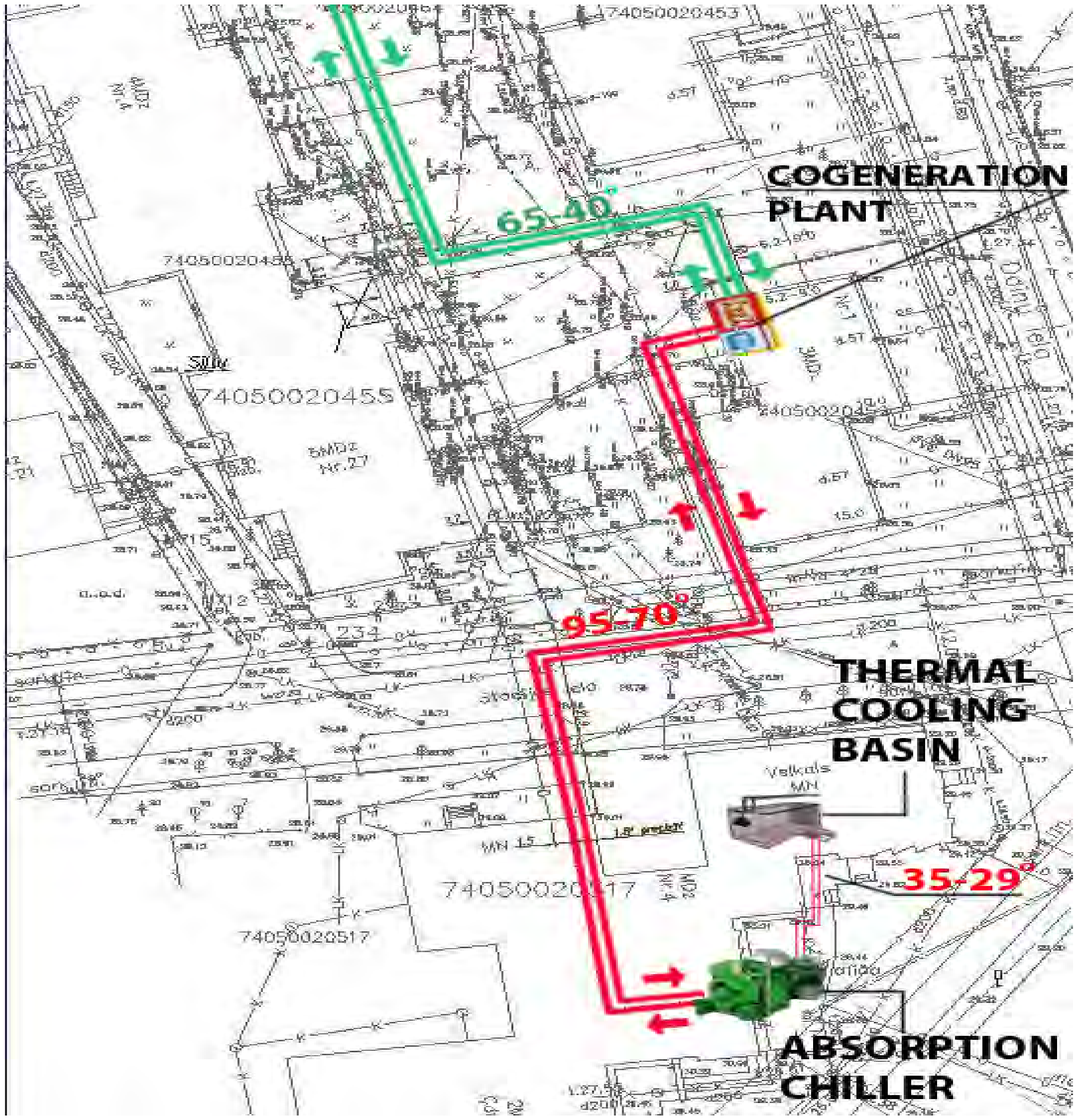

Fig. 1. Principal layout of a trigeneration system

2.2. Heat Evaporation Pools as an Alternative to Cooling Towers

Heat conversion into cold energy takes place at heat absorption chillers. A heat absorption chiller can be seen in Figure No. 2. Two connection points to the cooling tower are shown on the layout, the heat absorption facility may instead be connected to a heat evaporation pool. In order to contain a concentrated fluid, heat absorption facilities require a fluid supercooling cycle. The heat carrier temperatures within this cycle (depending on the manufacturer, this value may vary) are usually low, such as 35-29°C. In order to ensure a temperature schedule for such a cycle, the manufacturer usually recommends building heat evaporation towers, although these are expensive and often clash with the landscape. For practical as well as aesthetic reasons, a heat evaporation pool may be used here, employing water sprinklers to boost cooling efficiency. Water sprinkling is necessary for increasing the area of contact between water and air because the area of contact is equal to the sum of the areas of all airborne droplets of water.

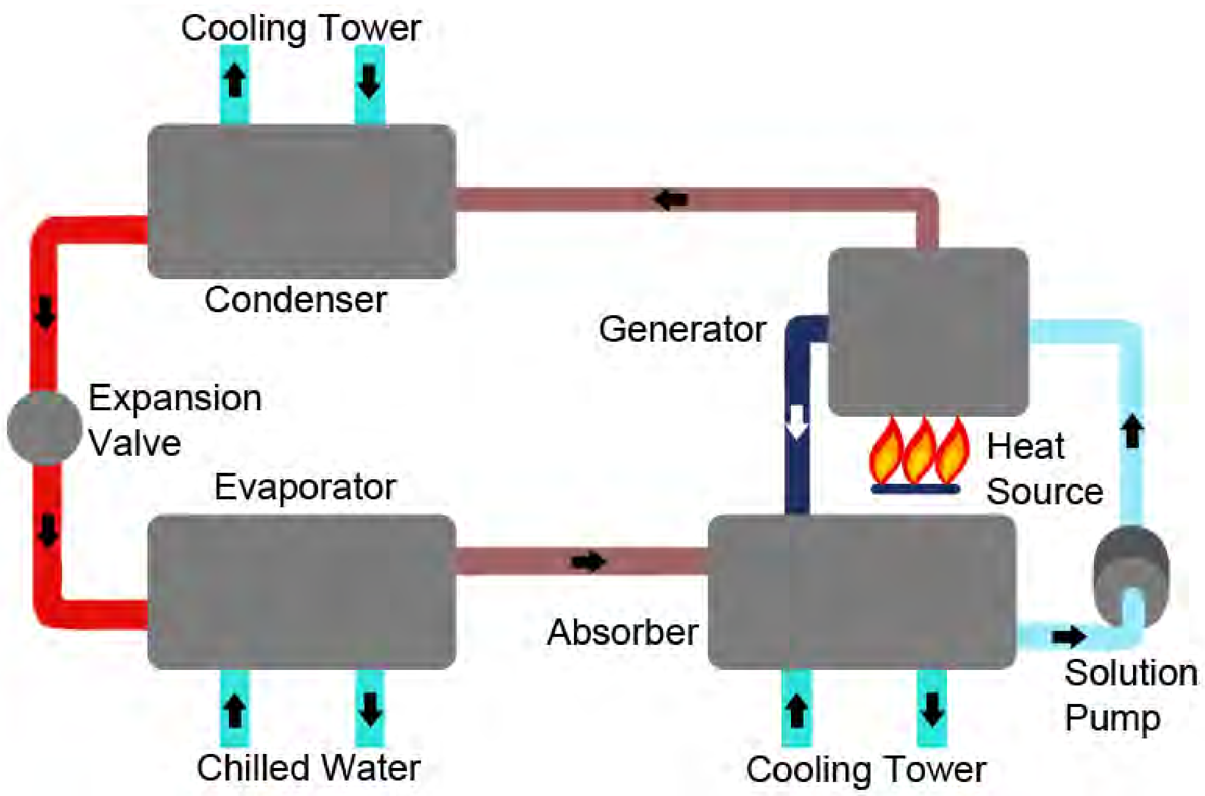

Fig. 2. Heat absorption chiller

The pool may not be shallower than 1.5 m, to prevent heating by solar rays. The cooling properties of the pool will improve with sprinkling of finer droplets, although this leads to higher water losses as well.

A heat evaporation pool (as seen in figure No. 3) may be a heat engineering structure; its advantages include:

- A heat evaporation pool is much cheaper to build than an evaporation tower
- An evaporation pool is a closed system which may therefore be located in public areas
- An evaporation pool is a significantly smaller structure than a tower
- An evaporation pool is more visually appealing and landscape-friendly than an evaporation tower.

2.3. Analysis of Heat Evaporation Pools for Heat Engineering Calculations

The purpose of this research is to perform a study and compare the experimental data to similar studies done previously across the world in order to determine the possibility of practically implementing a heat evaporation pool, as well as to develop a full prototype that would make the basis for building similar structures. In the past sever Russian scientist's worked at this scope, thermal cooling basins where located nearby nuclear and thermal power plants because turbine cooling required heat potential reduction. Those pools where open systems without heater. Water from turbines was supplied directly to the basin and sprinklers. In such a system it's easier to cool because heat potential is usually much higher than the outdoor air temperature (the coolant temperature is considerably higher). Remove maximum heat from the heater and refrigerate with the sprinkler spray in sufficient quantity within the prescribed limits is a challenge in closed – cycle refrigeration. Closed system allows locate basins in public places because the cooling circuit is protected against pollution.The research stand visualisation is provided in Figure No. 3.

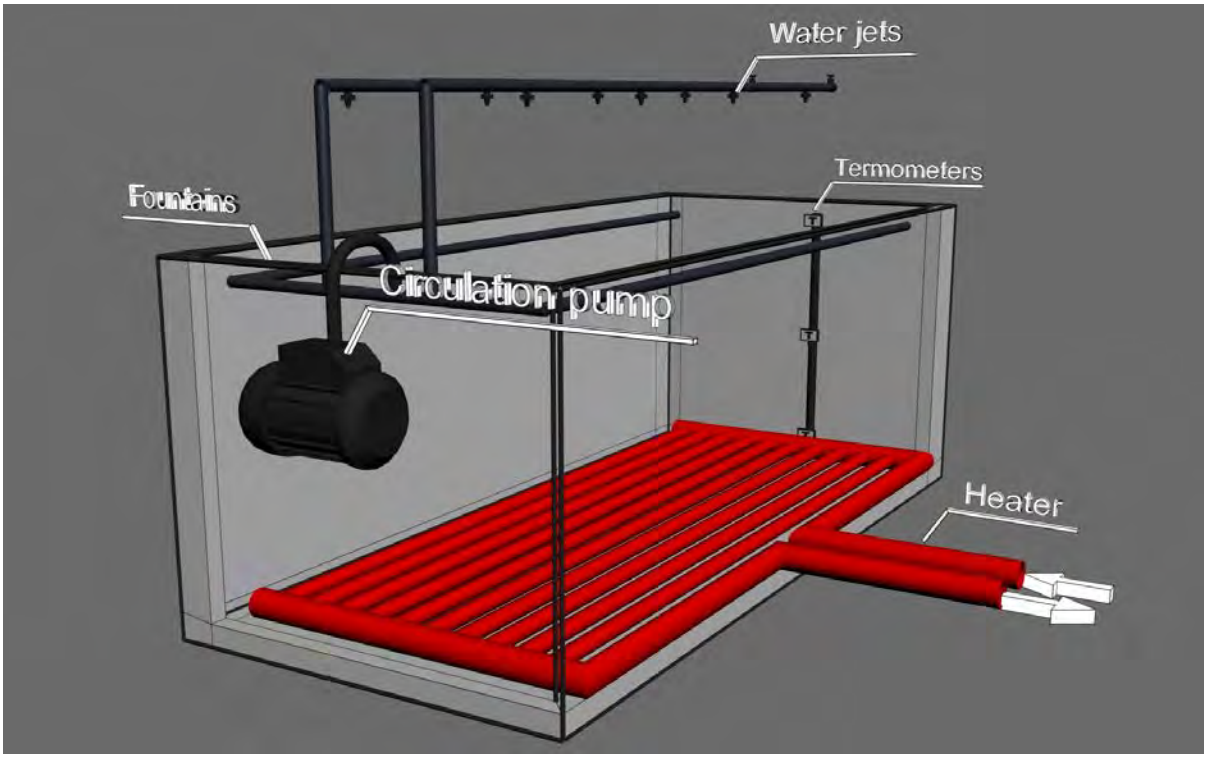

Fig. 3. Visualisation of Heat Evaporation Pool

The heat evaporation pool idea is based on the concept of uniting two systems; a heating element is placed inside the pool and a circulation pump is connected to deliver water inside the pool into sprinklers located above its surface. Compared to an evaporation tower, which is an open system, a pool is a closed system, which means that an evaporation pool may be located in inhabited areas, such as towns, parks, parking spaces etc.

Circulation pump: by adjusting the circulation pump's throughput, the intensity of droplet sprinkling may be adjusted, which will in turn be reflected in the cooling performance of the fluid. It should be considered that the cooling performance of a pool is also affected by a number of outside conditions, such as external air temperature, relative humidity, external wind speed; these parameters must are measured during the experiment, and the parameter value will be applied to the results of the heat engineering calculations. The heat transfer ratio must be adjusted depending on external air parameters. Near the basin is located weather detection station to obtain ear condition data during the experiment, up to now fully equipped experiment has lasted only for days in October 2010, when the outdoor air temperature at the ranged from +7 till +12° C per day. It was clear after comparing the temperature curves that at low outdoor air temperature cooling capacity was directly related the outdoor air temperature fluctuations, it can be seen in Figure No. 4. Graf shoes that basin cooling properties increases when outdoor temperature drops, it cannot be observed literally because of a heat storage. The other parameters made a minor impact on cooling capacity, except wind speed, it increases cooling properties and water loss. There are three thermometers placed in the basin to determine temperature changes in different strata. First is placed 0.3 m above the heater, the second 0.5 m below the air / water contact surface, the third is already over the air and water contact surface. All of these thermometers show the different temperatures.

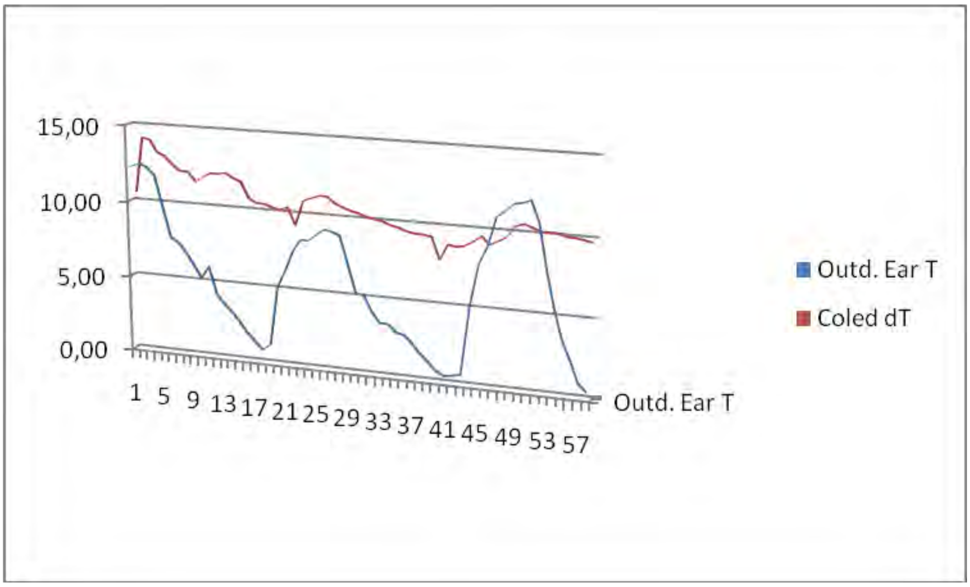

Fig. 4. *Outdoor air temperature impact on the cooling basin properties*

Heating element: a heating element is placed inside the pool, adapting it to the shape and area of the pool – in any case, the configuration of the heating element must be selected so as to create maximum heat carrier resistance and heat loss both as radiation and as hydraulic loss. The pool in question is connected to the boiler room's heat exchanger, which allows adjustment of heat carrier input temperature as well as heat carrier throughput.

The purpose of the heat evaporation pool is to retain the installed cooling parameters regardless of fluctuating external conditions.

Thermal cooling basin exploration for thermal calculations:

- Basin size $S = 11\text{m}^2$;
- Basin volume $v = 22\text{m}^3$;
- Basin temperature Schedule 35° – 29°C;
- Basin heat input $Q = 3.20\ \text{m}^3/\text{h}$;
- Circulation pump yield $Q = 8\ \text{m}^3/\text{h}$;
- Heat transition coefficient K kJ/m^2;
- Spray jet yield V m^3/s;
- Spray jet diameter $F = 0{,}001$m;
- Relative water weight $\alpha_p = 1\text{kg/m}^3$;
- Yield coefficient η - (0,6 – 0,75)
- Nozzle pressure drop $\Delta P = 0{,}00032\ \text{kg/m}^2$
- Gravitational force $g = 9{,}8\ \text{m/s}^2$;
- Pressure supply in lines 3,2 atm, 324240Pa;
- Relative air pressure P_g, Pa;
- Outdoor air temperature T_a, °C;
- Air relative moisture d, %;
- Wind speed v, m/s;

Water loss, depending on the outdoor temperature, coefficient k values shown in Table 1.

$$\Delta = k \cdot \Delta T, \% \qquad (1.)$$

Table 1. Coefficient k value depends on air temperature [2]

Air temperature, °C	0°	10°	20°	30°	35°
Coefficient k	0,10	0,12	0,14	0,16	0,17

Guided thermal basin volume:

$Q_{heat}=M\cdot C\cdot(T1 - T2)$; [3] (2.)

$Q_{heat}=22.34\ kW/h$;

Heat transition coefficient:

$K = Q/S \cdot \Delta T$; [3] (3.)

K= 0,33kW/m^2;

Sprayed water volume, changes depending on weather conditions:

$V = \eta\cdot F\cdot \sqrt{(2g)}\cdot \Delta P/\alpha_p$; [1] (4.)

$V = 1.5\cdot 10^{-6}$ m^3/s;

3. Conclusions

Experimented will be repeated and basins cooling properties measured according with whether when the cooling is necessary – in summer.

Graf shoes there is minor influence on the basins cooling properties by wind speed, there must be assurance that fluctuating is insubstantial in suitable weather conditions.

Water jets and fountains musts be located to exclude terrorism danger.

There is a slight difference between the first and second thermometer readings, but significant deferent's with third thermometer readings because its located above ear and water contact area, but the deferent's between first and second thermometer is called by location, first thermometer located 0.3m above the heater and readings are 0.2-0.5°C higher, but when the heater is shut down readings shift and the second thermometer shoes 0.1-0.2°C higher temperature, this indicates heat flow change and basin heats from the outdoor ear and sunlight when the heater switched on basins heat potential is higher and heat flow changes.

The sprinkling intensity is determined and the heat transfer ratio is adjusted depending on external air parameter fluctuations in order to keep the Δ T value above the installed minimum.

The influence of external air parameters on Δ T changes must be determined during the study.

The most profitable sprinkling intensity must be determined considering the results.

Water volume has properties for heat accumulation, that's why after water jets are shouted down basins retains its cooling properties, for a while.

There musts be investigation before adapt thermal cooling basin to certain system, basins cooling properties changes depending on weather conditions.

Thermal cooling basin could be combined with equipment with absorption and compression cycles, solar collectors, PV and PVT solar cells.

Experiment will be continued and the results will be published.

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Development of a tool for the evaluation and improvement of the energy management in small and medium enterprises (SMEs)

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Abstract: A new tool is presented in this article. The main objective is the improvement of the small and medium companies' energy management systems in order to obtain energy savings and the adaptation of the organizations according to the recognized standard UNE-*EN* 16001:2010. The application of the tool lets companies reduce their energy consumption and improve their processes in an energy efficiency perspective. The methodology is based in questionnaires and tests which will report information in order to identify all standard requirements. In a near future, the expected benefits are going to be a knowledge about the companies' EMS situation, information to prioritize actions to improve, identification of critical areas, comparison between different EMS evaluation results (for example: company' EMS with industry average, etc.), improve companies knowledge about energy, energy efficiency, etc.

Keywords: *Energy, Management, System, software, companies.*

Nomenclature

EMS Energy Management System
SME: Small and medium enterprise
IAT: Instituto Andaluz de Tecnología (Andalusia Institute of Technology: company name).

1. Introduction

In the last few years, society, governments and companies have changed their philosophy in order to protect and preserve the environment. Nowadays, instead of being watched as an economical consumption, this philosophy has become in a competitive factor.

At the same time, laws have included topics related to environment which gives an answer to the general interest.

The purpose of this paper is to introduce a tool (named EVALENER) that offers companies the possibility of evaluating the management system focused on energy efficiency according to the recognized standard UNE-EN 16001:2010 "Energy Management System – Requirements with guidance for use´" (Spanish version of EN 16001:2009).

UNE-EN 16001:2010 [1] standard just became an European standard, so not many other evaluating software has been developed to help companies and no relevant result have been set. Even more so for SMEs. In Spain only few companies has got its EMS certified and most of them are big organizations.

The use of this tool will let companies reach both environmental and business benefits. Regarding environmental benefits the following goals could be achieved: CO2 emissions, global warming and climate change impact and exterior energetic dependence could be reduced. According to business benefits, companies will obtain financial savings (energy bills reduction), achieve legal requirements, social responsibility and corporate image improvement.

Another important aspect is the fact that the tool is focused to be applied in small and medium enterprises (SMEs) since they do not have as much economical resources as big companies have. So the tool's main objective is helping SMEs to achieve an effective EMS carrying out their own evaluations and measuring the impact of the development improvements in the organizations.

2. Methodology

EVALENER has been based in recognized standard UNE-*EN 16001:2010 'Energy Management Systems - Requirements with guidance for use'* that provided a model of excellent energy management to the organization to compare their energy management system with the model one.

The methodology for developing EVALENER has been the same following for the Instituto Andaluz de Tecnología (www.iat.es) to develop other evaluating tools that exist in its organization. IAT has wanted to provide companies (emphasized in small and medium companies) with a set of tools to evaluate different aspects into the organization with the same aspect and the same operation. The results are shown in the same way as well to help companies understand the results.

The methodology for developing the tool in order to evaluate the Energy Management System (EMS in advance) has been the following:

1.- A questionnaire has been developed to cover all standard requirements.

This questionnaire has several questions for each UNE-EN 16001 aspect. Each question is accompanied for evidences examples to help the evaluator to find into his/her organization what they are doing to compliance the aspect asked.

2.- Question weighting has been developed to reach a value for each standard requirement.

The evaluator will have to mark each question between 1 and 5 to show the maturity level as shown in Table 1.

Table 1:Marking of every Maturity level and sub-level for standard aspects

Maturity Level	Marking (Maturity sub level)		
	Basic	High	Advanced
1	1	1,4	1,7
2	2	2,4	2,7
3	3	3,4	3,7
4	4	4,4	4,7
5	5	5	5

To choose the value in this table 1, the evaluator will use first Table 2

Table 2:Maturity Level of every standard aspect

Maturity level	Approach	Performance	Improvement
1	It isn't very sound	It isn't done systematically and not always as planning.	It is done just to repair problems
2	It is sound and it is based in a recognized standard, model, etc.	It is done systematically and not always as planning.	Non conformities are detected in order to plan and to star improvement actions
3	It support the management policy and established targets	It is done regularly and in many relevant areas	Improvement actions are set to avoid future problems. Effectiveness of these actions is measured
4	It consider the influence of all management areas and relevant stakeholders.	It is done in nearly all relevant areas	Results are analyzed and compared with company targets in order to get information to improve activities, process, etc.
5	It is done considered internal and external data	It is done in all relevant areas to guarantee good results for all stakeholders	Best practices and comparison with other companies results are taken into account to set up improvement plans.

This table may be used to set the Maturity Level: The user will mark approach, performance and improvement levels (one mark in each columns). Maturity base level will be given by the lower value.

To find the maturity sub-level (Table 1) the following criteria are considered:

- Basic: the 3 marks in the array have the same level.
- High: one of the mark (approach, performance or improvement) is above the basic level.
- Advanced: 2 of the 3 marks are above the basic level.

By using both tables above, it can be obtained a value between 1 and 5 for each question. In an example both tables will be used as follows:

<u>Set the maturity level</u>: user will mark with a cross the maturity level of approach, performance and improvement (each column in Table 2). The maturity level will be the lower of these three values.

Table3:E.g. of setting Maturity level.

Maturity level	Approach	Performance	Improvement
1			
2		**X**	**X**
3	**X**		
4			
5			

Maturity level will be 2 in this example

<u>Set the maturity sub-level</u>: In the above example: sub-level is “high”, therefore this question points with a value of 2,4 (Fig.1) using Table 1 to set it.

Maturity Level	Marking (Maturity sub level)		
	Basic	High	Advanced
1	1	1,4	1,7
2	2	2,4	2,7
3	3	3,4	3,7
4	4	4,4	4,7
5	5	5	5

Fig.1. Example of setting the question value

Thus, for each question the user get a value between 1 and 5.

3.- Some tests have been passed to the tool in order to identify errors and to check the smooth running of it.

4.- The tool has been validated in 15 real cases to assure it provides companies key focus areas and the possibility to compare its EMS evolution throughout the time.

<u>EMS EVALUATION</u>

User, during the evaluation, will answer several questions within each part of the standard. The screen layout of the tool for each question is the following (Fig. 2):

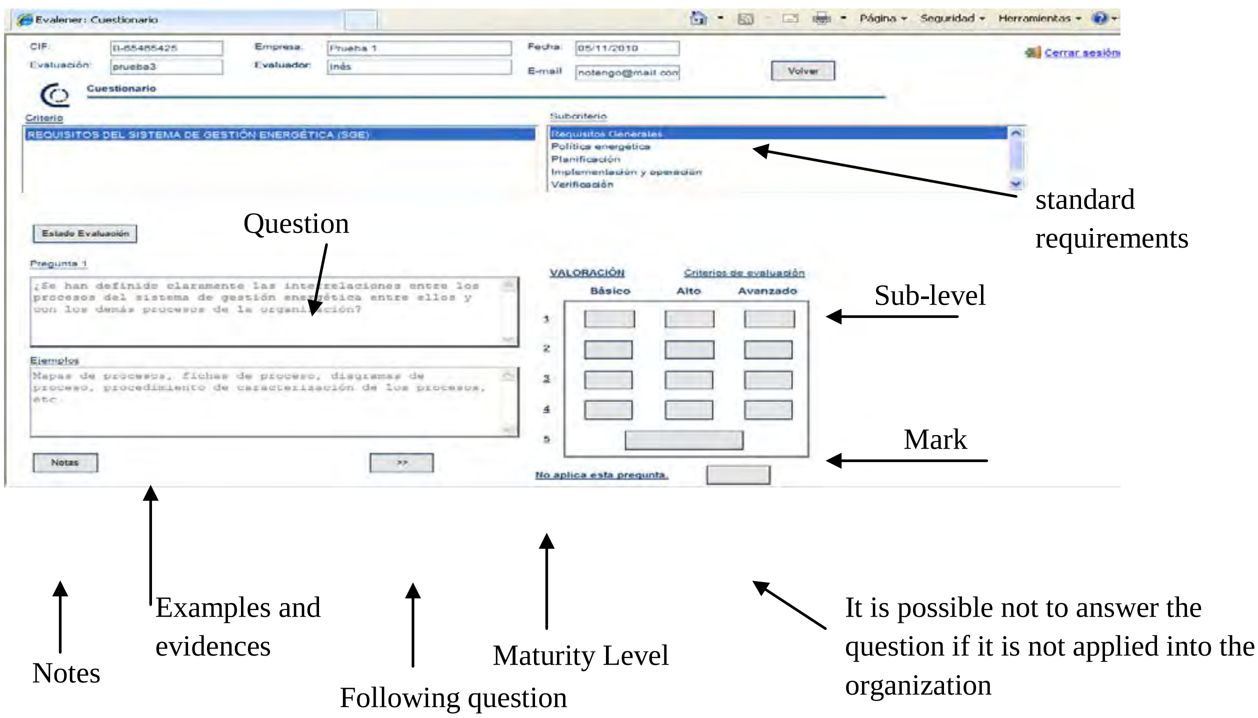

Fig.2. Screen layout of EVALENER

Furthermore, the user could highlight strengths and improvement areas by clicking the Notes button (Fig. 2), which will help detecting during the global analysis the most important areas to be improved. All this information will be shown in a report named "evaluator's notebook" (Fig. 3)

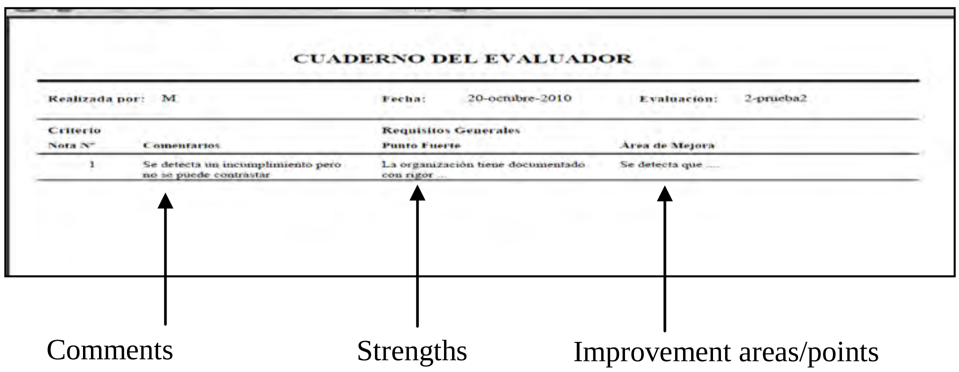

Fig.3. Example of Evaluator's Notebook report

At the end of the evaluation, EVALENER offers a report with the obtained scores and the evolution from previous evaluations (if exist) as shown in Fig. 4.

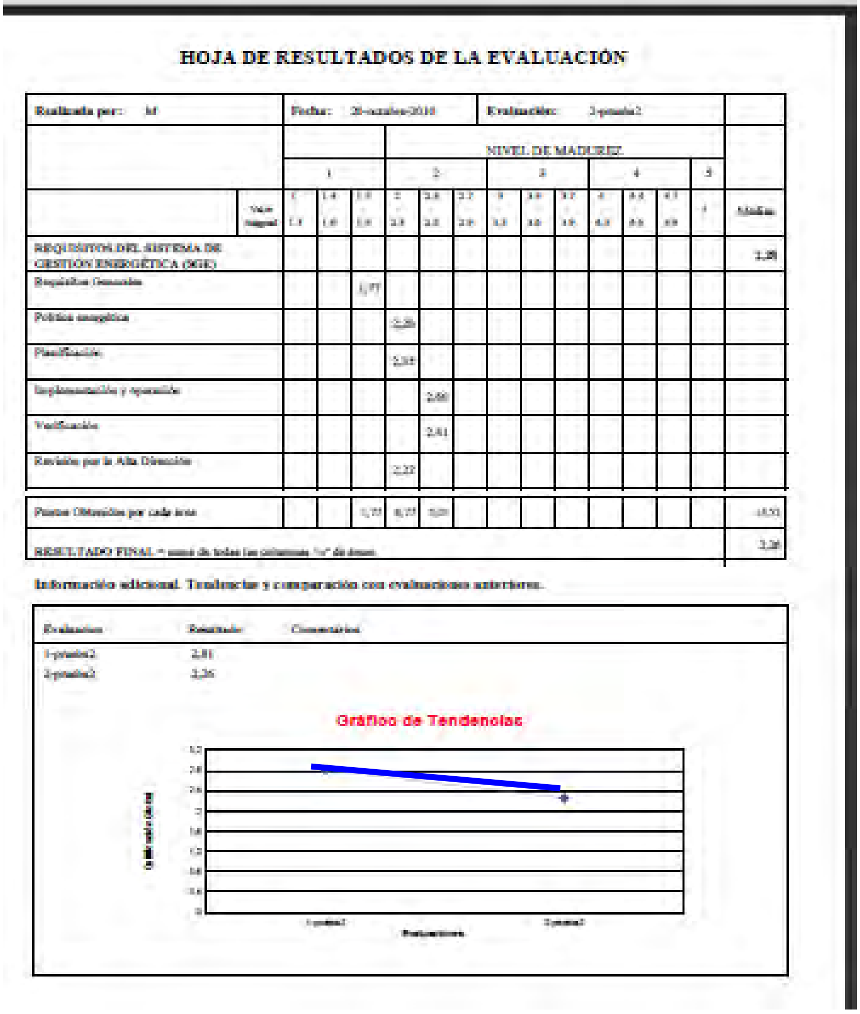

Fig.4. Example of Evaluation Report

3. Results

Companies that took part in this project were SMEs. Some of them have set their own environment management systems (according ISO 14001) but some others don't. None of them have got EMS, although some would consider its use in a future.

A varied set of companies participated during the tool's validation process, companies like a pharmacy, manufactures, or a health care company.

Those companies that have decided to become certified according to UNE-EN 16001:2010 standard want to show customers that these companies are consistent with their business (for example engineering and/or architecting firms that works with energy efficiencies) and others to get more points going to qualify for government public tenders.

Those which are using an environment management system have achieved better scores and found easier during the evaluation understanding the question and evidences compared to those companies that don't use any environment management system. The companies that don't use it even found hard to understand concepts like operational control and significant energetic aspects, besides they achieved low scores in the auto evaluation.

All of the participants used the experience to think about their use of energy, considering new metrics and, the most important, improvement areas in the aspects that they could afford given the current economical circumstances (change machines to other that consume less energy, change to LED technology, used better enclosures, changes in human behavior…)

4. Conclusions

SMEs in Andalusia are currently passing through an economical delicate moment, as in the rest of Spain but increased by a weakest regional and local industry.

In this scenario, an efficient energy management is a must in order of reducing costs and looking after the environment, taking part of the European compromises for reducing the greenhouse effect, consumption, etc.

The main obstacle for these SMEs is the access to information related with energy management, contracting experts to help with it or even economically afford some of the improvement options available in the market.

Because of the mentioned reasons, this tool tries to help small companies that cannot make use of any EMS because of a lack of resources. The software has been organized following the standard requirements with the purpose of helping companies approach to the standard and it has been adopted the question-evidences formula to ease its understanding.

The option of evaluator's notebook makes considerably easy bringing up improvement areas after finishing auto-evaluation as well as highlighting the strengths of the company.

Beside of evaluator's notebook, EVALENER offers the chance to de companies to compare evaluations and see the EMS evolution. This information will be useful to know how efficient were the improvement actions undertaken by the company and will help with the continuous improvement of the organization.

In any case, the system has to be improved because it has been revealed as not very flexible (it doesn't allow weighting each question or section) and not very intuitive in the use of both tables (Tables 1 and 2). The way of looking for the score for every question (Table 2) requires using an auxiliary paper sheet as it is not automated in the software, and makes it hard until further practice had been acquired. For this reason, this functionality should be improved in a second version of the tool (now developing by IAT and to be integrated with other evaluation tools that have been developed by IAT).

The software could be enhanced by adding help tags and screens to let the evaluator a better understanding of each question or standard aspect.

Despite all, the goal of approaching EMS to SMEs and letting them, in an affordable way, analyze and reflect on their way of use of energy and consider actions for improvement has been achieved.

The main advantage of this methodology is the used of a questionnaire to analyze that companies done about their EMS and to be able to get a goal easily to compare different situations (with other companies, with the own company after to carry out improvement actions, etc.). That is easy to use for SMEs and not require a lot of knowledge or experience.

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"Uncovering Industrial Symbiosis in Sweden" -exploring a possible approach

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Abstract: Industrial Ecology (IE) is a relatively new field that is based on the ideology of nature. IE uses nature as a "reference" to study resource productivity and environmental burdens of industrial and consumer products and their production and consumption systems.

Industrial Symbiosis (IS) is a subset of Industrial Ecology with a particular focus on cyclical flows of resources through networks of businesses. One definition is that IS "engages traditionally separate businesses in a collective approach to competitive advantage involving physical exchange of materials, energy, water and/or byproducts. "The keys to IS are collaboration and the synergistic possibilities offered by geographic proximity" [1].

This paper presents a methodology that aims at developing a method for uncovering IS in the Swedish energy sector. The method is exemplified by district heating and consists of data collection of the occurring resource and energy flows to and from district heating plants in three different Swedish regions. The results show that the method presented in this article can be used in future and more comprehensive "uncovering" studies. The material from a broader, nationwide study is expected to make it possible to develop tools to facilitate the conditions for IS to be developed.

Keywords: *Industrial Symbiosis, Methodology, Uncovering*

1. Introduction

Industrial symbiosis (IS) has been defined as "engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products"[1]. IS emerge as a self-organizing business strategy among firms that are willing to cooperate to improve their economic and environmental performance [2]. According to Chertow [1] "The keys to IS are collaboration and the synergistic possibilities offered by geographic proximity". Businesses that are collocated can, in accordance to IS, reach environmental benefits and competitive advantages by physical exchange of resources with each other or with residential areas [3]. In Sweden, the occurring identified cases of IS show fruitful collaboration and integration from the companies´ point of view as well as increased environmental performance [4, 5]. However, there is a gap of knowledge when it comes to an overview of the occurring IS in Sweden. It is currently not known how common these kinds of mutual exchanges and collaborations are.

In the United States Chertow [6] conducted an uncovering study that investigated IS in a broader perspective. In Sweden there have previously been single case studies of IS. Therefore there is both a knowledge gap about the occurrence of IS in Sweden and also when it comes to methodologies to systematically gather data in order to analyze whether IS occur or not.

1.1. Aim and research questions

This article presents a method for uncovering Industrial Symbiosis and how this method can be applied to the Swedish energy sector. The method is exemplified by district heating. The aim is to illustrate and explain a method used to conduct an uncovering study of IS in Sweden and to discuss how the method can be used to create more in-depth knowledge about IS in Sweden when it comes to the extent of collaboration and mutual exchanges. The discussions are based on a pre-study where the method is tested on three Swedish regions.

2. Background

Efforts to understand and replicate Industrial Symbiosis in the form of inter-firm resource sharing like what was largely self-organizing in Kalundborg, Denmark have since 1989 followed many paths. The success has varied, some of the efforts have been very successful and some have not [6]. Chertow [6] describes the year of 1989 as "an inspirational year for industry and environment". The main reason behind the success is described as two key events following the Bruntland Commission report in 1987. The first was a seminal article in Scientific American illustrating "industrial ecosystems" in which "the consumption of energy and materials is optimized and the effluents of one process serve as the raw material for another process." The article was written by Frosch and Gallopoulos [7]. That same year the Industrial Symbiosis in Kalundborg was discovered as a concrete realization of the theory described by Frosch and Gallopoulos [7]. The cluster of intensively resource sharing companies from different industries in Kalundborg, Denmark was uncovered unexpectedly [6].

Previous research shows many, both public and private, benefits of IS as a result of "spontaneously co-location" of different businesses in industrial areas. Duranaton and Puga [8] describe these benefits as labor availability, access to capital, technological innovation and infrastructure efficiency. Key rationales for advancing IS projects as a way of trying to recreate the same types of collaboration and mutual exchanges include economic development, remediation of pollution associated with heavy industry, water and land savings, and greenhouse gas reductions [9]. Another reason for collaboration around energy savings and greenhouse gas reduction is the construction of shared visions and goal, which also makes projects less vulnerable [10].

Examples from previous research from Sweden and the Swedish forest industry show that there are several occurring cases of IS and that the conditions for implementing IS varies [5]. Also, these studies indicate that IS can have advantages both from an economic and environmental perspective [4]. Mapping these existing cases of symbiotic activity makes it possible to use the knowledge in the IS field to study and develop the partnerships further.

3. Method

As mentioned above, this article presents an approach to uncover industrial symbiosis in Sweden. The overall approach to these uncovering activities is data collection from several sources to obtain triangulation of data for each found case. This is an approach that strengthens the validity and to facilitate deeper analyses [11].

Yin [11] recommends four methods of analysis: Explanation–Building, Pattern–Matching, Time–Series Analysis and Program Logic Models. For this type of study, with large amounts of data, it is of great importance to have a fully functional database. In this case the database is designed to show the different flows that occur, as well as between which actors the flows occur. This gives a good overview and understanding of the situation within the studied regions.

Explanation–Building can mean two things: according to Yin [11] it primarily means building an explanatory narrative, which shows the causal relationship, it also can be about creating a coherent and credible overall picture of a phenomenon [12].

Pattern-Matching means that patterns that can be observed are compared to patterns that have been predicted or known from other cases. To analyse the cooperation and mutual exchanges between the studied district heating plants and related, nearby industries and companies within a specific cluster, comparison with previously known cases of similar character as an ideal type is a form of Pattern-Matching.

In the next step the various actors involved in the symbiosis cluster is studied deeper to understand the sequence in which the development of the cooperation and exchanges develop. Time–Series Analysis means clarifying the order in which events or actions occur, with what intensity they vary over time or how far they are in time.

As a last step the Program Logic Models is used to analyse the assumptions about the connections. In this case, the previous knowledge will enhance the understanding and of the elementary conditions for IS.

4. Methodology

To be able to map ongoing cases of IS empirical data about occurring collaboration and mutual exchanges needed to be collected. In order to test if the chosen approach to uncover IS is appropriate a diversity of empirical material is needed. Therefore three geographically diverse regions with different types of industrial conditions were selected for this study; one region with dominating forest industry, one with a dominating agricultural sector, and one with a diverse industrial sector including food industry, manufacturing as well as pulp and paper industry.

Investigating every single industry in these regions was not feasible for this pre-study, therefore district heating industry was chosen as the main actor to start empirical research from. The motive to choose district heating plants in order to uncover IS was that district heating occur in more or less all Swedish municipalities. In addition, activities from the business of district heating generate large flows of material and energy which are important prerequisites for IS.

The first step in process is to collect data of the occurring resource and energy flows to and from the different district heating plants within the three different regions. All of the district heating plants are also studied more in detail, one plant at a time, based on information from websites and additional interviews. All interviews were conducted via telephone and in semi-structured format, which means that the same question guide was used for all interviews, but the interviewer had the opportunity to ask supplementary questions. This type of interview is recommended since it helps structuring the interview [13]. However, this interview method also allows new and unforeseen issues to arise during the interview and hence is an effective tool for gathering information that is difficult to obtain otherwise [14].This method is expected to provide data that will show which of the studied district heating plants who has some kind of collaboration or mutual exchanges with other nearby business or industries.

To be able to identify and classify occurring cases of IS there is a need of a consequent definition with clear criterions. This study will use the same criterions as the previous study

"Uncovering Industrial Symbioses" made by Chertow [6]. Chertow defines the minimum criterion of IS as "3–2 heuristic". This means that at least three different entities must be involved in exchanging at least two different resources. An example of a 3–2 heuristic relationship within this study is industry 1 providing industry 2 with a flow of resource and industry 2, in turn, provides industry 3 with another flow of resource, figure 1.

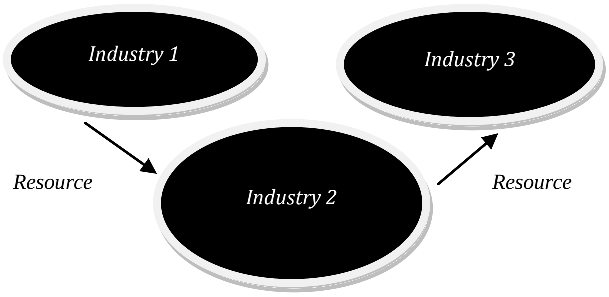

Figure 1. Example of a "3-2 heuristic" relationship. Inspired by Chertow [6].

4.1. Structuring the empirical data

The results from this study are stored in a database designed to address the collected data and to demonstrate the flows of different resources that occur between the actors involved in the detected clusters of symbiotic activity. The structure of the database is built on a model that makes it possible to link "plants" with different "flows" of resources in several steps. The database is also designed to be able to store specific information about the different flows of resources as well as the different plants involved. The information of the plants regards what type of plant it is, the size of the plant, the occurring ownership and the location of the plant. When it comes to the flows, the additional information regards what type of resource it is and of what amount, origin- and destination pant and if the specific resource is used as resource in the industrial process or functions as a utility, see figure 2. It is also possible to specify whether the resource originates as a main product (on which production the industry is based) or a byproduct (waste) from the industry. This information about each resource flow opens up for analyses about for example which kinds of exchanges are more common in relation to different kinds of plants. Martin [15] mean, for instance that by-product synergies are the most abundant type of synergies and that utility synergies in the form of shared use of energy and utilities are not as common.

The implementation of the data is done by two different formulas created in the database. The first formula manages data for each "plant" and the second formula manages data for each "flow" of a specific resource. The formulas are based on the tables within the database where the data is stored and they are created to facilitate the implementation of the collected data. Figure 2 shows the model and how the different data are related.

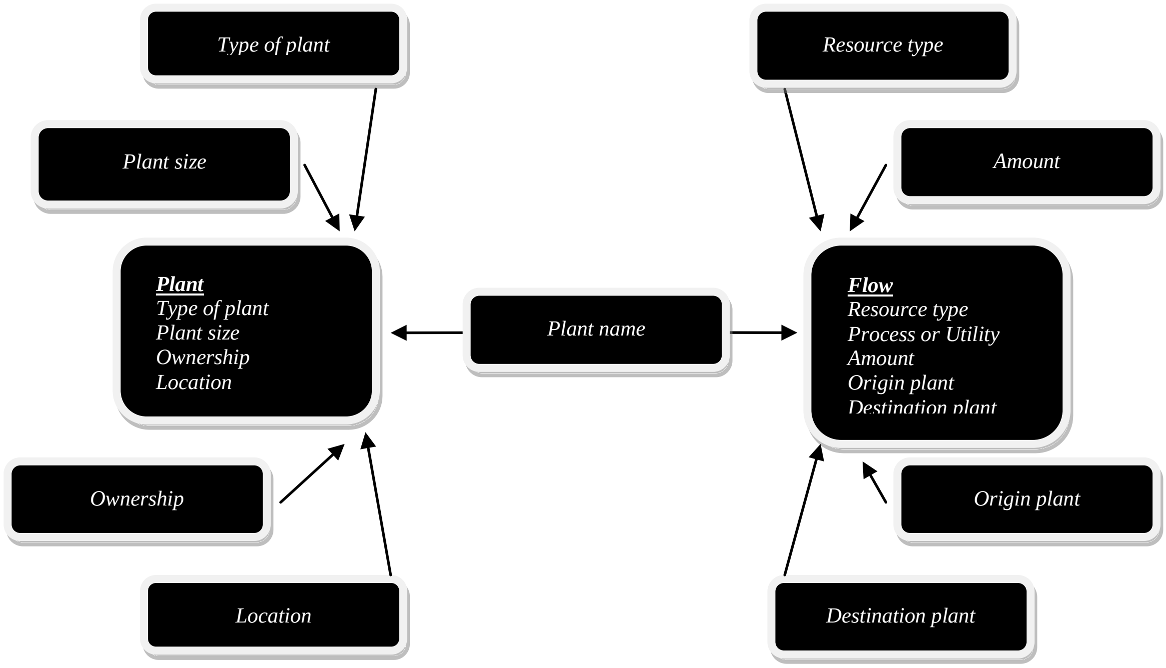

Figure 2. A model of an extract from the database demonstrating how the different data in the database are related.

5. Expected results

The collected data from the three different regions indicate that there is occurring cases of IS within these regions. The most common forms of collaboration is in the form of "3-2 heuristic" relationships, especially in the smaller municipalities. In some of the larger medium size municipalities, where the conditions of collaborations are better, the results show more complex ongoing cases of IS. One example is a forest industry and energy plant co-location, Figure 3. In this (fictional) case it is possible to define five different flows: wood, wood chips, sawdust, process steam and nutrients (ashes). Forestry, the sawmill and the district heating plants all pose as both origin and destination plants, depending on which resource flow is described. It is also possible to define both main products and by-products: wood is a main product from forest industry and ashes are by-products from incineration plants. Furthermore there are resources that pose as both process input and utilities to the destinations plants: sawdust goes into the main process at the main pellet producer and process stem is used as a utility. It is however too soon to draw general conclusions about the data material.

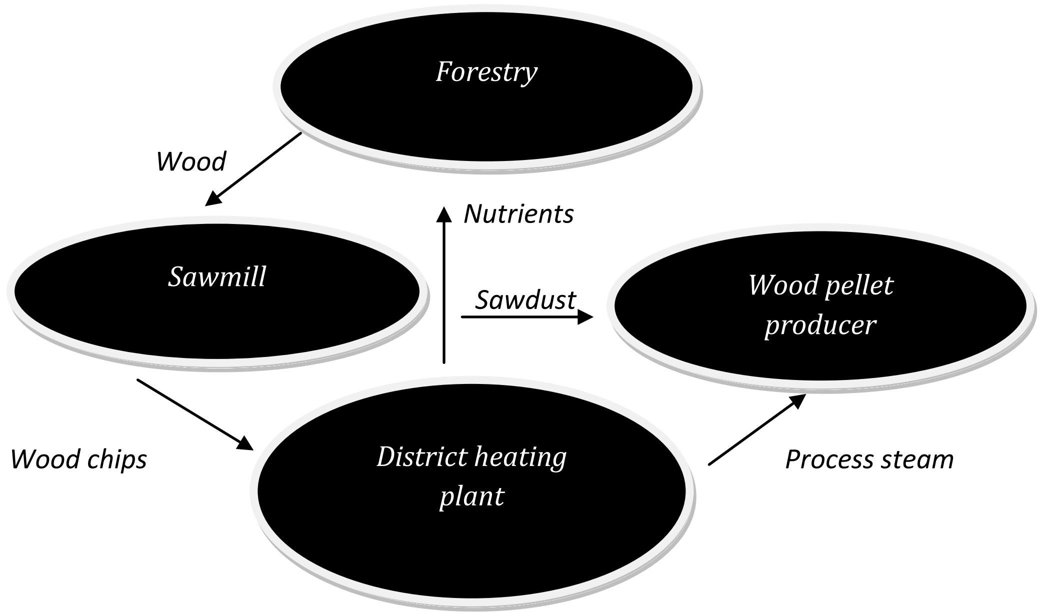

Figure 3. Example of resource flows that can be mapped in the described approach to uncovering industrial symbiosis.

The four methods of analysis described in the methods section can be used to analyze the collected data. This way of arranging the data creates a coherent and credible overall picture of the flows connecting the plants. When mapping the relationships between resource flows and plants is made for a whole region, it will be possible to analyze patterns of occurring collaborations. Thereafter observed patters can be compared to previous research but also to other regions or businesses. In this sense this will function in accordance to the Pattern-Matching as described by Yin [11]. As a continuation of the analysis, Time-Series Analysis can be used to clarify the order in which the different steps in the Symbiotic process occur, to understand the sequence in which the development of the cooperation an exchanges develop. This kind of analysis would however need additional empirical data.

When a deeper understanding of the development of discovered symbiotic activity has been created, it may be used to develop proposals on measures to improve the conditions and the facilitation of the implementation of IS in the future analogous to Yin's [11]the Program Logic Models.

6. Concluding discussion

This article has presented a method for uncovering Industrial Symbiosis and how it can be applied to the Swedish energy sector. Experiences so far have shown that the method for collecting data an organizing them in a database functions well. This method is probably suitable for uncovering IS, however it may be too demanding if it comes to cover large areas, for example the whole of Sweden. A broader, nation wide, study like that with more and broader data would probably need a less personnel intense method than semi-structured interviews with all actors. It is therefore a need to further develop the methods for uncovering industrial symbiosis to be able to expand the studies.

According to Chertow [6] the "Uncovering" of existing kernels of symbiotic exchanges has led to more sustainable development and designing of eco industrial parks. Knowledge about the occurring and ongoing cases of IS in Sweden is expected to provide the basis for more in-depth knowledge of how these collaborations and mutual exchange evolved and what the important elements for them to arise and function are. Therefore it would be of great interest to develop the methods for uncovering industrial symbiosis in Sweden. This would help to create more in-depth knowledge about IS in Sweden when it comes to the extent of collaboration and mutual exchanges and subsequently the prerequisites for such collaboration. Such knowledge in turn can contribute to develop more efficient, environmentally adapted and prosperous business.

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Towards increased energy efficiency in industry – a manager's perspective

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Abstract: Industry is one of the major users of fossils fuels resulting in emissions of GHG (Green House Gases), leading to global climate change. One means of promoting energy efficiency in industry is energy management. The aim of this paper is to outline a number of energy management related factors which affects energy management in industry positively. The paper is a result of collaboration between industry professionals and researchers within an ongoing research project and addresses the issue using a bottom-up energy management perspective. Results indicate that that the "soft" issues of energy management play a crucial role in the success (or not) of energy management in industry, e.g. the manager's role and attitude towards the employees cannot be understated. Instead it addresses that implementation is not only about technology but equally or even more important, concerns the diffusion and adoption of energy management practices and principals.

Keywords: *Industrial energy management, Organizational change, Industrial energy efficiency*

1. Introduction

Research indicates that global climate change resulting from the use of fossil fuels is one of the major challenges for future decision makers worldwide. Industry is one of the major users of fossils fuels resulting in emissions of GHG (Green House Gases), leading to global climate change. EU and other regions are now working proactively to reduce GHG emissions resulting from use of energy. One example is the 20-20-20-targets within the EU which in relation to energy means that each EU Member States should reduce the use of energy with 20% by reducing energy intensity with 3.3 % annually from 2005 to 2020. Industrial energy efficiency is one of the most efficient means of reducing GHG [1]. However, a number of barriers to energy efficiency exist in industry which inhibits adoption of energy efficient technologies and energy conservation [2-4]. One means of promoting energy efficiency in industry overcoming a number of barriers to energy efficiency is energy management [5-6]. Even though the potential is vast, research in the area is scarce [7]. One reason for this is its interdisciplinary character calling for interdisciplinary methods such as collaboration between researchers and industry professionals. The aim of this paper is to outline a number of energy management related factors which affects energy management in industry positively. The paper is a result of collaboration between industry professionals and researchers within an ongoing research project within Swedish industry and addresses the issue of promoting energy efficiency using a bottom-up energy management perspective. This paper is unique in the sense that is leaves the realm of focusing solely on energy efficient technologies when studying industrial energy efficiency.

2. Methodology

Previously, research has focused on energy management practices using questionnaires and in-depth interviews, e.g. [5] and [7]. In this study, the scope is to try to take the research on energy management in industry a leap further. Moving beyond questionnaire and in-depth interviews, an attempt is made to incorporate the manager's own ideas and concepts, not merely study an array of factors (using a questionnaire) or respondents' views and opinions (using interviews) on various themes or topics. As the applied method is narrowed down to fewer respondents, it naturally may be more difficult to generalize results from this type of research, see Fig 1. A previous literature review on energy management [7], shows that this research, so far is lacking in the academic literature, as well as clear results on how to apply successful energy management practices. We therefore conclude that this type of methodological approach is needed.

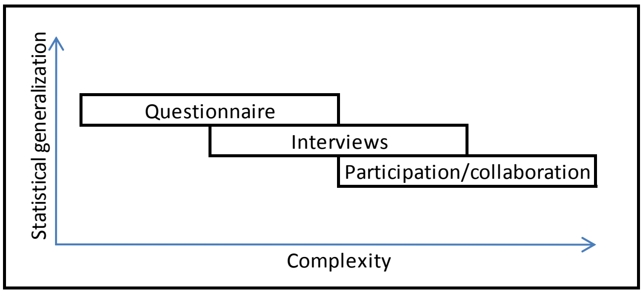

Fig. 1: Differences between participation/collaboration and interviews and questionnaires (Inspired by [8].

According to [8], systems may be categorized depending on degree of complexity. [8] state nine levels and write that research concerning social interaction, i.e. interaction between two individuals is the most complex system to study. He moreover criticizes management research for not moving beyond the lower system levels. In response to [8]'s critique on management research, we aim to move beyond the more common methodological approaches using questionnaires and interviews applying participation/collaboration. Naturally, this limits the ability to generalize results, compared with questionnaires and interviews, as these methods cover several respondents. On the contrary, participation/collaboration methodology enables research to move into the more complex levels of (energy) management. This paper has applied a participation/collaboration methodology where the researchers have collected the manager's ideas and philosophies of successful energy management practices, based on more than 20 years of experience in the field. In doing so, it is evident that this relies on relatively a few cases, and naturally faces an increased risk of being biased, compared with questionnaires and interviews. When analyzing results from this paper, it is therefore important to keep in mind the statement by [5] *"there is no one size fits all"* when it comes to energy management.

3. Results - driving forces for successful energy management practices

In the following section, a number of important factor for successful organizational change related to energy management practices are presented. The stated factors come from the participation/collaboration approach, i.e. a bottom-up energy manager's perspective, a perspective which is derived from the truck manufacturer Scania's more than 20 years of successful energy management practices.

3.1. Culture

An organization has its own culture which is created by a number of factors, such as individuals own values [4]. Culture is an important factor when striving to change an organization, as culture governs the behavior of the individuals of the group, and it is their behavior that creates the organization's results. If any major changes are to take place within the organization, the behavior among the individuals has to change. In the long run, this will change the organizational culture, a change which is needed, if the individuals within the organization are to maintain their changed behavior.

3.2. Will

The second factor of importance is that normally, people want to change things they are not satisfied with, while maintain that which one is satisfied with. The will to change is thus dependent on how dissatisfied a person is, and also how risk averse a person is. The importance for those who lead the change is to perceive that the challenge lies in that person's want the change to take place in their own way.

3.3. Acceptance and recognition

The third factor of importance is that people in general wants attention and positive recognition from personal achievements, from other persons. Many people can go a long way to receive recognition and acceptance. It can range anywhere from fame and compensation in the form of money for the effort one has made, to encouragement and a "thank you" for a good result that the person has accomplished. The former can never replace the encouragement from a manager, thanking the employee for good work. This holds in particular if the manager is also the informal leader, i.e. someone the employees look up to.

In general, people go to their work with a goal to be part of it as they wants to do a good job. If not, this creates discomfort, discouragement and frustration that often take the expression in unwillingness to cooperate, or an unwillingness to change situations at work. Paradoxically, people tend to do exactly the opposite of what it takes to get what one really wants. What this behavior gives in return is attention and an opportunity to be seen in the absence of recognition. Reasons why such an individual have lost sight can be, e.g. lack of attention, challenge or admission from those who are managers. It may also be due to an inadequate role and mission in the group the individual belong to. One may call this a deficiency in the organization caused by poor leadership.

The above three factors, culture, will and acceptance and recognition interact between each other and create the conditions one have in an organization, department and group. It is these challenges that the leader has to work with in order to achieve the expected results.

3.4. Establishing change within an organization

When a manager is leading a change in the organization, he or she can choose one of two main roads or paths. The difference between these two paths can be described by the following: To get from location A to B can be done in two principally different ways. The first option is to run in the sand at the water's edge. Although the road is long, it goes relatively quickly. The tracks in the sand are washed away rapidly and soon, no one else can, by the help of the first person's achievement, manage the very same way. Instead, each one has to take its own way to position B. The load to be moved from A to B depends on the individual's capacity and external conditions and circumstances. In summary, the first path is that of individuality, a path which does not help or support the persons that later wants to take the same path.

The second option is to build a road. It will take much more time, demands much more resources and effort, but when it is finished, there are clearly more people being able to travel from position A to position B. Moreover, people can get more loads with them on the road. The modes of transport can also be developed so that more cargo than was previously possible to carry can be included in each trip. The time to carry out the shipment may eventually be reduced. The load to be moved from A to B is through a road much less dependent on the individual's capacity and external conditions. In summary, the second path is that of the standardization and continuous improvement, a path which help and support the persons that later wants to take the same path.

Road number one may be stated as to govern by results. This is a road which with the right leadership often creates positive results relatively quickly, but the lasting result is often not maintained. The way to influence behavior is by getting members of the group to do what they request. As the manager does not require how results are achieved, solutions often rely upon individual solutions, i.e. the employees own way. Moreover, duplication of these individual solutions is generally not possible. This, in turn, leads to the fact that structural capital is not being built up within the organization, department or group. The culture is affected only to a limited extent and the impact it does create takes time. There is great risks that if the leader loses focus, or change job, the good results will not last.

Road number two is to use what we define as method governing. This is about influencing the behavior by using good methods and approaches. The modified behavior provides better results both in the economic sense, but also regarding the conditions to do a good job of maintaining or improving quality and work environment. The positive change one gains may be linked to the group and the positive spiral which then creates the opportunity to influence the culture of the group. As method governing focuses on how the work is done, conditions for working with continuous improvement are established.

Things which can be improved are the methods, routines and instructions. These are always the same; everyone in the group performs the operations in a similar way and can contribute to the improvement of the method. This will benefit both the individual and the group, even if the work and the physical and psychological conditions of the work are continuously changing. Method governing thus, and unlike the first road, builds structure capital, and with the right leadership, in the long run, an improvement in the culture of the group is achieved. This also reduces the risk of a manager changing job. However, and this must not be understated, bad leadership will always be able to bring down an organization, independent on which road that is taken.

3.5. Successful organizational change

Fig. 2. displays how an organization may successfully be transitioned by the second road, method governing. If one choose to work after the second road, there are some fundamental principles that should be followed, e.g. focus on the organization's value stream and continuous improvements. These are presented in the coming sections.

3.6. Basis – the organization's value stream

Start from the company's product's value stream and the company's services and do not view energy management as a means which creates value by itself. All work which is done in the organization (be it external or internal) must be valued based on the product's value stream. This provides the ability to sort and evaluate, not based on function, but on value. What is waste and what is value? Waste can also be divided into that which is necessary but not value-adding and that which is simply waste. What is value adding is often of no reason to attack first. It only involves the risk of new losses.

That which is necessary but not value adding should be minimized. That which is solely waste must be eliminated as quickly and smoothly as possible. It usually does not cost so much, it is often achieved relatively quickly, and the risk is often low.

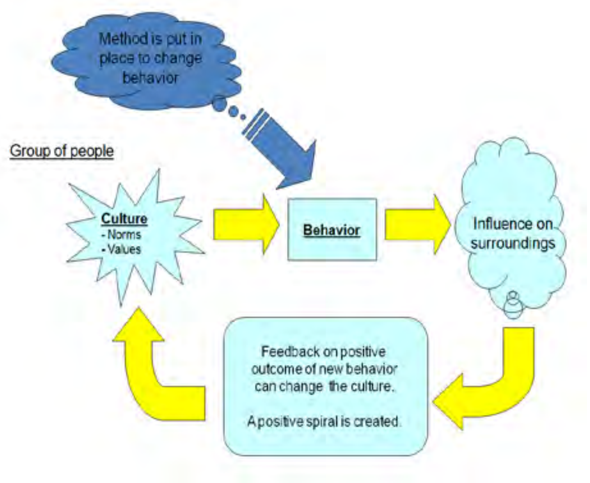

Fig. 2. Example of how an organization may be transitioned successfully based on method governing.

If the organization is a manufacturing company, it is important to understand how the production technologies, maintenance and energy management work is related. Increasing process efficiency is an effective way to reduce energy use for the product. To have a system perspective is necessary when improvements are carried out.

Moreover, aiming to achieve stable systems is of great importance. If for example, the shutdown of a machine or a process, leads to problems when the machine or process is being started, i.e. it may not work properly after shutting it down, employees may be unwilling to shutdown equipment. The root cause to this is not a system which is impossible to change, but rather an unstable system.

The eight types of waste which are relevant also in terms of industrial energy efficiency are: overproduction, unnecessary operations, transportation, discards, waiting, unnecessary movement, storage, and unused skills. Working to minimize and eliminate these both in the organization's value stream, but also in regard to the organizations energy use.

3.7. Basis – continuous improvements

The basis for long-term success is to work according to the principles of continuous improvement. This means that the leader must create an improvement culture within the group/company. The engine in the process of improvement is improvement groups and a systematic work with deviation.

To create an organization in which the principles of continuous improvement are used, and create a continuous improvement cycle, will not be made without effort. It demands leadership in order to be formed, kept active, and further developed. Fig. 3. visualize the above presented approach.

Work with improvement in small steps is of great importance, and one should aim to use all the tools for continuous improvement at disposal, such as deviation control. In order to be able to improve a system, one must be able to describe what the normal state or level is. If one does not know what the normal level is, improvements are not likely to take place. What is described and perceived as normal in the organization is what one can expect. When the outcome deviates from the expected normal state, the organization receives a signal that something has gone wrong. Detecing deviations may be achieved from, e.g. deviation management methods, the use of standards and routines etc. When a deviation from the normal state has been detected, the system can be improved in small steps, which in turn slowly increase the normal state level.

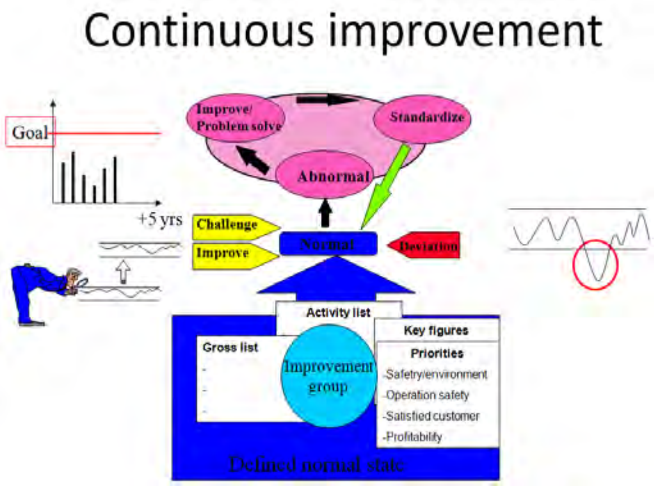

Fig. 3: Principles for continuous improvement in regard to energy efficiency.

Identify where the organization stand in terms of the performance it delivers. All phases have different needs for improvement. Improve from the defined normal state, do it with small steps but take steps often. Fig. 4. visualize the above presented approach.

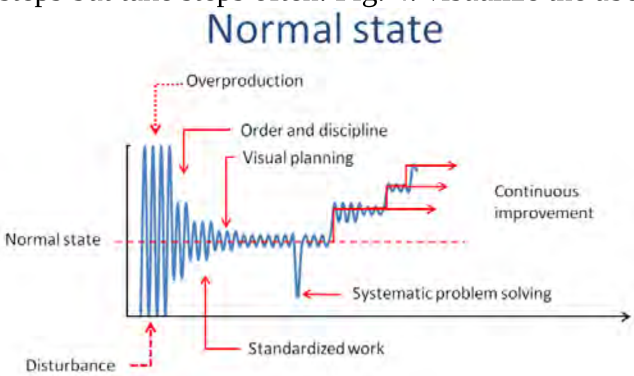

Fig. 4: Principles of defining and working with continuous improvement based on a normal state.

Ending improvement is as important as initiating them. Aim to try to find effective methods to evaluate when an improvement is “effective enough”. Describe the new normal mode, implement it, and move on to the next improvement that gives the best effect on the overall efficiency.

Moreover, one should put focus on the flow (creating smooth flows, governed by demand, be sure to reduce the variance). Also, do not forget the work- and information flow. Otherwise, adequate conditions for improvements will not be established. Furthermore, one should focus on quality and time, and make sure to keep the correct delivery parameters, i.e. avoid variation and overproduction. Make sure to deliver on time and let demand govern as much as possible. By describing what is normal, delivery can be assessed, and the root cause for the deviation can be corrected.

Some general issues related to successful energy management practices are similar, no matter which one of the two main roads one chooses for implementing change. These are presented in the coming sections.

3.8. The role of leadership

The role of leadership is independent of which main road one chooses to take. Leaders must lead through visions and overall goals. The larger the group/organization is, the more important it becomes. One of the reasons that this is so universal is that it provides space for the group and its members to use their individual creativity to solve the tasks. It uses the collective expertise of the group. However, it requires that the leader, e.g.:

- Is willing to join and show how tasks must be carried out (if required). Moreover, the leader has to be so knowledgeable that he or she, if needed, can act as a role model. Notably, this does not mean that the leader should do all the work for the employees.
- Serve as the creator of contacts, not as problem solver.
- Work with the monitoring of agreed activities and targets. Send feedback and let the person who made the job receive recognition for the accomplishment. Focus on those in the group who have the ability to influence.
- Work with action plans developed by those who must do the job. Do not let the action plans run over a too long period of time. Half a year may often be a good time horizon. Make sure to keep activity plans short and prioritize what is most important. Working with gross list and make decisions on new items on the list if space is available. Follow up about this on a regular basis, e.g twice a month: provide support, feedback and encouragement when the data is completed. Be sure that the agreements on completion dates are kept. Measure and visualize the number of items completed on time. If events are "slipping", find the root cause to this. In principal, this is a leadership issue. However, it may also be due to that the employee does not fit for the specific assignment or lacks time. In general, it is not due to unwillingness from the employee.
- Create conditions for a rapid feedback of the key indicators chosen to measure. Use them to guide and evaluate the work. The feedback often needs to be done weekly or whether it is possible, in real time.
- Try to create a positive atmosphere where “anything is possible”. A positive spiral. It is therefore important to ensure that "easy victories", particularly early in the process, are achieved.
- When one set goals and prioritize activities always base this on the organization’s value stream flow. It is the value stream which should be improved and not primarily single processes. It is only from the basis of the organization’s value flow, ones effort can be measured correctly. Working with energy in general may not provide much value, but rather to be effective in reducing waste.
- Put effort into understanding the system links. There is always a larger improvement potential in a system than in a single component or process. Let the need control demand.
- Develops a strategy for how the plant should be operated in the long run. Do this in terms of the desired operational strategy, and the desired technology strategy, and how the desired system strategy should look like. When done, one can be flexible, and make changes when available opportunities occur in the business. Streamlining systems and components are not so costly when a major change is to be made but may be very costly if done as an operational acticity, e.g. lead to production disruptions.

4. Conclusion

This paper addresses that increasing industrial energy efficiency is not only about technology, but equally important concerns the diffusion and adoption of energy management practices. In particular, the three factors, *culture*, *will* and *acceptance and recognition* interact between each other and create the conditions one has in an organization, department and group. It is these challenges that the leader has to work with to achieve the expected results. Moreover, results may be achieved in principally two different ways, where method governing is the way advocated for in this paper as it builds structural capital in the organization. If one choose to work with method governing, there are some fundamental principles that should be followed, e.g. focus on the organization's value stream, normal situation, standardization and continuous improvements. It is also of importance to define the system's normal state. From that position, improvements may be carried out in small steps. If a manager follows these basic recommendations outlined in this paper, and allows employees to understand and see the connections, improved results are achieved in the long run. Energy management practices using these principals may lead to employees showing improvements far above what the manager or organization thought was possible.

The applied methodology was shown to contribute with increased knowledge on how energy management practices successfully can be carried. Further research in the field using the applied methodology is suggested.

In conclusion, a fully successful in-house management program is dependent on both sound leadership and adoption of sounds methods. If either one is lacking, the full embodied (energy efficiency) potential in the organization is not released.

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Comparison of repowering by STIG combined cycle and full repowering based on exergy and exergoeconomic analysis

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Abstract: Nowadays, repowering is considered as the most common methods for improving status of current power plants. Repowering is the transformation of an existing steam power plant into a combined cycle system by adding one or more gas turbines and heat recovery capacity. It is a cost-effective way to improve performance and extended unit lifetime while adding capacity, reducing emissions and lowering heat rejection and water usage per kW generated. Each methods of repowering from “para repowering” to “full repowering” shall probably be the best choice for special national and economical power plant. In this paper different repowering methods have been introduced. The design concept consists in adding a gas turbine to the combined cycle, integrated by steam injection into the existing gas turbine. The steam is produced in a simplified heat recovery steam generator fed by the additional turbine’s exhaust gas.
A 156MW steam cycle power plant has been chosen as a case study. Two repowering scenarios have been utilized for this case. Thermodynamics code has been supplied for combined cycle and STIG combined cycle and compare with each others. The exergy and exergoeconomic analysis method was applied in order to evaluate the proposed repowered plant. Also, computer code has been developed for exergy and exergoeconomic analysis. It is anticipated that the results provide insights useful to designers into the relations between the thermodynamic losses and capital costs, it also helps to demonstrate the merits of second law analysis over the more conventional first law analysis techniques.The efficiency of the STIG repowered plant compares favourably with repowered combined cycle.

Keywords: *Repowering, Gas turbines, Steam injection, exergy, Exergoeconomic*

Nomenclature (Optional)

c	*cost per unit exergy ($/MW).....($/MW)*	*f*	*........ fuel*
C	*cost flow rate ....($/hr)*	*a*	*........ air*
e	*exergy rate per mass ....(MW/kg)*	*GT*	*........ gas turbine*
E	*specific exergy........(MW)*	*CRF*	*........ capital recovery factor*
Z	*capital cost rate of unit ....($/hr)*	*PWF*	*........ Present worth factor*
St	*........ steam*	*PW*	*........ Present worth*

1. Introduction

The country of Iran is experiencing in all fronts and areas and thus, consumption of electrical power is on the increase on a daily basis. Based on the ever increasing electrical energy consumption, changes in generating system load requirements, lower allowable plant emissions and changes in fuel availability, steam power plants repowering has been investigated much more as a method for energy conservation. Considering the increased electrical energy consumption and annual growth rate of 4.5 percent and according to the end of existing steam power plants life in Iran(like Montazer Ghaem power plant), repowering could be used as an economical method for increasing the output power with less investment than building a new power plant. Repowering of steam power plant can be achieved in several ways. In a full repowering, several gas turbines (GT) and heat recovery steam generators (HRSG) are installed in a parallel arrangement dispensing with the conventional boiler. Live steam from HRSG is used in the original steam turbine [1]. Industrial gas turbines are one of the well established technologies for power generation. Various additional cycle configurations such as reheating, regeneration, intercooling and steam injection have been suggested [2, 3]. All of them offer increased performance and increased output compared to a dry gas turbine cycle. Several types of water or steam injection gas turbine cycle (STIG) have been proposed in previous studies and the performance characteristics of them investigated [4]. The exhaust gas from the turbine is used as an energy source in a heat recovery steam generator (HRSG) where energy is transferred from the exhaust gases to the boiler feed water. The high pressure steam is generated from HRSG. The steam is then injected into the combustor. Injection of steam increases the mass flow rate through the expander and so the power output and the efficiency of the turbine increase. Steam injection also helps in reducing the NOx emissions from the gas turbine [5]. Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy-generation of the components [6]. Furthermore, exergoeconomic analysis estimates the unit cost of products such as electricity, steam and quantifies monetary loss due to irreversibility. Also, this analysis provides a tool for the optimum design and operation of complex thermal systems [7]. Combined and steam injected gas turbine cycle power plants are being installed all over the world as compared to other plants. The current emphasis is on increasing the plant efficiency and specific work while minimizing the cost of power production per kW and emission. In this paper, simple repowered combined cycle and combined cycle with added steam injected gas turbine have been modeled as a repowering design for 156MW steam power plant. For each cases exergy and exergoeconomic analysis has been studied and compared as a economical analysis for product cost estimation.

2. Process description

In this paper, 156MW steam cycle power plant has been selected as a case study for exploring two repowering methods and comparing with each other. The steam cycle power plant encompasses three turbines, that work with three different pressures and 6 feed water heaters. The Steam cycle has been modeled by MATLAB code and STEAM PRO (THERMOFLOW). Results of modeling steam cycle have been introduced and compared with real data in table.1.

Table1. Compare result of modeling steam cycle

	THERMOFLOW	Simulation code	Real
Plant Gross power(kW)	156300	156305	156294
Plant Gross Heat Rate(kJ/kWh)	9010	9120	8976
Plant Gross Efficiency (LHV)	39.9%	39.4%	40.1%
Superheater Capacity(kg/s)	133	130	136
Reheater Capacity(kg/s)	115	114	117

3. Repowering

There are several alternatives to combine and integrate a gas turbine into an existing steam power plant. As a result of ending boiler life time and exploring another aspect for this case, the best alternative is full repowering. Full repowering is defined as complete replacement of the original boiler with a combination of one or more gas turbines (GT) and heat-recovery steam generators (HRSG), and is widely used with very old plants with boilers at the end of their lifetime. It is considered as one of the simplest ways of repowering for existing plant.

For this power plant, Full Repowering with SGT5-4000F (formerly known as CC 2.V94.3A) with triple pressure reheat cycle has been considered as a first method for repowering old steam cycle power plant. Schematic flow diagram of combined cycle with the components is shown in Fig. 1. The gas cycle is selected as a topping cycle.

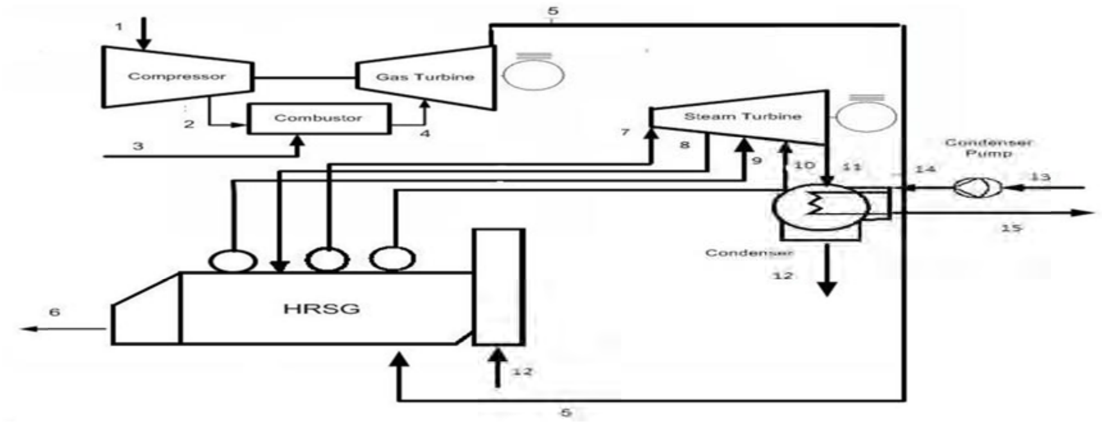

Fig 1. Combined cycle power plant (Repowering 1)

Second repowering scheme is based on the addition of a gas turbine and of a HRSG to a baseline of combined cycle. This method includes two main parts, the first part is combined cycle and the second part is a small gas turbine with a single pressure HRSG. These new components are integrated within the existing plant by injecting the steam produced by the additional HRSG into the existing gas turbine. The second part generates needed steam for injecting into main gas turbine of combined cycle in addition of producing extra power. In this way, the original turbine is transformed into a STIG (steam injected gas turbine), thereby increasing power. CC power augmentation is, thus, the sum of the power generated by the new gas turbine and the additional power of the original plant, comprising both the gas turbine and steam cycle. This scheme figure is shown in Fig.2.

As can be seen, the steam line feeding the original gas turbine connects the plant to the added section that comprises a gas turbine and a heat recovery steam generator. However, many other subsystems may be shared to reduce the repowering cost such as, for examples, flue gas treatment, electric power conditioning etc. One major addition to the plant is the water flow entering the new HRSG, which is inevitably lost at the stack. This can be a major drawback in certain situations and limits the applicability of the present scheme to sites with large fresh water availability, though the specific water requirements are fairly low, as will be shown later. If a low temperature thermal load is available nearby the power plant, the steam in the exhaust could eventually be condensed and the water could be recovered. Obviously, the very large size and the very low temperature level of such a heat sink restrict this option to quite uncommon cases, and its feasibility has to be carefully evaluated. Another significant feature of the proposed repowering scheme is its operational flexibility. Because of the inherent flexibility of the gas turbine, the entire additional section can be switched off in a short time, yielding part load efficiency equal to that of the original plant. At full load, the efficiency does not differ substantially, as will be demonstrated by the thermodynamic simulation. Fitting both the new and original gas turbines with variable intake guide vanes (IGVs) should provide a fairly wide operating range with efficiency close to rated.

4. Exergoeconomics analyses

All costs due to owning and operating a plant depend on the type of financing, the required capital, the expected life of a component, and so on. The annualized (levelized) cost method of Moran [9] was used to estimate the capital cost of system components in this study. The amortization cost for a particular plant component may be written as:

$$PW = C_i - S_n PWF(i,n) \tag{1}$$

$$\dot{C}(\$ / year) = PW \times CRF(i,n) \tag{2}$$

The present worth of the component is converted to annualized cost by using the capital recovery factor CRF (*i*,*n*), i.e [7]. Dividing the levelized cost by 8000 annual operating hours, We obtain the following capital cost for the *k*th component of the plant.

$$Z_k = \Phi_k \dot{C}_k / (3600 \times 8000) \tag{3}$$

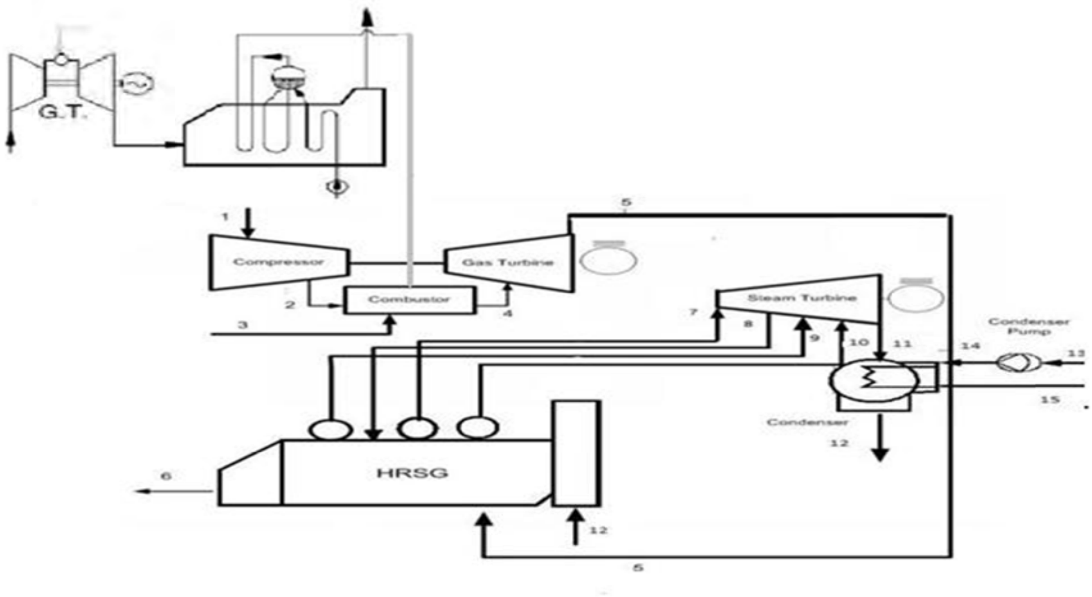

Fig 2. Combined cycle with STIG power plant (repowering2)

The maintenance cost is taken into consideration through the factor $\Phi_k = 1.06$ for each plant component whose expected life is assumed to be 15 years [9].

4.1. Thermoeconomic Modeling

The results from an exergy analysis constitute a unique base for exergoeconomics, an exergy-aided cost reduction method. A general exergy-balance equation, applicable to any component of a thermal system may be formulated by utilizing the first and second law of thermodynamics [10].

The cost balance expresses that the cost rate associated with the product of the system (C_P), the cost rates equals the total rate of expenditure made to generate the product, namely the fuel cost rate (C_F), the cost rates associated with capital investment (Z^{CI}), operating and maintenance (Z^{OM}) [12].

In a conventional economic analysis, a cost balance is usually formulated for the overall system (subscript tot) operating at steady state [12]:

$$C_{P,tot} = C_{F,tot} + Z_{tot} \tag{4}$$

Accordingly, for a component receiving a heat transfer and generating power, we would write [4]:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} - \sum_i \dot{C}_{i,k} + Z_k \quad (5)$$

To solve for the unknown variables, it is necessary to develop a system of equations applying Eq. (6) to each component, and it some cases we need to apply some additional equations, to fit the number of unknown variables with the number of equations [11].

A general exergy-balance equation, able to any component of a thermal system may be formulated by utilizing the first and second law of thermodynamics. In a conventional economic analysis a cost balance is usually formulated for the overall system operating at steady state. To derive the cost balance equation for each component, we assigned a unit cost to the principal product for each component. Depending on the type of fuel consumed in the production process different unit cost of product should be assigned [11].

5. Result and discussion

In this paper full repowering method for 156MW steam power plant has been applied. Table 1 indicates specification of repowered plant. It shows that, 68% of total power is produced by gas turbine cycle with 39% efficiency, in addition remained power are produced by steam cycle with 34% overall efficiency.

Repowered cycle produces 250MW more than old power plant. Heat rate in repowering power plant is 6500(KJ/KWh) and 1500(KJ/KWh) more than old power plant. Efficiency increases 15% for repowering model more than old power plant.

Table 2- combined cycle results

	Repowering
Gas Turbine(kW)	278041
Steam Turbine(kW)	125655
Plant Total (kW)	403695
Plant net LHV efficiency (%)	55.27
Plant net LHV heat rate(kJ/kWh)	6514
Gas turbine LHV efficiency (%)	39.05
Steam turbine efficiency (%)	34.59

Second proposed method uses STIG and adds a small gas turbine with single pressure HRSG. Result of this method with three model of gas turbine for producing steam injected, is shown in Table 2. For each three gas turbine model efficiency and exergy efficiency has been calculated. These results show that, increasing amount of injected steam mass flow can improve efficiency, but obviously only a limited amount of steam can be injected into the original gas turbine. This method can improve efficiency also increasing net power. In second stage, exergy and exergeoconimcs analyses are studied for both repowering method as an economical analyses. Table 3 and 4 show Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in both repowered power plants.

Table 3- combined STIG cycle results

	V64.3A	V84.2	V84.3
Injected steam mass flow (kg/s)	26.2	49.2	53.2
added gas turbine power (MW)	68.7	108.2	138.2
Gas turbine power (MW)	306.1	330	334.5
Steam turbine power (MW)	123.8	140.2	142.1
Added gas turbine efficiency (%)	37.2	33.7	35.9
Gas turbine efficiency (%)	48.8	52.6	53.3
Steam turbine efficiency (%)	32.8	36.6	36.5
Net power (MW)	498.7	578.8	615
Efficiency (%)	61.2	60.32	60.8
Exergy efficiency (%)	59.6	58.6	59.1

Table 4-Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in combined cycle

Component	Exergy Destruction(MW)	CF0 ($/MW)	CP0 ($/MW)	CD0 ($.s)	CF ($/MW)	CP ($/MW)	CD ($/s)
COMP	46.2489	0.0061	0.0073	0.2821	0.0064	0.0078	0.2959
COMB	152.5663	0.0049	0.0059	0.7475	0.0051	0.0061	0.7780
GT	17.0101	0.0059	0.0061	0.1003	0.0061	0.0064	0.1037
ST	36.2881	0.0083	0.0092	0.3011	0.0089	0.0101	0.3229
HRSG	38.6824	0.0063	0.0073	0.2436	0.0065	0.0078	0.2514
COND	4.8385	0.0083	0.2376	0.0401	0.0083	0.2603	0.0401
FWP	0.0236	0.0064	0.0113	0.0001	0.0064	0.0177	0.0001
CWP	0.6226	0.0064	0.0006	0.0039	0.0064	0.0007	0.0039

These results represented that combustion chamber and heat recovery steam generator in repowered combined cycle has most exergy and exergy cost destruction due to nature of combustion; however combustor in combined cycle plant shares about 51% TED, 44% TCD0 and 43% TCD. In next steps, compressor and steam generator have most exergy and exergy cost destruction.

Comparison of cost fuel and product of turbine for both schemes is shown in table 5. Gas turbine produce major of net power therefore cost product of gas turbine has important role in whole cost product. Gas turbine cost product for STIG combined cycle is less than ordinary combined cycle. However Cp of HPST in STIG cycle is more than ordinary combined cycle, HPST power is not as much important as other power product utility such as GT, LPST and IPST. Rate of total cost exergy destruction is specified in table 6.As shown, second repowering method can decrease TCD and TCD0 and therefore this scheme is more economical. Although exergy destruction increases in this method, ratio of exergy destruction to net power improves appreciably. Combined cycle with STIG can produce 498MW net power and has 356 MW exergy destruction but ordinary combined cycle produce 400MW net power with 346MW exergy destruction.

Table 4-Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in STIG combined cycle

Component	Exergy destruction(MW)	Cf0 ($/MJ)	Cp0 ($/MJ)	CD0 ($/s)	Cf ($/MJ)	Cp ($/MJ)	CD ($/s)
Compressor	55.3869	0.0057	0.0073	0.3157	0.006	0.0079	0.3323
Combustion	120.8498	0.0049	0.0056	0.5921	0.0051	0.0058	0.6163
Gas Turbine	10.4329	0.0056	0.0057	0.0584	0.0058	0.006	0.0605
HPT	3.3937	0.0059	0.0078	0.0200	0.0074	0.0086	0.0251
IPT	21.4033	0.0069	0.0079	0.1476	0.0074	0.0087	0.1583
LPT	11.199	0.0069	0.0084	0.0772	0.0074	0.0093	0.0828
HRSG	38.2549	0.0056	0.0065	0.2142	0.0058	0.0069	0.2218
Condenser	9.6905	0.0069	0.202	0.0668	0.0074	0.2238	0.0717
CEP	0.0239	0.0069	0.0106	0.0001	0.0074	0.008	0.0001
deaerator	0.2376	0.0057	0.0074	0.0013	0.006	0.017	0.0014
LPFP	2.9043	0.0057	0.0067	0.0165	0.006	0.0151	0.0174
IPFP	0.4698	0.0057	0.0065	0.0026	0.006	0.0101	0.0028
HPFP	0.0878	0.0057	0.0063	0.0005	0.006	0.0075	0.0005
CWP	0.78	0.0057	0.0053	0.0044	0.006	0.0024	0.0046
added Comb	49.8	0.0051	0.0064	0.2539	0.0052	0.0066	0.2589
added Comp	15.8891	0.0064	0.0085	0.1016	0.0069	0.0091	0.1096
added GT	4	0.0064	0.0066	0.0256	0.0066	0.0069	0.0264
added HRSG	11.789	0.0066	0.0086	0.0778	0.0086	0.0089	0.1013

Table 5-comparsion of cost fuel and product with and without considering capital investment for both schemes

	combined cycle				STIG combined cycle				
	G.T.	HPST	IPST	LPST	G.T	HPST	IPST	LPST	added GT
Cf0 ($/MJ)	0.0064	0.0062	0.0074	0.0074	0.0056	0.0059	0.0069	0.0069	0.0064
Cf ($/MJ)	0.0065	0.0069	0.0083	0.0084	0.0057	0.0078	0.0079	0.0084	0.0066
Cp0 ($/MJ)	0.0065	0.0064	0.0078	0.0078	0.0058	0.0074	0.0074	0.0074	0.0066
Cp($/MJ)	0.0067	0.0073	0.0091	0.0092	0.0060	0.0086	0.0087	0.0093	0.0069

Table 6-comparsion of cost exergy destruction with and without considering capital investment for both schemes

	Exergy destruction(MW)	TCD0 ($/s)	TCD0 ($/h)	TCD ($/s)	TCD0 ($/h)
Simple C.C	346.2758	2.3209	8337.083	2.4188	8686.63
STIG C.C	356.5925	1.9771	7117.703	2.0925	7533.21

6. Conclusions

In this paper an old steam cycle has been chosen as a model for repowering. At first full repowering has been examined for this model and it changed into combined cycle that has 400MW net power. This repowering increases net power and improves efficiency. As a result of old boiler and power capacity for this model, full repowering is one of the useful an economical method. After that, a gas turbine and a single pressure HRSG added to combined cycle and it has been changed into STIG combined cycle. Net power increases with adding new gas turbine and using STIG in this method. However increasing amount of mass flow steam injected can heighten net power, there is limitation for mass flow. Exergy and exergoeconomic methods have been applied for analysis and comparison both repowering method. An exergy-costing method has been applied to both cases to estimate the unit costs of electricity produced from steam turbines. The computer program that was developed which shows that the exergy and the thermoeconomic analysis presented here can be applied to any energy system systematically and elegantly. If correct information on the initial investments, salvage values and maintenance costs for each component can be supplied, the unit cost of products can be evaluated. These analyses shows that cost product of combined cycle with STIG is less than ordinary combined cycle. Also net power and efficiency of combined cycle with STIG is more than ordinary combined cycle. Although using water for steam injection is the most problem of this new method, there are some suggestions to recycle water and reused in the cycle.

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Possibilities to implement pinch analysis in the steel industry – a case study at SSAB EMEA in Luleå

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Abstract: Steelmaking is an energy intensive industry. Much development work has been accomplished during the past years to make the processes more efficient. Process integration has come to play an important role for identifying efficiency measures, using mathematical programming as general tool. So far only a few minor process integration studies using pinch analysis have been made in this type of industry, and only on smaller sub-systems. This paper presents the results of a pinch targeting study that was conducted at the Swedish steel making company SSAB EMEA in Luleå. The pinch analysis methodology was originally developed to study heating, cooling and heat exchange in process systems with many streams. In the steel industry there are relatively few streams that are appropriate for heat exchange. This limits the use of pinch analysis. However, this study demonstrates that pinch analysis is a powerful tool for certain subsystems, especially the gas cleaning unit of the coke plant. The paper includes several suggestions for improved energy efficiency in this section of the steel plant.

Keywords: *Pinch analysis, Energy efficiency, Steel industry, Process integration*

1. Introduction

1.1. The steel industry

The steel industry sector is the second largest industrial user of energy in the world. In 2007 it used 24 EJ or 6700 TWh according to IEA [1]. Steel is an important construction material and the production has increased with the growth of the world economy. The development of the world production of steel is shown in Fig. 1.

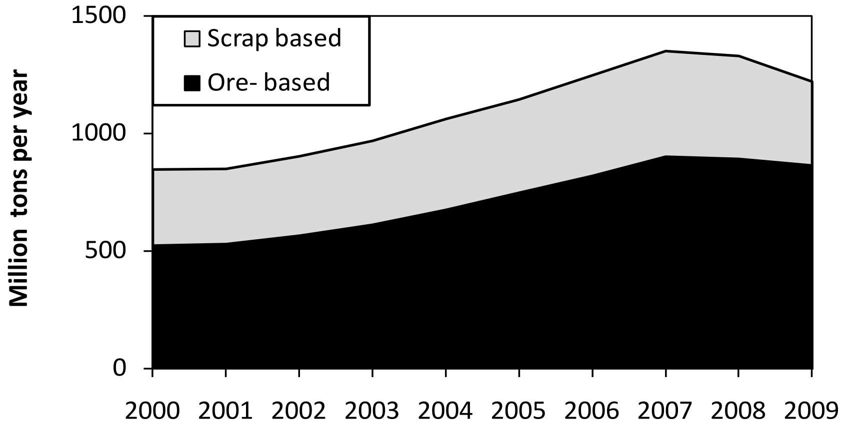


Fig. 1 Development of world steel production from ore and scrap based route[2]

The diagram shows a steady growth except from the recession years 2008-2009. A considerable part of reactants and fuels that are used in the processes are of fossil origin. The combination of production increase and use of fossil energy puts an emphasis on work to decrease energy consumption. One road to achieve this is to improve the processes to decrease their consumption. A large amount of work is and has been carried out in this area. It is, however, considered out of scope for this paper and not described here. A second road is to improve the system efficiency, with process integration as one important tool. That type of work is the subject of this paper.

Steel is produced using two alternative routes: an ore based route where primary steel is produced from iron ore and a scrap based route where recycled steel (scrap) is re-melted (Fig. 2).

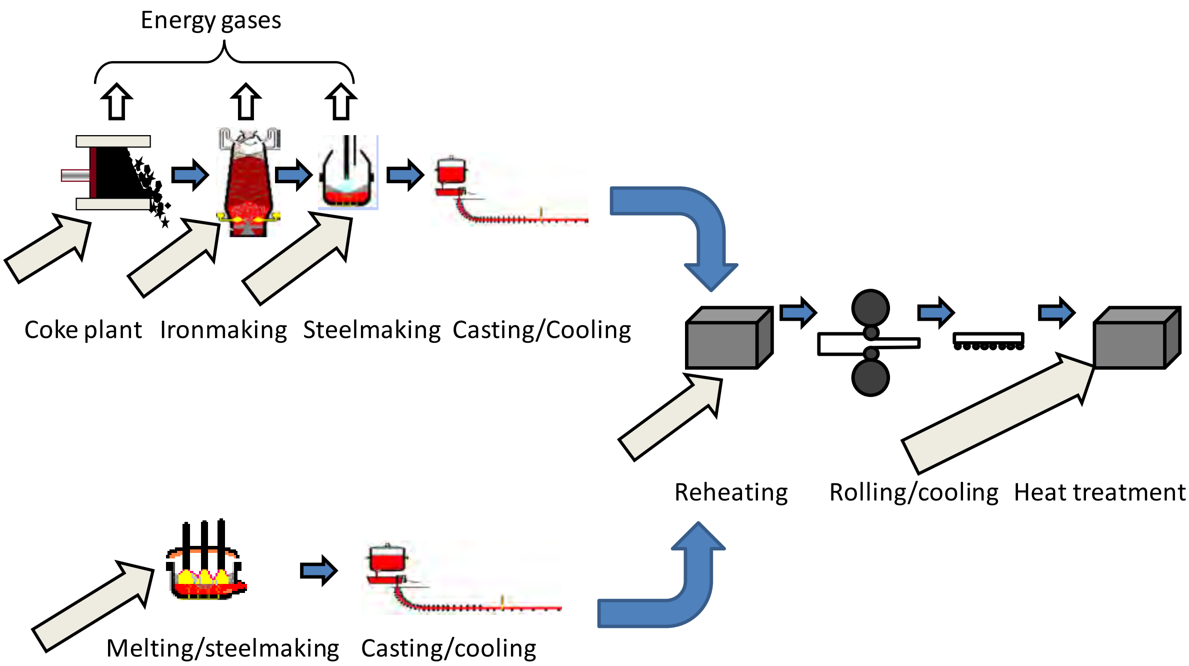


Fig. 2 Process route for ore and scrap based steel production

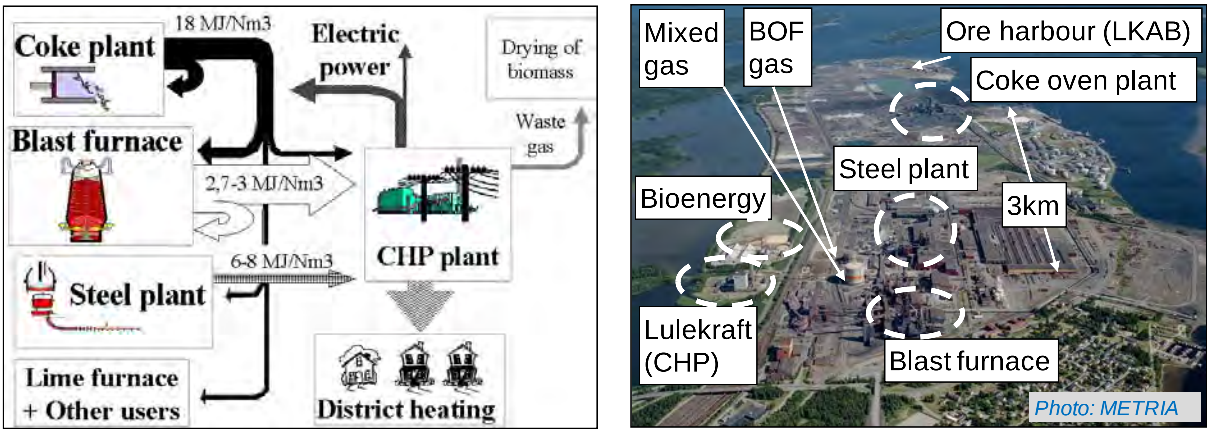
The upper branch in Fig. 2 illustrates the ore-based route. The production is based on coal and ore (mainly iron oxide). The coal is converted to coke by dry distillation in a coking plant. Approximately 25% of the weight is recovered as energy rich gas, tar and chemical products. The ore, e.g. in the form of pellets, is fed into the blast furnace along with coke and preheated blast air. The blast furnace produces a hot liquid metal with high carbon content. A combustible gas is obtained as a by-product. The hot metal is transformed into steel in an oxygen converter (BOF). An energy-rich gas is obtained as a by-product. After ladle treatment the steel is cast in a continuous casting machine. The semi-finished cast steel is cooled and transported to a rolling mill where it is heated to rolling temperature and rolled (or forged) into products and cooled on a cooling bed. Depending on the product, there may be additional treatment, such as heat treatment, cold rolling and metal coating (e.g. zinc). In most cases by-product energy gases from iron and steel-making are used in the reheating furnaces.

After some time the steel products are returned as scrap, and converted into new steel using the scrap based route (lower branch in Fig. 2). The scrap is melted and heated, usually in an electric arc furnace. The molten steel is then refined. This post-processing can be carried out in the furnace, in the ladle treatment or in a separate unit, e.g. refining with oxygen in a so-called AOD converter. Then the finished steel is cast and treated in the same way as in the ore-based route. This recirculation is an important part of the steel economy.

The system studied in this work is the SSAB EMEA steel plant in Luleå. This is an ore-based plant. The by-product energy gases cannot be used for preheating as the rolling mill is situated 800 km from the steel plant. Instead they are used in a local CHP plant, which co-produces electricity for the steel plant and district heating for the community (see Fig. 3 a.

1.2. Process integration and Pinch analysis

A typical process industry does not consist of independent process units. Instead, it is a network of units exchanging energy and energy media with each other. Very often the local community is also involved in the network, e.g., through power generation and/or district heating. The flowsheet and photo in Fig. 3 show the network that is studied in this paper.



a) Flow sheet　　*b) Actual plant*

Fig. 3. Network of the Luleå energy system.

The different units exchange energy and material with each other. Changes in one unit have side effects on the other units. Energy saving in one unit does not necessarily lead to energy saving of the total system. A global approach is needed to avoid sub-optimization. A flowsheet does not tell the whole truth. At the actual plant site there is usually a great distance between some units, in this case up to 2-3 km (see Fig. 3 b). Some connections that would be optimal from an energetic point of view may be impossible from a practical and economic point of view. A good analysis tool should be able to select the solution that is technically and economically most attractive.

A first attempt to make a more systematic analysis of this type of problem using pinch analysis was made at Manchester University in the UK [3]. In this type of analysis, the heat-carrying media are categorized as either cold streams (media that require heating during the process) or hot streams (media that require cooling). Based on this information it is possible to construct *composite curves* in order to determine the minimum energy-consumption target for the process. The curves are profiles of the process' heat availability (hot composite curve) and heat demands (cold composite curve). The degree to which the curves can overlap for a specified value of minimum temperature difference for heat exchanging (ΔT_{min}) is a measure of the potential for heat recovery. The point of closest approach of the composite curves, i.e. where ΔT_{min} is reached, is known as the pinch point. The effect of different operations and/or process modifications can be studied using pinch analysis. The relative position of such operations in the composite curves with respect to the pinch point is often a determining factor. Further details are described in Section 2 (Methodology). Pinch analysis has since then become a wide-spread tool for process integration in many industrial systems. Ref [4] can be seen as an example.

Steel industry energy systems are characterized by large high temperature flows of molten, solid and gaseous materials, as well as by energy intensive chemical reactions. Mathematical programming is considered particularly suitable for optimizing energy flows in this type of system. A specific simulation and optimization tool (reMIND) was developed and implemented for steel plant applications ([6], [7]) and has reached a position as standard process integration tool for those applications.

Pinch analysis was originally developed for large systems with many streams that require heating and cooling and that are suitable for heat exchanging. This makes implementation in the steel industry somewhat restricted as there are relatively few streams, and the ones with the largest energy content are in the form of molten metal, hot slag or as radiation from slabs, i.e. unsuitable for conventional heat exchanging. Only limited uses of pinch analysis in the steel industry are reported ([8], [9]). However, previously conducted system studies carried out in the steel sector and PRISMA indicate that there are subsystems where pinch analysis could be a powerful tool. The Swedish Energy Agency and the national program for process integration decided to carry out a study on the possibility to use pinch analysis in the steel and mining sector. A major part of that work was a smaller pinch targeting study of the Luleå Steel plant system.

1.3. Scope of paper

The main scope of this study is to describe the above mentioned targeting study and the conclusions on possible use of pinch analysis in the steel industry.

2. Methodology

The analysis procedure for one of the subsystems (the gas cleaning system of the coke oven plant) is described in more detail to illustrate the methodology.

Data was collected together with coke plant staff. The energy streams were compiled and characterized as hot or cold streams. The cold streams, or ”heating loads”, are shown in Table 1. A similar table (not shown here) was made for the hot streams.

Table 1 Heating loads in the coke oven gas cleaning area

Process part	Unit	T_{start} (°C)	T_{end} (°C)	Flow	Load (kW)
Ammonia stripper	DB 602 A/B	MP steam			5 852
	EB 605 cold side	6.8 [1]	63	22 t/h	≈1 500
Benzene stripper	EA 2363	LP steam			42.3
	DB 2362	LP steam			633
	EA 2361	178	178.1		950
	EB 2261 A-D cold side [2]	27	143	51.8 m^3/h	2 620
2nd feed water preheat	FL 1401	63	124	22 t/h	1 566
Sulfur stripper	EB 601 cold side	26	51	61.1 m^3/h	1 770

[1] Yearly average water temperature in Lule River
[2] Heat capacity of 2.13 kJ/kg K is used for the circulating oil (petroleum) Density = 881 kg/m^3. The load is the average value of the two streams: (3132 kW + 2108 kW)/2

Composite curves (CC) were constructed for the gas cleaning section of the coking plant, shown in Fig. 4, using the stream data. The minimum distance between the curves is set by ΔT_{min}, set at 10 K in this study. Internal heat recovery is theoretically possible where the curves overlap (shaded area). A larger ΔT_{min} would push the curves further apart, thus decreasing the overlap and cause an increasing demand for heating and cooling media ($Q_{H,minimum}$ and $Q_{C,minimum}$).

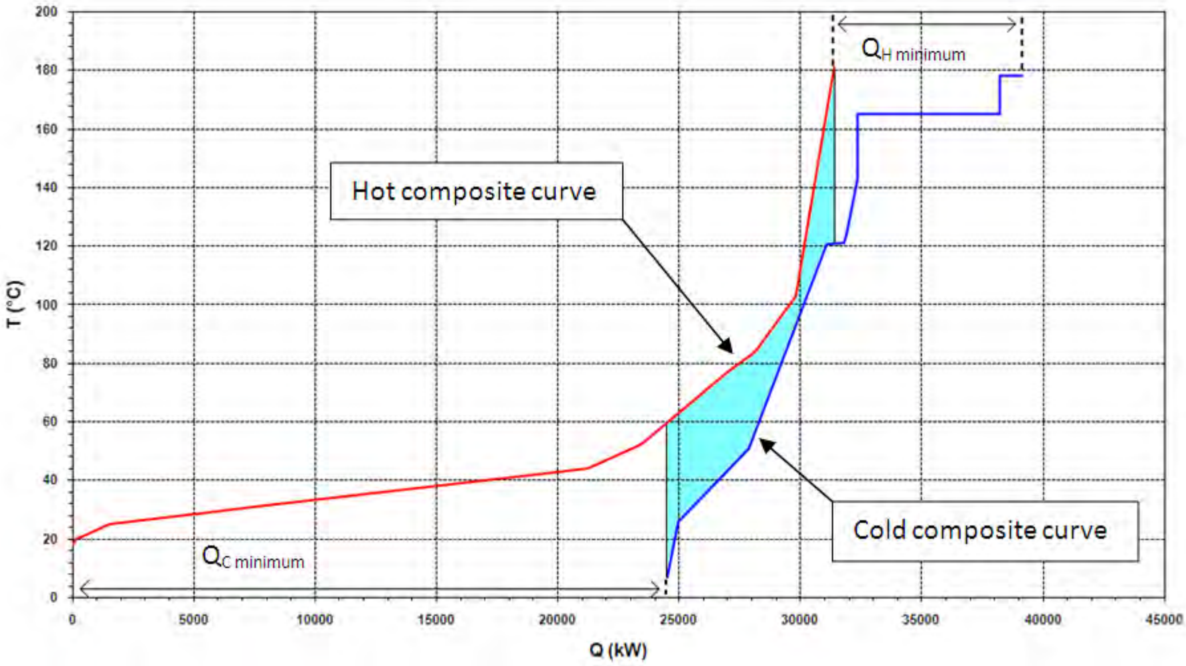


Fig. 4 Composite curves (CC) for the coking plant's gas cleaning area

The CC establish the energy targets (minimum hot and cold utility demand), but are not suitable for identifying appropriate utility steam levels and loads, or whether excess process heat can be used for hot water production instead of using cooling water. The Grand Composite Curve (GCC) is more appropriate for analyzing the interaction between the process and the utility system. Therefore a GCC was constructed for the gas cleaning area. To visualize the correspondence between CC and GCC, these are put next to each other in Fig. 5. The hot and cold composite curves are merged into one curve, i.e. the GCC, by calculating the net heat load in each temperature interval. A new interval can often be identified by a gradient change in the curve.

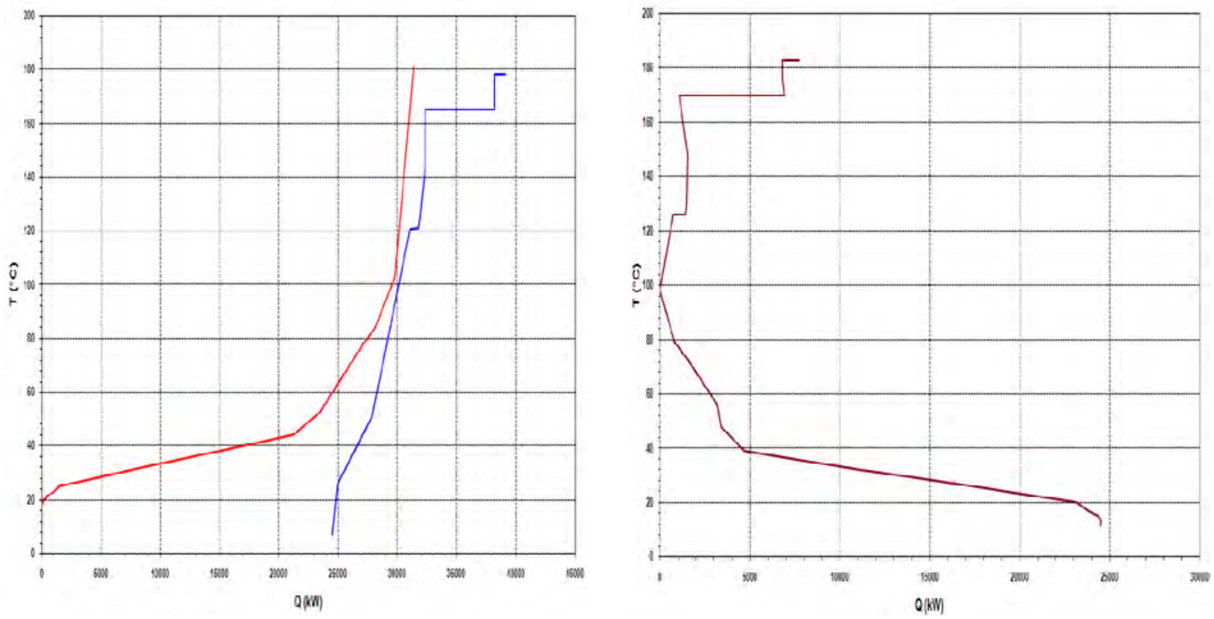


Fig. 5 Composite curves (CC) and corresponding grand composite curve (GCC) for the coking plant's gas cleaning area

A more detailed view of the GCC is shown in Fig. 6, enabling an analysis of different possible utility level setups.

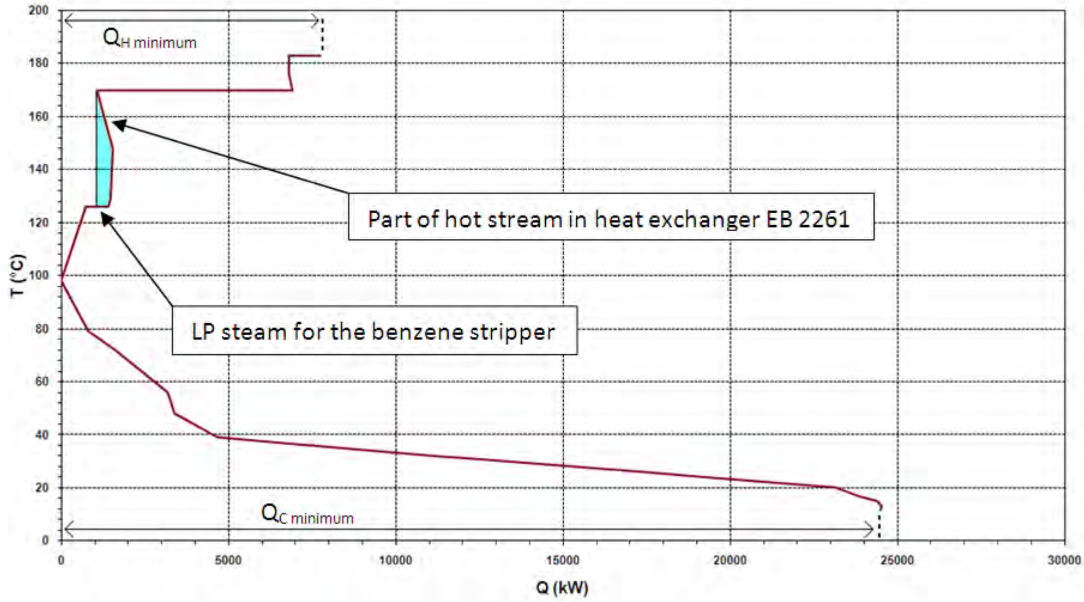


Fig. 6 Grand composite curve for the coking plant's gas cleaning area

One can for example examine whether there is any heat surplus (below the pinch) at useful levels, which could be used for steam generation, district heating, electricity production in a Rankine cycle, etc. The shaded part shows where internal heat exchange between temperature intervals is possible, i.e. a so-called pocket. The curve shows that part of the hot stream in EB 2261 is used to generate LP steam for the benzene stripper. The same methodology was used to analyze the other subsystems and the total plant.

3. Results

3.1. Coke plant

The analysis of the gas cleaning section of the coking plant (Fig. 4) shows that the demand for feed water preheating will decrease since less steam is needed in the process. The current preheating load is approximately 1500 kW in heat exchanger EB 605 and 1566 kW in FL 1401 (Current preheating load ≈3066 kW). The minimum preheating requirement turned out to be 2779 kW in total in this first step of the analysis of the coking plant. The horizontal parts of the lower line represent the demand for condensing steam in the strippers. The slope is determined by the flow multiplied by the heat capacity [kJ/°C] in each temperature interval. In all, the gas cleaning area currently uses 25.7 MW of cooling water whereas the minimum cooling demand, determined by pinch analysis, is 24.5 MW ($Q_{C,minimum}$ in Fig. 4). The process uses 9 MW of external heat, compared to 7.7 MW ($Q_{H,minimum}$.). This means that there is a 14% steam savings potential if a maximum energy recovery heat exchanger network were to be built, assuming ΔT_{min} = 10 K. The pinch temperature is 103°C for hot streams and 93°C for cold streams. That tells us, for example, that external heating media has to be at least 103°C and that the cooling media can be 93°C at the most, in order not to violate the ΔT_{min} of 10 K for heat exchange between utility and process streams.

An extended study (diagram not shown) was carried out to study the effect on heating and cooling loads in the total coking plant area assuming that steam is used at as low pressure as possible. This is particularly important if the steam is extracted from a turbine, in order to maximize electricity production. This showed a 1290 kW steam saving potential. The main reason was elimination of the use of LP steam for feed water heating and avoiding heat exchange through the pinch.

A lot of heat at high temperature is wasted when washing water at around 70°C is used to cool the hot coke oven gas directly after it leaves the ovens. It should be possible to heat exchange the gas down to the tar dew point. A study was made to study what could be gained from such an arrangement. The dew point is between 350 and 150°C. An inlet temperature at a temperature of 450°C (i.e. significantly above the dew point) was assumed to give a safety margin. A gain of 9 MW was indicated if the heat is used to replace steam from the boiler.

3.2. Blast furnace and steel plant

A first attempt was made with separate studies of the blast furnace, the steelmaking converter plant, the ladle metallurgy and the continuous casting. However, limited availability of cold streams limited meaningful implementation of process integration based on pinch analysis. Since the distance between the units was not very large, a merged study of the Blast Furnace-Steel Plant system was tried. The analysis showed a potential hot utility savings of 2.7 MW that could be accomplished by using BOF steam for preheating the inlet gas to the cowper. This is further commented in the discussion chapter.

3.3. Total system

The study indicated that there actually is a match between the two sites, where the steel plant fits in the coking plant's "pocket". Flue gases and hot coke oven gas are in that case used to heat the blast air and steam from the BOF converters is used to run the strippers in the coking plant. There is a difference in load magnitude between the two sites, where the blast furnace and steel plant demand lots of external utility.

4. Discussion

4.1. General results

The expected result was that many sources of excess heat at hot water temperature level would be found. However, that is not the case assuming that this study shows the whole picture. Excess heat is available either at low temperatures, where utilization is more or less impossible, or at levels where steam could be generated. The dominating energy carrier suggested in this study is steam at fairly moderate pressure and temperature (below 200°C). Before heat recovery of that kind is realized, there must be heat sinks where the steam can be utilized. Several options are available but the simplest solution appears to be a steam turbine for electricity production.

4.2. System blast furnace + steel plant

The study in section 3.2 suggested that BOF steam should be used to preheat input cowper gas. For different reasons this is not technically feasible. However, it indicates another option that was not visible with the available stream data. A solution that has been used in some plants is preheating of the combustion air using a heat exchanger with the off-gas from those burners. The results confirm that this is interesting, although a different technical solution was suggested due to lack of detailed data regarding internal cowper streams.

4.3. Analysis of the total system

The analysis shows a large energetic gain by transportation of flue gases and steam between the sites. However, under present conditions this can be judged as less realistic due to the transport distances. Combining the two sites does not seem to be a feasible option just by investigating integration possibilities. It would, however, add a degree of flexibility to have a common steam net.

4.4. Effect of process integration on sustainability

The effect is usually indirect, energy that would otherwise have gone to waste is used elsewhere, e.g. to replace consumption of fuel. Pinch analysis is useful where matches can be found at proper temperature between heat sinks and excess heat.

4.5. Future work

It would be interesting to carry out further studies at other plants. It is suggested that this is done as integrated projects where Pinch analysis is used together with other methods. Commonly available software and educational tools could increase industrial general awareness about pinch analysis.

5. Acknowledgments

The authors of this paper would like to thank Ida Engström and Rickard Broström at SSAB in Luleå, for guidance about the processes and for providing data to this work, and Chuan Wang, MEFOS, for valuable comments. We also would like to thank the Swedish Energy Agency for financing the study.

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Energy efficient dual command cycles in Automated Storage and Retrieval Systems

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Abstract: Sustainable manufacturing claims for more energy efficient operations in warehouse management. In AS/RSs they can be pursued by optimizing storage and retrieval cycles so that the least energy is required to move the crane. While picking operations have been traditionally optimized in order to minimize picking times directly linked to the service level perceived by customers, a sustainable approach leads to change this perspective by optimizing storage and retrieval cycles to lower energy requirements. In this paper we propose an energy-based heuristic to re-sequence retrievals in order to perform dual command cycles with the least energy requirements. Impact on both energy savings and round trip times is assessed when moving from single command to dual command cycles, if storage and retrieval operations are combined by the common first-come first-served policy. Further improvements on energy and time performances achievable by adopting different re-sequencing heuristics are then investigated. Factors affecting energy consumption and round trip times such as the storage allocation strategy, the re-sequencing time-based or energy-based policies, the demand distribution, and the shape of the rack, are analyzed by a 2^4 factorial design of experiments.

Keywords: *energy efficiency, Automated Storage and Retrieval Systems, dual command cycles.*

1. Introduction

An automated storage and retrieval system (AS/RS) is a fully automated facility, where cranes running on rails between fixed storage racks pick up and drop off unit loads without the need of human operators.

AS/RSs have been recognized as sustainable facilities [1]. Since they allow to store inventory more densely and vertically than traditional warehouses, they reduce, in facts, energy consumptions to heat, cool, light and ventilate excess square footage. Furthermore, allowing storage of the same number of units in a smaller footprint, AS/RSs require less concrete, reducing carbon dioxide emissions.

From an operations management point of view, energy efficiency can be pursued in AS/RSs by optimizing also their storage and retrieval cycles, so that the least motion energy consumption can be achieved [2]. While picking operations have been traditionally optimized in order to minimize picking times directly linked to the service level perceived by customers [3], a sustainable approach leads to change this perspective by matching time performances with energy efficiency ones.

Dual command cycles couple a storage operation to a retrieval one into the same trip, in order to avoid idle travels of the AS/RS machine to/from the I/O station as in single command cycles, where only one operation (storage or retrieval) is performed at a time. In a dual command cycle, therefore, the AS/RS machine departs from the I/O station with a load on board and reaches the desired storage location, then it moves directly towards the selected retrieval location where the load is picked up, and then it comes back to the I/O station. The possibility of performing dual command cycles depends on the simultaneous availability of both storage and retrieval requests. When this occurs, dual command cycles have been recognized by literature to lead to significant time savings if compared to traditional single command ones in the order of 30% [4]. Adopting a sustainable perspective, the first question

to be addressed is therefore how much energy consumption can be reduced by adopting dual command cycles with respect single command ones.
Time savings are strictly related to the storage assignment policy adopted. Graves et al. [4] demonstrated by both analytical and enumeration analysis that maximum time savings are achieved by mandatory interleaving, that means performing dual command cycles whenever possible, with a full turnover strategy rather then the common random allocation. The full turnover strategy is a dedicated assignment policy, which exclusively assigns a given number of locations to a product, on the basis of its demand rate sorted by decreasing order. In this way the most frequently moved items are located to the most convenient positions with respect to the I/O station and maximum improvement on the selected performance is achieved. From the traditional time-based perspective convenience has been read in terms of minimum picking time, which has been the performance to be enhanced. Since it was found that interleaving time accounts for 30% of the total round trip time (equal to the sum of the travel time from the I/O station to the storage location + interleaving time from storage to the retrieval location + time to travel from the retrieval location to the I/O station), the time-based full turnover strategy allows to minimize the one-way travel component from/to the I/O station of a dual command cycle, thus is able to affect the 70% of total time.

In our opinion, when a sustainable perspective is adopted convenience should be read in terms of energy efficiency. Therefore, in order to assess the maximum energy savings achievable by dual command cycles, we introduce a full turnover strategy based on the least motion energy, that means assigning high turnover items to locations requiring the least energy to be served. Energy performance achievable by the energy-based full turnover policy can therefore be considered as upper bounds of energy savings achievable with other less performing but more easy to apply storage policies, such as the random allocation (i.e. each open location can be occupied by every item) or the class-based storage allocation. It was already shown in our previous work [2] how energy-based dedicated zones differs from time-based ones; from the traditional rectangular or L shapes of time-based approach, in fact, step-wise zones are identified by the energy-based one, with a general shift towards upper levels of the rack, due to exploitation of gravity.

Performance improvement gained by dual command cycles depends also on the capability of optimally combining storage and retrieval requests in order to optimize the interleaving phase. A common practice is to adopt a First-Come First-Served (FCFS) policy, which means processing storage requests in the exact sequence they arrive and combining each storage with the first available retrieval request respecting the order it has been inserted into the information system. While processing storage in FCFS order reflects the fact that in general input unit loads are moved by a conveyor to the I/O station of the AS/RS and therefore their sequence is fixed, retrieval requests can be considered as electronic messages, which can be rearranged in any desired sequence.

When a random allocation is performed, and only one open location is available at a time, Bozer et al. [5] explained that the dual command scheduling of AS/RSs can be formulated as a Chebyshev travelling salesman problem, which is known to be NP complete. When multiple open locations are available for storage, the problem involves finding the best storage locations other than coupling storage and retrieval requests and it is in general NP-hard [6]. This is the reason why several heuristics were developed to overcome such complexity. By analytical analysis, Han et al. argued that in order to gain an improvement in throughput greater than 10%, travel-between (i.e. interleaving time from storage locations to the retrieval ones under the hypothesis of rectilinear constant speed motion) must be reduced by over 50%

with respect to FCFS retrievals as it is achievable by the Nearest-Neighbor Heuristic [6]. The overall performance of this heuristic can be enhanced by adopting a class-based storage policy rather than a random one [7]. Near-optimal solutions can be achieved under random storage by the ε-optimum algorithm proposed by Lee and Schaefer [8]. An O(n^3) heuristic for dedicated storage with one open location at a time (meaning that storage locations have been previously identified and no storage choice has to be performed) was also proposed by authors [9] with very good performance with respect to the optimal solution.

In this paper, a heuristic approach to couple storage and retrieval requests within a given time period aiming at minimizing motion energy requirements rather than picking time is proposed for the energy-based full turnover strategy. Time and energy are related by power, but it should be considered that due to simultaneity of movements along vertical and horizontal axes the Chebyshev metric applies to travel time (i.e. machine travel time is the maximum between x-time and y-time), while energy is the sum of the requirements of both the x motor and the y motor installed in the crane. This is the reason why energy savings potential could be different from time savings potential gained by dual command cycles and should be analyzed. Furthermore one can wonder to what extent energy-based dual command cycles overcome time-based ones as regards energy saving if compared to single command cycles and FCFS dual command ones.

Therefore, picking time and energy performances of dual command cycles identified by the proposed heuristic are compared to the commonly use First Come First Served combination approach and Lee Schafer time-based heuristic's one by simulation. Energy saving potential related to dual command cycle optimization is assessed as well as the impact of a sustainable approach on client service levels. Factors such as the shape of the rack affecting motion energy, the ABC demand curves affecting the turnover frequency or the type of full turnover strategy (time-based versus energy-based heuristics) are considered in other to analyze the amount of energy savings obtainable by optimizing both location assignment and picking cycles.

The paper is organized as following. In par. 2.1 the energy model developed in order to compute energy required for crane movements is described. In par. 2.2 an energy-based heuristic for combining storage and retrieval requests is proposed, while in par. 2.3 the design of simulation experiments is described. In par. 3 results are analyzed and conclusions on energy saving potential are collected in par. 4.

2. Methodology

To adopt the new perspective aiming at energy efficient manufacturing, new models and performance measures should be introduced in order to assess energy saving potential of different operation policies.

The first step is the development of an energy model so that motion energy required by the crane to reach each storage location of the AS/RS rack can be estimated. The second step is therefore an energy-based heuristic to combine storage and retrieval requests into dual command cycles. Finally, factors which are expected to affect energy efficiency performance of dual command cycles should be identified and a factorial design of simulation experiments provided. In the following subsections previously described steps are discussed.

2.1. The energy model

The crane movements along the horizontal axis (namely x) and the vertical one (namely y) are described as a rectilinear motion with constant acceleration. A trapezium speed profile is adopted, where three phases can be recognized: acceleration until the maximum speed is reached, constant speed motion, and deceleration in order to stop at the desired location in the rack. When the shift to be performed by the AS/RS machine isn't great enough to reach the maximum speed, a triangular speed profile with only symmetric acceleration and deceleration phases is adopted. The AS/RS machine movements are characterized by their simultaneity along the two axes, and therefore the Chebyshev metric has been applied in literature to calculate travel time. As regards energy, the crane in equipped with 3 independent motors per axis. Since fork cycle to insert and/or drop off unit loads from the rack is independent from their location and can be considered a fixed component of energy requirements, energy for the z axis is neglected in our model. New generation crane are controlled so that their movements along x and y axes not only start simultaneously, but also end at the same time. This allows to avoid the additional torque needed to maintain the load in position while completing the slowest movement as in traditional cranes. To adhere to market behavior, we slow down the fastest motion by decreasing the acceleration/deceleration times so that the maximum speed value achievable is lower than the nominal one, while keeping acceleration at nominal value, as described in [2].

Energy is then computed per axis on the basis of the torque provided at the motor shaft, supposed constant during acceleration due to A.C. 3-phase inverter duty motors. Torque has to counterbalance inertia of load and masses (motor + crane), friction and gravity (for the y-axis). It was so possible to assign to each location in the rack the value of energy required to store into or retrieve from by departing/arriving from/to the I/O station supposed at the lower left corner of the rack. Furthermore, the model allows to dynamically compute energy for interleaving between any pairs of locations in a dual command cycle.

2.2. The energy-based dual command cycle heuristic

We imagine to process storage requests in the same order they arrive, since unit loads are supposed to be moved to the I/O station of the AS/RS by a loop conveyor. Retrieval requests, instead, are re-sequenced in order to save motion energy. In order to limit computational time but also to adhere to a dynamic environment, the list of available retrievals requests is commonly split into blocks which are sequenced one at time [3]. We adopt blocks of 15 storages and 15 retrievals to be combined into N = 15 dual command cycles at time. In our computation we considered unchanged each block until all the pairs have been identified, thus adopting a static approach. In a very turbulent environment, however, it is possible to adopt a dynamic approach by updating the block with new retrievals requests at each iteration before selecting the successive pair of operations.

Let be L_S the list of N storage requests and L_R the list of N retrievals requests in the analyzed block. The energy-based heuristic consists of the following steps.

1. Assign to each element in L_S the open location with the lowest energy required to store the load moving from the I/O station. Let S the set of such locations.
2. Assign to each element in L_R the retrieval location among the available with the lowest energy required to pick the load to the I/O station. Let R the set of such locations.
3. For each pair (s, r) with $s \in S$, $r \in R$, compute energy requirements for moving from storage location s to retrieval location r;

4. Select the pair (s^*, r^*) $s^* \in S$, $r^* \in R$ with the minimum energy requirement and perform the related dual command cycle;
5. Set $S = S - \{s^*\}$, $R = R - \{r^*\}$;
6. Go to step 4 until $S = \emptyset$ and $R = \emptyset$.

The rationale of steps 1 and 2 is attempting to positively affect the one way travels from and to the I/O of a dual command cycle, so that the minimum energy is consumed for them. Steps 3-5 try to minimize energy required by interleaving, which is the only energy component that can be changed with a different combination of storage and retrievals requests. As it has been already assessed [4], in fact, given a block of N storage locations to be served and N retrieval ones, one-way travels from/to the I/O station are fixed both in terms of time and energy, since all the selected locations must be served anyway. The variable component remains the travel between a storage position and the coupled retrieval one in a dual command cycle, that strictly depends on how retrievals are re-sequenced. The above heuristic has a $O(N^2\log_2 N)$ complexity, as shown in Appendix.

2.3. Simulation

By simulation experiments we compare energy consumption and round trip times of dual command cycles with single command cycles under different re-sequencing policies, namely FCFS, time-based, and energy-based ones. We consider only one side rack and one crane per aisle, since results can be modularly extended to all the fronts of an AS/RS. A reorder point replenishment policy is adopted and the size of each dedicated zone corresponds to the Economic Order Quantity (EOQ) of a given items. According to Graves et al. [4] EOQ is calculated assuming an equal ratio of inventory to order costs, so that the introduction of disturbing factors such as the supply policy can be avoided. In this way, zone size and frequency of access to a given location are affected only by demand distribution, as required by the full turnover strategy. Since the storage location policy has been showed in literature to significantly affect picking performances, we apply both the time-based full turnover strategy and the energy-based one. In this way we analyze whether adopting a sustainable perspective even when establishing dedicated zones could lead to significant energy savings with respect to the traditional time-based allocation.

In order to apply Lee-Schaefer heuristic to identify time-based dual command cycles, we need to first select storage and retrieval locations, since this heuristic applies only to re-sequencing of retrievals when locations involved in the decision process have been already established. We introduce a rule similar to step 1 of our energy-based heuristic, that is sorting all open locations dedicated to a given item by their one-way travel time from the I/O station and selecting at each iteration the position with the lowest time to be reached. Similarly to step 2 of the energy heuristic, all occupied locations of a given item are sorted by their one-way travel time to the I/O station and the position with minimum required time is selected for retrieval.

Since the adopted storage policy is strictly related to the ABC demand distribution curve of items stored in the analyzed AS/RS, we consider the ABC shape as a main factor in our analysis and select two levels: a 20-50 curve, meaning that the 20% of items account for the 50% of picking operations, and a more skewed one such as the 20-80 curve.

Nominal speed and acceleration of the crane, angular speed and inertia of motors etc. and shifts to be performed in order to serve locations are related to the shape of the AS/RS rack. Since all these quantities represent an input of the energy model as described in par. 2.1 and in previous research [2], we select also the shape of the rack as a factor of analysis. In particular we compare a horizontally laid AS/RS with 99 columns and 10 levels to a more vertically developed one, characterized by 45 columns and 22 levels for a total amount of 990 available locations in both cases. We used actual data provided by System Logistics SpA, an international manufacturer of AS/RSs, to properly select a crane for each rack.

We first compare single command performances to First-Come First-Served dual command ones by a 2^4 factorial design, including the storage policy, the movement strategy, the ABC distribution and the rack shape as main factors to be analyzed, each at the two levels previously described. The rationale is to assess if dual command cycles can contribute to energy efficiency so significantly as they were proven to do for time reduction. This is the reason why the most actually used policy for re-sequencing retrievals, the FCFS one, is initially adopted. As regards the movement strategy, we mean how storage and retrieval locations to be served are selected before the coupling process based on the FCFS policy is performed. Empty locations for storages as well as available location for retrievals basically depend on the position of dedicated zones established by the storage strategy, but among these the selection of the order by which they will be served depends if movements are optimized by the time-based perspective or by the energy-based perspective. By the former, the location with the minimum one-way time from/to the I/O station is selected among the available, by the latter, instead, the location with the minimum motion energy requirement for the one-way travel from/to the I/O station is identified.

Once established if and how much FCFS dual command cycles overcome single command ones, an analysis on further improvements achievable by dual command cycles when replacing FCFS re-sequencing policy with time-based and energy-based heuristics is performed. A 2^4 factorial design of experiments with 4 factors (storage policy, re-sequencing policy, demand curve, and rack shape) at two levels is selected again. Main factors and related levels are summarized in Table 1.

Table 1.Factors and levels of the 2^4 design of experiments

Factors	**Low Level**	**High Level**
Re-sequencing policy	Time-based heuristic	Energy-based heuristic
Storage strategy	Time-based full turnover	Energy-based full turnover
Demand distribution	20-50 ABC curve	20-80 ABC curve
Rack shape	99×10	45×22

Simulation of 450 storage operations plus 450 retrievals is therefore performed. It is supposed that storage and retrievals operations can be always coupled, meaning that requests for both operations are available when planning the AS/RS machine cycles. Heuristics for re-sequencing retrievals are applied to block of 15 storage operations and 15 picking operations at time, for a total amount of 30 blocks to be analyzed. The size of the block is selected as a reasonable trade-off between opposite patterns. On one hand, in fact, computational effort increases as the block size is increased. Furthermore, if a dynamic approach should be adopted, meaning that the list of retrieval requests is updated as much frequently as possible to be aligned with client requirements, then the size of the block should be kept small in order to reduce the frozen window in the planning process. On the other hand, the capacity of really optimizing cycles in the whole planning horizon increases as the block size increases, since more operations are involved in the optimization process.

3. Results

Results from simulation runs show how dual command cycles gain significant performance improvements in comparison to single command cycles.
The average round trip time decreases of 29.7% when moving from single command to First-Come First-Served dual command cycles, in line with well-known results reported in literature.

Energy consumption to move the crane towards the desired storage and retrieval locations is lowered by a 26.6% on average, when storage and retrieval operations are combined into dual command cycles. Thus, dual command cycles are showed to be an effective operative mean to foster energy efficiency in warehouse management other than improve the service level perceived by client, for which they have been traditionally conceived. Main effects of the identified factors on lowering energy requirements are positive, but of limited importance. It comes that deleting one-way idle travels to/from the I/O station and replacing them with interleaving from a storage location to the coupled retrieval one leads itself to a significant improvement, which can be weakly affected by other characteristics of the system.

When replacing FCFS policy with heuristics to combine storage and retrieval requests into dual command cycles, a little improvement on the desire performance can be further achieved. Simulations analysis highlights how a 32.4% of improvement on round trip times is gained on average, and a 30.11% of energy savings can be obtained on average. As concern factorial analysis, the major effect on round trip time reduction if compared to FCFS policy is played by the time-based heuristic, whose implementation gains a 2.4% improvement with respect to the energy-based one. Concerning factorial analysis on motion energy savings when applying heuristics, instead, the major effect is achieved by applying the energy-based full turnover storage policy rather than the traditional time-based one, with a 1.7% increase. This confirms how the storage policy affects results obtainable successively by a proper management of AS/RS machine operations.

It is worthwhile to notice how adopting a full energy-based management of the AS/RS, meaning that both storage and re-sequencing are based on the least motion energy, leads to an energy saving increase of 30.77% with respect to single command cycles, but a time decrease of 30.78%. When a full time-based management is selected, instead, we obtain a 33.2% improvement of round trip times in comparison to single command cycles, and 29.61% improvement of energy requirements. It comes that if the most critical performance for a company is energy consumption, then an energy-based approach leads to the maximum benefit in terms of energy consumption, but renouncing to a 2.4% of improvement in times and the associated service level perceived by customers.

4. Conclusions

Sustainable manufacturing claims for more energy efficient operations in warehouse management. While AS/RS operations have been traditionally optimized in order to minimize picking times directly linked to the service level perceived by customers, a sustainable approach leads to change this perspective by optimizing storage and retrieval cycles so that the least motion energy is required to perform them.

Adopting dual command cycles instead of the more common single ones leads not only to reduce picking time, as traditionally expected, but also to strongly increase energy saving. Comparing single command cycles to dual command ones obtained by coupling storage and retrieval requests by the easy-to-use and largely applied First-Come First-Served policy, a

26.6% of energy saving was found on average. Further improvement of about 3.5% on energy saving can be achieved by implementing heuristics to optimize dual command cycles. In this case, current results show how the major benefit can be gained by a full energy-based approach, thus adopting both an energy-based full turnover storage strategy and an energy-based re-sequencing heuristic.

Appendix

For implementing step 3 of the energy-based heuristic described in par. 2.2, one can compute the N^2 energy values related to all the N^2 possible couples (s, r) and then choose the minimum. However, if an ordering of this N^2 length list is made, the following steps can be implemented faster.
Therefore, let E the ordered list of N^2 tuples (s, r, En(s, r)), where En is the interleaving energy requirement associated to (s, r). It can be computed in time $O(N^2\log_2 N^2) = O(N^2\log_2 N)$.
For each $s \in S$ we build a list L(s) pointing to those elements concerning s and a list L(r) pointing to $r \in R$. Then step 4 can be executed in constant time (the first cell of the list stores the minimum). We use the lists L(s) and L(r) for accessing E and remove the cells of the kind (s,..,...) or (..,r,…). This can be done in time $O(N)$. The loop is repeated N times, therefore the overall complexity is $O(N^2\log_2 N + 2N^2) = O(N^2\log_2 N)$.

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Energy system optimization for a scrap based steel plant using mixed integer linear programming

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Abstract: In this work a mathematic model to simulate and optimize the energy system of a scrap based plant has been developed. Scrap based steelmaking is an energy intense production system. The potential for energy saving by system optimization is therefore high, even if the percentage of saved energy is relatively small. The model includes scrap pre-treatment, electrical arc furnace, ladle furnace and continuous casting units. To estimate the chemical compositions of the scrap charged into the EAF a statistical model based on an existing EAF plant has been used to provide the inputs to the model. Distribution factors have been used to describe the distribution of elements and oxides between the steel, slag and off gas/dust. To calculate the energy consumption in the electrical arc furnace a combination of an empirical and theoretical energy formula has been used. The model represents a general description of the most common process in electric steelmaking. It is suited to be adapted for specific plants with adjustments to the model parameters. The model gives reasonable results which follow the chemical composition of steel and slag and yield. The model can be a powerful tool to optimize the scrap mix and injectants towards energy and costs.

Keywords: *Energy systems, optimization, steelmaking, EAF, MILP, linear programming*

1. Introduction

Energy has been and will always be one of the most important production factors in the iron- and steel industry. In Sweden approximately one third of the total steel production is produced in electrical arc furnaces (EAF) and two thirds in basic oxygen furnaces (BOF) [1].

In the steel industry system, several processes are often connected together. A change in one process unit may result in unpredicted changes in other parts of the system. A literature study has been made of the best available technique and state-of the-art processes to decrease the specific energy consumption in the electrical arc furnace steel making.

The purpose of this work is to create a mathematic model to simulate and optimize the energy system of an EAF plant. In the past similar work has been made on the integrated blast furnace route energy system [2]. It is likely to presume that the scrap based steelmaking will increase in the future and more efforts will be spent to optimize the energy used in this area.

For the scrap based steel plant, it is often difficult to know the exact chemical compositions of the scrap charged into the EAF. In this work a scrap material statistical model based on an existing EAF plant has been used to provide the inputs to the model. The process steps in scrap based steelmaking are raw materials handling, pre-treatment EAF scrap melting, steel and slag tapping, ladle furnace treatments and casting.

1.1. Scraped based steel plant

With respect to the end-products, distinction has to be made between production of ordinary, so-called carbon steel as well as low alloyed steel and high alloyed steel/stainless steel. In the EU, about 88 % of steel production is carbon or low alloyed steel.

1.1.1. Energy consumption in electrical steelmaking

Electric arc furnace steelmaking uses heat supplied from electricity that arc from graphite electrodes to the metal bath to melt the solid iron feed materials. Although electricity provides most of the energy for EAF steelmaking, supplemental heating from oxy-fuel burners and oxygen injection is used. To produce EAF steel, scrap is melted and refined, using a strong electric current. Several process variations exist, using either AC or DC currents and fuels can be injected to reduce electricity use.

EAF steelmaking can use a wide range of scrap types, as well as pig iron, direct reduced iron (DRI/HBI) and hot metal. The EAF operates as a batch melting process, producing heats of molten steel with tap-to-tap times for modern furnaces of 30 minutes [3]. Current on-going EAF steelmaking research includes reducing electricity requirement per ton of steel, modifying equipment and practices to minimize consumption of the graphite electrodes, and improving the quality and range of steel produced from low quality and low cost scrap.

The best practice EAF plant is state-of-the-art facility with eccentric bottom tapping, ultra high power transformers, oxygen blowing, and carbon injection. The "best practice" is to use as much scrap as possible, as melting of DRI/HBI requires more energy. An efficient electric steelmaking plant with 100 % scrap as iron bearers has an electrical energy consumption of 409 kWh/t liquid steel for the EAF and 65 kWh/t liquid steel for gas cleaning and ladle refining, as well as 42 kWh/ton liquid steel of natural gas and 8 kg/t liquid steel of carbon [4].

There are various techniques to decrease the energy consumption for scrap based steelmaking. The Best Available Technique (BAT) to consider is to preheat the scrap and to replace the continuous casting, hot rolling, cold rolling and finishing with thin slab casting, also called near net shape strip casting [5]. The two most common methods to preheat steel are the CONSTEEL process and the post combustion shaft furnace (FUCHS). The electricity savings reported are 60 and 100 kWh/t liquid steel respectively [6]. An example of a thin slab casting technique is the Castrip® process. Potential energy savings are estimated to be 80 to 90% over conventional slab casting and hot rolling methods [7].

2. Methodology

The method used in this work is a model for industrial systems where the process is described as a network of nodes (sub-processes) which are connected by energy and material flows. The potential of this method is that it enables a simultaneous representation of the total industrial system, and that it makes it possible to optimize the whole system, in contrast to the optimization of each sub-process individually. The method is described by Nilsson [8], and later developed for complex material production systems by others [9]-[11].

The method is based on Mixed Integer Linear Programming (MILP). The model described in this paper contains no integers. There are four main nodes that symbolize the different processes in the system. These are a pre-treatment node, an electric arc furnace node, a ladle furnace node and a continuous casting node. There are nodes that provide the main processes with resources such as raw material, slag formers, alloys, energy sources and destination nodes for products and by-products.

2.1. Scrap pre-treatment

The scrap pre-treatment nodes main function is to summarize the different ingoing elements and oxides from each scrap grade and slag former, and transport them to the EAF node. There is one flow for each element or oxide. There is also a possibility to restrict the amount of each scrap grade or slag former going into the EAF. As well as it is possible to set boundaries on each scrap grade it is also possible to set a fixed scrap recipe. Fig. 1 describes the ingoing and outgoing flows for the scrap pre-treatment node.

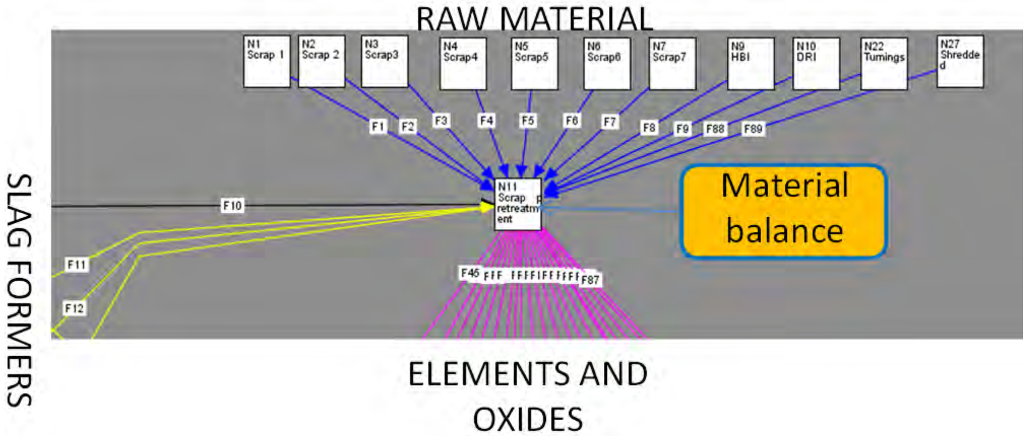

Fig. 1. Ingoing and outgoing flows for the scrap pre-treatment node

The chemical composition of scrap grades have a tendency to vary over a period of time as well as from heat to heat. For the raw material with well-known chemical composition the content are written according to that [12]-[14]. For scrap grades that have a more uncertain chemical composition the values have been estimated with multiple linear regression (OLS – Ordinary Least Squares) or “by hand”.

Process data from approximately 1400 melts have been used in the OLS regression analysis. The data contained information about both scrap mix and steel analysis and an assumed distribution factor for each element/oxide to steel in the EAF for each element. From this information a material balance was made. The outgoing flows from the pre-treatment node represent the weight of each element and oxide and total weight of charged material.

2.2. Electric arc furnace

Ingoing raw material to the EAF node is the different amount of each element and oxide that is determined in the pre-treatment node. As ingoing material there are also three types of slag formers. Carbon and fuels in form of natural gas, LPG and oil are represented. The electrode consumption is also represented as an ingoing flow. The ingoing gases are nitrogen for stirring, oxygen from lance and air leakage from slag door and from off-gas duct opening after the 4th hole. There are three different flows for by-products; flue-gas, slag and dust. Fig. 2 describes the ingoing and outgoing flows for the electrical arc furnace.

All incoming elements and oxides from all sources are treated in a material balance. A very central part of this node is the distribution factor table between steel, slag and off-gas/dust. This table decides how much of each element that remains in the steel and how much that are transferred to the slag or off-gas. The distribution factor for an element/oxide applies for the sum of that element/oxide for all incoming flows. The distribution coefficients have been determined statistically by calculation of average weights and concentration of elements and oxides in steel, slag, dust and off-gas.

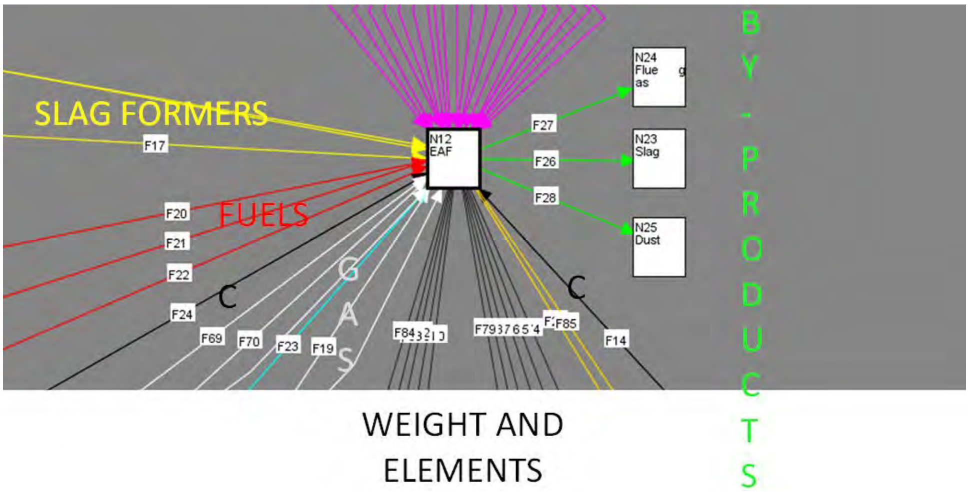

Fig. 2. Ingoing and outgoing flows for the EAF node

2.2.1. Energy calculation

For calculations regarding energy consumption for the electric arc furnace one empirical formula (Köhle-Formula) [3, 15] and a theoretical formula (Adams' formula) [16] has been used. Köhle's formula determines the electrical energy demand based on the use of other energy carriers, added materials, tapping temperature and tap-to-tap time. The Adams' formula determines the total energy consumption where quantities of non-electric energy are converted into kWh. The coefficients in the Adams formula have been used to assign "energy costs" for chemical fuel (kWh/kg or kWh/Nm^3) so that a "cost function" (kWh) for total energy consumption can be defined.

All the values that are needed for the formula are selected from the calculations or flows in the model. The values that are fixed constants are tapping temperature, power on time and power of time. Hot metal is not included in the model but there is a possibility to add it in the pre-treatment node along with the chemical analysis and also include it as a factor in the Köhle formula.

In the EAF-node there is an equation for pre-heating of scrap. The user can choose the preferred pre-heating end temperature of the charged scrap. If this function is activated this will also affect the electric consumption that is calculated. The energy added to the scrap is calculated with a fixed heating value (Cp) for the scrap mix. The Cp value has been estimated as the average value in the temperature range of 0 to 500 °C [17]. The reduced electric energy is calculated from the added energy value multiplied by the efficiency factor of the electric arc furnace.

2.2.2. Assumptions

It should be noted that factors for Oil and LPG are included in the Adams formula but not in the Köhle formula. Factors for Oil and LPG were therefore added to the Köhle formula as well. For calculation of these additional factors to the Köhle formula it was assumed that the heat transfer efficiency to the scrap/steel is the same for all kinds of chemical fuel (natural gas, oil and LPG). Then the factors for oil and LPG in the Köhle formula can be estimated as the factor for natural gas in the Köhle formula multiplied by the ratio of the factors for oil/LPG and natural gas in the Adams formula (11/10.5 for oil and 8/10.5 for LPG).

It is possible to set specifications for the steel chemistry. This is made by restricting the calculations to fit the minimum and/or maximum allowed concentrations of each element in the steel. The slag weight must be greater than 7% of the steel weight and the amount of MgO in the slag must be greater than 8% of the slag weight. The slag basicity (CaO/SiO_2) is restricted to a constant that is determined by the user.

There are calculations regarding the off gas in two stages of the process, one calculation at the so called 4th hole and the other after the slip gap of the off gas duct. The calculations have been made in this way to show the post combustion energy potential of the off-gas before the air leakage in the slip gap. The calculations of the flue gas are depending on a number of assumptions. All C and H from the incoming flows leave the steel bath as CO and H_2 except the contribution from the burner fuel, which is completely combusted to CO_2 and H_2O. All Zn from ingoing flows that ends up in the dust leave the steel bath as Zn(g). These gases react with the air coming from the slag door and with the post combustion oxygen from the burners. At this point all the Zn(g) is oxidized to ZnO and the O_2 that is left reacts with CO and H_2 and generates CO_2 and H_2O. This reaction occurs according to a fixed distribution where a defined percentage of the remaining oxygen after Zn oxidation reacts with the CO and the rest with H_2. At the slip gap at the off gas duct it is assumed that there will be enough air flow for a complete combustion of the remaining CO and the H_2 in the off gas. The amount of excess oxygen in the flue gas after the slip gap is set to a constant.

2.3. Ladle furnace

The steel is going into the ladle furnace node with one flow for each element represented in the liquid steel. In this node there is a function where the user specifies the final steel weight. If a specified scrap weight and scrap mix is used there is a need to disable this function for the model to work properly. There is the opportunity to use the three slag formers that are used in the EAF node as well as a synthetic slag former. The model offers the user to add different kinds of alloys to the steel. The most common alloys that are available have been added but it is possible to add additional ones if that is needed. The chemical composition of the included alloys can also be changed. Fig. 3 describes the ingoing and outgoing flows for the ladle furnace.

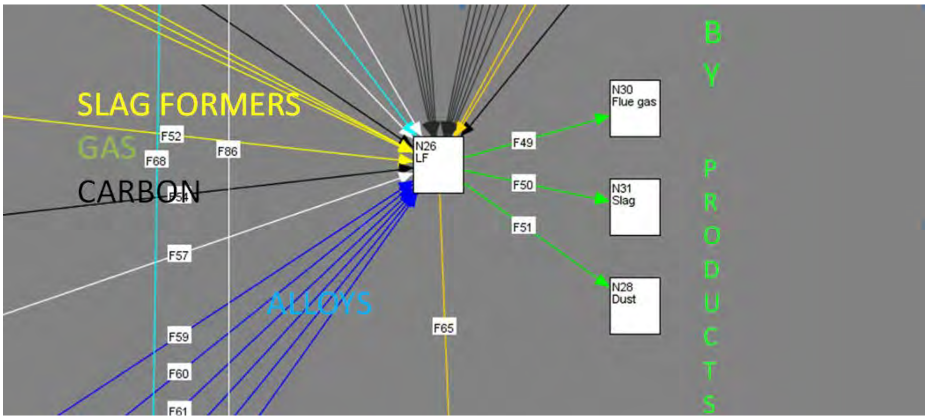

Fig. 3. Ingoing and outgoing flows for the LF node

The material balance in this node is as in the EAF node based on a distribution table between steel, slag and off gas/dust. The distribution coefficients have been estimated by empirical knowledge. The distribution coefficients refer to the materials that are added in the node. The contents of the ingoing steel are therefore not affected by any distribution factor. The exception from this is sulfur that has distribution coefficients also for the amount that is transferred with the steel into the ladle furnace node.

The ingoing temperature of the liquid steel to the ladle furnace is decided by the tapping temperature from the EAF which is reduced by a constant factor due to temperature loss during tapping of the EAF. The final temperature is decided by the demands of the following operation. It is also assumed that an average amount of slag is transferred along with the liquid steel from the EAF to the LF during tapping. There is a calculation of the electrode consumption that is based on a constant amount of electrode per kWh.

In the model it is assumed that argon is used for stirring the melt during the ladle furnace operation. The consumption is based on a fixed volume per ton of steel. This assumption is made from an average calculation from the process data. The amount of air that leaks into the system is also a constant per ton of steel.

2.3.1. Energy calculation

The electric energy consumption in the ladle furnace is based on the amount of steel and the increase in steel temperature needed to reach the final temperature. At first there is the difference between the ingoing temperature and the final temperature. But also the effect of the added material will contribute to a temperature drop. The temperature drop caused by each added material is based on an individual material constant. This constant determines how large the temperature drop, or in some cases a temperature raise, will be depending on the percentage of material added to the liquid steel. The temperature drop constants have been estimated by empirical knowledge.

2.3.2. Assumptions

It is possible to set specifications for the steel chemistry. This is made by restricting the calculations to fit the minimum and/or maximum allowed concentrations (wt. %) of each element in the steel. This is also possible in the EAF node so the user can choose if the specification is to be set at the LF or both. The slag weight is set to be greater than 2% of the steel weight and the slag basicity (CaO/SiO2) is restricted to a constant. The amount of elements and oxides in the off gas/dust that leaves the steel bath is calculated according to the same principles as the off gas in the EAF node. However, the reactions with infiltrated air are not considered.

2.4. Continuous casting

The continuous casting (CC) unit is treated in a simple way in the model. For the material flow, a material loss in percentage based on the total liquid steel amount from the LF unit is assumed when casting. A specific oxygen consumption (Nm^3 O_2/ton-slab) based on the final product (slab in this case) is assumed to calculate the total oxygen consumption. The oxygen is needed when cutting the slabs. For the electricity consumption in CC, it is based on assumed specific electricity consumption (MWh/ton slab).

3. Results

Simulations have been run in CPLEX with three different scrap mixes corresponding to average mixes for three different steel grades at Höganäs AB EAF plant in Halmstad. The model calculations in terms of chemical analysis of steel and slag and metallic yield have been compared with real data from Halmstad. The model calculates reasonable results which correspond well to real data.

An optimization test with the objective to minimize the total energy consumption (kWh) in the system (for a given quantity of a specific steel grade at Halmstad) was performed. During the optimization scrap preheating function was turned off and the EAF tapping temperature was constant.

In the optimized solution, the use of shredded scrap is maximized because of the lower specific energy consumption for this scrap grade (-50 kWh/ton compared to “normal” scrap) in the Köhle formula [3]. The maximum amount of shredded scrap is limited by the quality restrictions (chemical analysis) of the steel grade. The use of HBI/DRI is minimized (zero consumption) because of their higher specific energy consumption (+80 kWh/ton compared to “normal” scrap) in the Köhle formula [5].

For all chemical fuels (oil, natural gas and LPG), the optimizer chooses zero consumption in the EAF This is because the energy content according to Adams [16] for natural gas (10.5 kWh/Nm^3) is higher than the reduction of electrical energy consumption it gives according to the Köhle formula (-8 kWh/ Nm^3) [3]. As the efficiency of oil and LPG in the EAF burners are assumed to be the same as for natural gas it follows that the energy content of all chemical fuels are higher than their reduction of electrical energy consumption in the EAF.

The optimizer chooses to add as much post combustion (PC) oxygen through the burners in the EAF as possible, because burner PC oxygen has zero energy content and will reduce the electrical energy consumption (-2.8 kWh/Nm^3) according to the Köhle formula. The limit of PC oxygen is set by the available amounts of post-combustible gases (H_2, CO and Zn) in the furnace, as the amount of these substances in the 4th hole off-gas must be zero or higher. The amounts of post-combustible gases in turn are determined by the charge material mix and the amount of air leakage through the slag door.

The lance oxygen consumption is minimized in the optimized solution. This is because the energy development for oxygen injection (5.2 kWh/Nm^3) according to Adams [16] is higher than the reduction of electrical energy consumption that it gives according to the Köhle formula (-4.3 kWh/Nm^3) [3].

4. Concluding remarks

Scrap based steel plants around the world differs a lot in terms of scrap mixes and final products. The model described in this paper represents a general description which shall be adapted for specific cases. The model is built up to easy adjust to the processes of interest. To use the model correctly the incoming data needs to be correct and the model parameters (raw material analysis, slag basicity, air leakage, etc.) must be adjusted to represent the conditions of the specific plant. Then the model can be a powerful tool to optimize the scrap mix and injectants towards minimized energy consumption or production cost. In upcoming work the model will be used to optimize specific processes and plants.

The future work will also include further development of the scrap preheating function and move it to a separate node. A cost function for monetary units for all incoming flows will be added so that the total production cost can be optimized. Nodes for alternative solidification processes such as ingot casting and atomization will be considered and coefficients for specific energy consumption for different scrap grades in the EAF will be adjusted and added. Interaction with external systems like district heating can also be added.

Moreover different feeding and charging systems and a water cooling system for EAF are planned to be implemented and the processes after casting such as transport, heating and metalworking processes needs to added to complete the system.

Acknowledgement

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Environmental system effects when including scrap preheating and surface cleaning in steel making routes

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Abstract: The main part of the steel manufactures producing alloyed steel use scrap as an essential raw material. To increase the corrosion resistance of steel a coating is often applied. The share of steel being coated and galvanized is today globally increasing, which is resulting that the amount of scrap with different types of coatings are increasing. This result in that more of the scrap used in steel making is contaminated with for example Zinc and organics. Scrap preheating is a known method for reduction of energy use in steelmaking. However due to environmental restrictions a widespread implementation of scrap preheating have not been achieved in the steel industry. Combined surface cleaning and scrap preheating is a way to handle the problem that coatings give rise to in the melting cycle and is a new concept suggested and developed at Swerea MEFOS. The pre-treated scrap (cleaned and preheated) is charged hot into the oxygen converters with direct savings of energy, as the demand of hot metal from the blast furnace decreases. The method opens for the possibility to widen the scrap base and to melt complicated scrap. Since the preheating process is a standalone solution, a large number of unwanted chemical components are removed prior melting resulting in that the dust generated from the melting process is easier to recover. In this paper the system effect of introducing a preheating and surface cleaning process for scrap in a Blast Furnace (BF) and oxygen converter (BOF) steelmaking route is analyzed according to energy and CO_2 emissions. The system analysis shows that surface cleaning of scrap makes it possible to use shredded scrap and ASR (automotive shredder residue) or other combustible waste to replace fossil fuels. The results from the analysis demonstrates that implementing surface cleaning leads to increased possibilities for recycling of otherwise non-recyclable material. The system model shows the interaction between different processes, which gives an overview picture including the whole steel making route. The model is used to investigate changes in process conditions from making use of shredded scrap and ASR as input material in the steel making process. The implementation of surface cleaning and preheating lead to both increased possibilities for recycling of scrap, and more efficient energy use in the steelmaking routes.

Keywords: *BOF, Scrap preheating, Surface cleaning, optimization, ASR*

1. Introduction

Currently, the blast furnace (BF), basic oxygen furnace (BOF) route is the dominating processes for iron ore steel making. The steel is produced from the hot metal produced in the BF by treatment in a BOF converter. In the converter process a surplus heat is generated during the oxygen blowing which is utilized for scrap melting. 15-20 % of the iron raw material input to the BOF is originated from scrap. Liquid steel (LS) from the converter is sent to an after-treatment station where the final adjustment of the steel analysis and temperature is performed before the casting procedure. Energy and material efficiency in a process system is closely linked together. A higher recycling rate and a minimization of landfill is energy efficient, since it decreases the demand of virgin materials.

The main part of the steel manufactures producing alloyed steel use scrap as an essential raw material. To increase the corrosion resistance of steel a coating is often applied. The share of steel being coated and galvanized is today globally increasing, which is resulting that the amount of scrap with different types of coatings are increasing. This result in that more of the scrap used in steel making is contaminated with for example Zinc and organics. In this paper the system effect of introducing a preheating and surface cleaning process for scrap in a Blast Furnace and oxygen converter (BOF) steelmaking route is analyzed according to energy and CO_2 emissions.

Scrap preheating is a known method for reduction of energy consumption for melting. However due to hazardous components generated in the exhaust, a widespread implementation of scrap preheating have been interfered due to the costly treatment required. A standalone combined surface cleaning and scrap preheating is a way to handle the problem that coatings on the scrap give rise to. This is a new concept suggested and developed at Swerea MEFOS [1]. The pre-treated scrap (cleaned and preheated) is charged hot into the oxygen converters with direct savings of energy, as the demand of hot metal from the blast furnace decreases. The method opens for the possibility to widen the scrap base and to melt complicated scrap. Since the preheating process also applies surface cleaning a large number of unwanted chemical components are removed prior melting resulting in that the dust generated from the melting process is easier to recover. [1-2]

1.1. Objective of the study

This study analyzes the system effect of introducing surface cleaning of scrap in a BF-BOF steel making route. An optimization model highlights the possibilities regarding cost and CO_2 emission. The model is used to do analysis on operation practice, scrap usage and cost. The intention of the study is to investigate the changes in the process system, when using shredded scrap in the scrap mix.

2. Methodology

The method used in this work is based on the MIND method [3]. The study is made in an optimization model of an integrated steel mill, where the process is described as a network of nodes (sub-processes) which are connected by energy and material flows. The potential of this method is that is enables a simultaneous representation of the total industrial system, and that is makes it possible to optimize the whole system, in contrast to the optimization of each sub-process individually. The optimization model of one integrated steel plant has been further developed with the requirements for scrap preheating [4-5]. The model used in this work is based on an existing energy optimization model designed for the iron and steel industry [6-8].

2.1. The optimization model

2.1.1. Objective function

This study uses two objective functions which are defined in the model as raw material and energy costs and CO_2 emission. Generally the objective function is imbedded within the optimization model but can in mathematical terms be written as follows.

$$\min z = \sum_{i=1}^{n} c_i x_i \tag{1}$$

where z is the objective function for the minimization problem. It could be CO_2 emission and cost, depending on what objective is set for the optimization. x is studied variables and c is coefficients set for the corresponding objective function and depends on which objective function. The coefficients set for the corresponding objective functions are shown in Table 1.

Table 1. Coefficients used for different objective functions.

	Unit	Cost (SEK)	CO_2 emission (ton)
Iron ore pellet	ton	675	0.051
Lime stone (wet)	ton	128	0.856
Mn ore	ton	488	-
Quartz	ton	180	-
Lime stone	ton	124	0.856
Dolomite Lime	ton	600	0.466
Raw Dolomite Lime	ton	263	0.931
FeSi	ton/ton RS	4875	-
CaC_2	ton	3225	-
Coal and coke	ton	293-331	2.492-3.064
External coke	ton	1950	3.744
Pulverized coal injection	ton	205-525	2.488-2.916
External scrap	ton	2300	-
Shredded scrap	ton	2000	-
BOF sludge	ton	-	-
Oil	MWh	5550	3.126
External energy	MWh	-	0.6
Excess coke	ton	-1950	-3.744
Benzene	ton	-1600	-3.287
Sulphur	ton	-40	-
Tar	ton	-1300	-3.349

In Table 1, the costs analysis is limited to raw material and energy and thereby not including the cost for energy and landfill of material. Furthermore credits are made in the model for by-products. Market values for the different raw materials and energy sources fluctuate whereby the costs for raw materials and energy used in the model is mean values calculated over a conjuncture cycle. Values of costs are estimations based on figures from The London Bullion Market Association.

2.1.2. Boundary conditions and limitations

To make sure to get reasonable results, some necessary boundary are introduced. The boundary conditions, which can describe variations in the system, maximum and minimum for various variables can be expressed as follows.

$$x_i \le b_i, \quad i = 1,...,n \tag{2}$$

where the x_i variable could be the corresponding flow variables, and the boundaries b_i, are the corresponding restrictions. As a boundary condition the production of prime slabs is fixed in the model. The BOF charges has limitations, such as hot metal, pig iron, slag binders and scrap are set to the production parameters of liquid steel, to ensure the right quality for the final products.

2.2. Model description

In the iron and steel industry optimization models considering effects on the entire production process chain have been used for investigations of performance of different aspects like energy consumption, CO_2 emission, costs and environmental issues [4-8]. The system boundary of the whole system is to casted steel slab, the boundary of this study is to RS (Raw

Steel) from the BOF converter. The process units included are coking plant, blast furnace (BF), basic oxygen furnace (BOF), and continuous casting (CC), oxygen plant, and lime furnace, etc. [9]

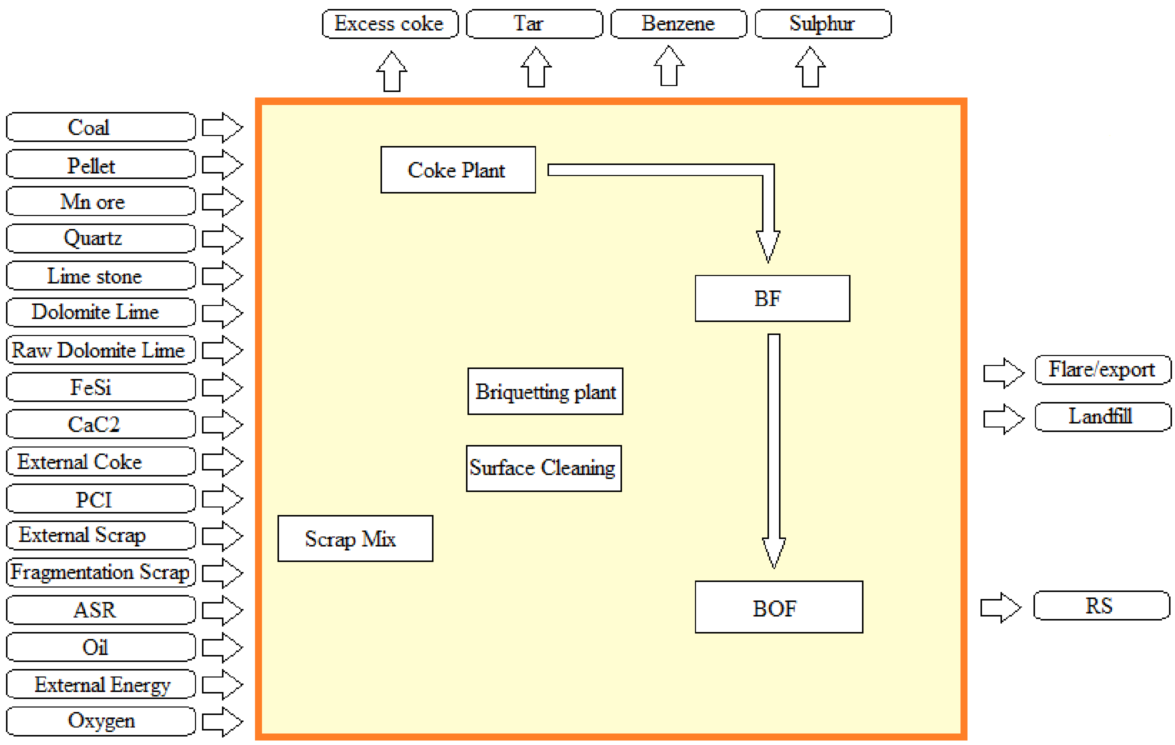

Fig. 1. Schematic outline of the modeled system.

The blast furnace is a very complex process and thus difficult to model. In this study different operational conditions for the blast furnace, which are feasible are defined. The model chooses and combines between these to overcome this problem. The prepared model is consisting of modules of process steps connected by mass and energy balances.

2.2.1. Operating conditions and modeling cases

The BF module is simulating the hot metal production in a Swedish BF with potential changes in briquette recipe and charged amounts. The BOF production process is described in the model by the mass and energy balance of the process. Different options can be optimized regarding the raw materials used due to the chemical composition. The coarse fraction of the generated BOF sludge is recycled through briquettes charged into the BF. The fine fraction of sludge from the BOF is normally land filled however it may be recycled in briquettes provided the zinc content is reduced sufficiently [10]. Including the scrap preheating unit in the system contributes to the scrap usage efficiency by the charging of preheated scrap. The introduction of the scrap surface cleaning unit in the model makes the use of shredded scrap as a scrap source to the BOF viable as it reduces the Zinc content in the scrap input to the BOF to zero. Scrap cleaning and preheating is performed on all the scrap charged to the BOF when the pre-treatment operation is implemented. Since the exhaust problem with the pre-treatment of scrap roughly identical with the combustion of many types of polluted fuels, Therefore the preheating process needs an advanced gas cleaning facility which gives that fossil fuel could be replaced with organic rest material. In this study ASR (automotive shredder residue) has been chosen as fuel in the preheating process since it has a good heating value and can be delivered in enough quantity to be interested for industrial use. Zinc sources to the BOF sludge and dust in the model is the external scrap and the shredded scrap. Sources of Zinc to the BF come from the iron ore pellets and briquettes. The possible integration and effect of the preheating and surface cleaning operation is analyzed in five cases compared against a reference case, Table 2. The input of scrap to the BOF is limited to 17 % in the reference case, case 1 and 2, since it is a reasonable amount. To ensure that the use of internal scarp is preferred, the external scrap use is limited to maximum 5 % of the scrap charge into the BOF. The optimization cases have a higher degree of freedom on the BF operation and on the raw material input in the BOF.

Table 2. Case study.

Case	Comments
Reference Case	BF operation with briquettes
Case 1	BF operation with briquettes, scrap pretreatment implemented, otherwise as the Reference Case
Case 2	BF operation without by-product briquettes, otherwise as the Ref. Case
Case 3	Optimization of cost, Scrap preheating/surface cleaning available
Case 4	Optimization of CO_2, Scrap preheating/surface cleaning available

3. Results

3.1. System optimization

Data from the system modeling of production and differences in the analyzed cases is illustrated in Table 3. Regarding the coke making there are only minor differences between the reference production and the five different cases. The production rate of coke is the same in all five cases. Small change in coal mix volatile matter and ash result in small increase in COG production compared to the reference case. To increase recycling inside the steel plant by-product briquettes are used. Data from the system model of BF operation show that the HM (Hot Metal) production is higher in the reference case and in case 2 which is using no briquettes. Increased use of briquettes is positively affects the cost- and CO2 emission optimized cases by the lower lime stone and pellet consumption in the BF.

3.1.1. Iron ore pellet consumption

The use of iron ore pellets in the analyzed cases vary. Iron ore pellets has a CO_2 emission burden of 0.051 ton, as a comparison to scrap which has zero, se Table 1, since scrap is a recycled material origin from iron ore. In case 2 where no briquettes are produced the major amount of pellets is being utilized due to less recycling of iron bearing by-products. In the case 4, where CO_2 emission is the optimization target, the lowest amounts of pellets are used.

3.1.2. Scrap consumption

Producing steel from scrap is better from an environmental point of view since the energy demand for producing steel from iron ore is more than twice the energy required in scrap based production. Scrap usage for the cases is illustrated in Fig. 2. Shredded scrap may only be utilized in the cases when surface cleaning is implemented. The Reference case, case 1 and 2 has a limitation on the scrap usage to a maximum load of 17 %, where maximum of external scrap is 5 % in the BOF. The largest amount of scrap utilized is in case 4, which is the CO_2 emission optimization case. Since energy use and CO_2 emissions from integrated steelmaking is closely related, increased scrap utilization results in less CO_2 emissions.

Table 3. Optimization results coke making, Blast furnace and BOF route.

	Ref.	Case 1	Case 2	Case 3	Case 4
Coke plant					
Coke production (t)	84.5	84.5	84.5	84.5	84.5
COG production (GJ/t coke)	8.4	8.4	8.4	8.4	8.4
Coke yield, dry (t coke/t coal)	1.287	1.287	1.287	1.287	1.288
Excess coke (t)	0.00	0.00	0.00	0.00	0.00
Ash (%, dry basis)	9.12	9.12	9.12	9.12	9.14
Volatile matter (%, dry basis)	25.60	25.60	25.60	25.60	25.66
BF					
HM production (t/h)	250.1	244.4	250.1	246.6	246.4
BF slag production (t/t HM)	0.162	0.162	0.156	0.164	0.164
Pellet (kg/t HM)	1356	1356	1394	1339	1340
Coke (kg/t HM)	320	320	330	317	317
PCI (kg/t HM)	141	141	141	141	141
Lime stone (kg/t HM)	30	30	46	20	20
By product briquettes (kg/t HM)	59	59	0	84	82
BOF slag (kg/t HM)	46	46	46	46	46
Other (kg/t HM)	4	4	5	4	4
Blast (kNm^3/t HM)	0.98	0.98	0.98	0.98	0.98
BFG (GJ/Nm3 blast)	1.13	1.13	1.13	1.15	1.15
COG (GJ/Nm3 blast)	0.71	0.71	0.71	0.72	0.72
BOF					
RS (t/h)	257.5	257.5	257.5	257.5	257.5
BOF slag (t/h)	0.08	0.08	0.08	0.08	0.08
HM (kg/t RS)	879	859	879	867	866
Pellets (kg/t RS)	0	8	0	11	10
Scrap mix (kg/t RS)	175	188	175	179	225
Lime (kg/t RS)	27	26	27	26	25
Dolomite lime (kg/t RS)	23	23	23	23	22
Raw dolomite lime (kg/t RS)	4	4	4	4	4
O_2 blowing (Nm^3/t RS)	50.0	47.7	50.0	47.7	47.6
Scrap preheating on/off (1/0)	0	1	0	1	1
O_2 (Nm^3/t scrap)	37	37	37	37	37
ASR (kg /t scrap)	32	32	32	32	32

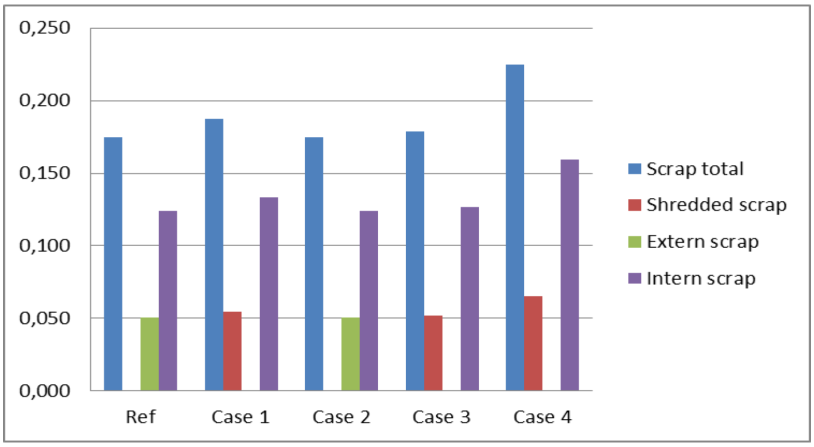

Fig. 2. Scrap consumption in the different cases, unit t/t RS.

4. Discussion and Conclusions

4.1. Results from the objective function analysis

Table 4. Results from the objective functions.

Case	Cost (SEK/t slabs)	CO_2 (t/t slabs)
Reference Case	1409	1.936
Case 1	1365	1.892
Case 2	1461	1.994
Case 3	1357	1.887
Case 4	1359	1.884

Comparison of the different cases with the reference regarding the cost objective is illustrated in Table 4. The results show that the cost optimization case followed by the case 1, where surface cleaning is utilized for the reference case, is generating the lowest production costs. The highest costs are shown to be generated in case 2, where no briquettes are produced. This shows that the use of briquettes and surface cleaning of scrap improves the cost analysis. In Cases 3 and 4, the cost decreases approximately 4 %, compared to the reference case. However the model only considers raw material cost related directly to the process and does not consider investment cost, salary, administration and other external costs. Furthermore no credits are made in the model for decreased landfill costs. Analysis of the results from using CO_2 emission as the object function demonstrates only minor differences between the cases, as seen in Table 4. The case with the highest CO_2 emission is Case 2 where no by-product briquettes are used; consequently an increased pellet and coke consumption generate higher CO_2 emissions.

4.2. Conclusions

The system model shows the interaction between different processes, which gives an overview picture of the whole steel making route. The model is used to investigate changes in process conditions from making use of shredded scrap and ASR as input material in the steel making process. The system analysis shows that surface cleaning of scrap makes it possible to use shredded scrap and ASR or other combustible waste to replace fossil fuels as a cost and environmental efficiency choice. The implementation of surface cleaning and preheating leads to both increased possibilities for recycling materials, which otherwise is difficult to recycle and a more efficient use of energy in the steelmaking routes. Increased recycling of materials is efficient ways to reduce the energy demand, since it often replace virgin materials. The optimization of the model shows that both cost and CO_2 can be decreased when scrap pretreatment is implemented, however none of the analyzed cases is simultaneous minimizing cost and CO_2 emission.

Acknowledgement

This work is part of the ongoing projects in the Centre for Process Integration in Steelmaking (PRISMA) for the possibility to present this work. PRISMA is an Institute Excellence Centre supported by the Swedish Agency for Innovation Systems, the Knowledge Foundation, and eight industrial partners within the iron- and steel industry. This study has also received funding form the SSF ProInstitute programme.

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Potential of fossil and renewable CHP technology to reduce CO_2 emissions in the German industry sector

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Abstract: Based on statistics about fuel demand in industry sectors a method is developed for the estimation of additional combined heat and power (CHP) potential in the main industry sectors. Electricity generation costs of several CHP technologies are then compared to the purchase of electricity on electricity markets. It is found that additional heat potential for CHP is limited in the chemical industry; additional potential is found in the paper industry, food industry and in the manufacturing industry. Additional electricity potential for CHP can be found in all sectors as electricity to heat share is 0.34 at the moment and can be increased with new installations to more than 0.7. The share of renewable fuels used in CHP is highest in the wood and paper industry, additional potential can be found in several branches, but costs are high at the moment.
Markets can pick up CHP electricity in the short term and installations are profitable when long operating hours can be reached. Looking in electricity markets with a higher share of renewable energy sources (RES), operation become more restricted making new operation strategies necessary. Times with electricity prices below short term generation costs of CHP installations increase in the future, so that operation will be less profitable.
In short term CHP can bring additional CO_2 reduction, specific emissions are below new combined cycle units. In the medium to long term additional use of RES fuels and adapted operation strategies will be necessary to lead to further CO_2 reductions.

Keywords: *Combined Heat and Power, Renewable energy, Electricity market, Industrial applications*

1. Introduction

Reduction of CO_2-emissions in all energy consuming sectors will be necessary to fulfill short and long term goals to stabilize climate change. The usage of combined heat and power technologies (CHP) is promising to provide cheap CO_2 reductions especially in the industry sector, but is questioned to be the right technology option regarding long term goals [1]. The EU commission tries to promote CHP technologies with the CHP directive 2004/08/EC [2]. Various support schemes has been implemented throughout Europe [3] and the member states have to report progress to the EU commission. So far progress in the German industry sector has been limited although potential is expected to be large [4]. The purpose of the work is to identify reduction potential in the German industry sector based on fossil but also on renewable fuels. Furthermore the work analysed the possibilities of selling CHP electricity on future power markets with increasing renewable electricity generation.

2. Methodology

2.1. Approach

Statistics of final energy demand in Germany's industrial sector and estimates of the electricity demand in the future were used as a basis for the identification of the industrial heat demand and industrial CHP potentials [5], [6]. The final energy consumption less electricity demand was applied as an indicator for the heat demand. Sector specific energy intensity and indicators of sectoral economic development served as important influencing factors for the estimation of the future heat demand of the German industry. With the help of estimated heat demand the technical potential which could be covered by CHP was then projected (Fig. 1). In this projection the evaluated distribution of heat demand according to the temperature levels for different industry sectors and technical assumptions of conversion efficiency and CHP heat coverage were also integrated.

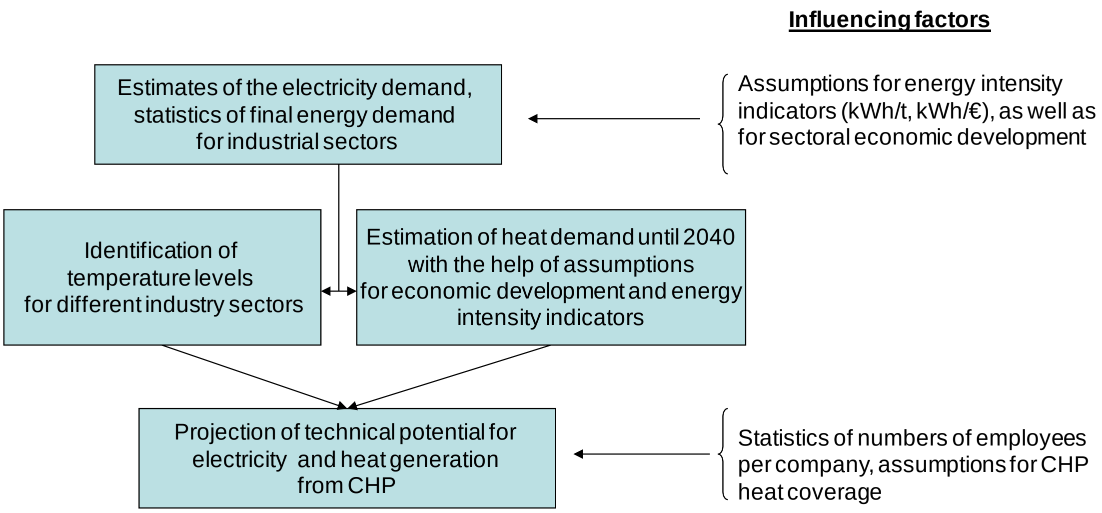


Fig. 1. Methodical approach for estimation of the heat demand in German industry and technical CHP potential.

The evaluation of heat demand according to the temperature distribution for different industry sectors was performed on the basis of previous estimations by Wagner et al. [7] as shown in Fig. 2. As one can see this temperature distribution provides indication for temperature levels of heat demand applicable for possible CHP generation. In this case the process heat at temperature levels lower than 500 °C and heat use for space heating and process water were of high relevance for the identification of the technical CHP potential.

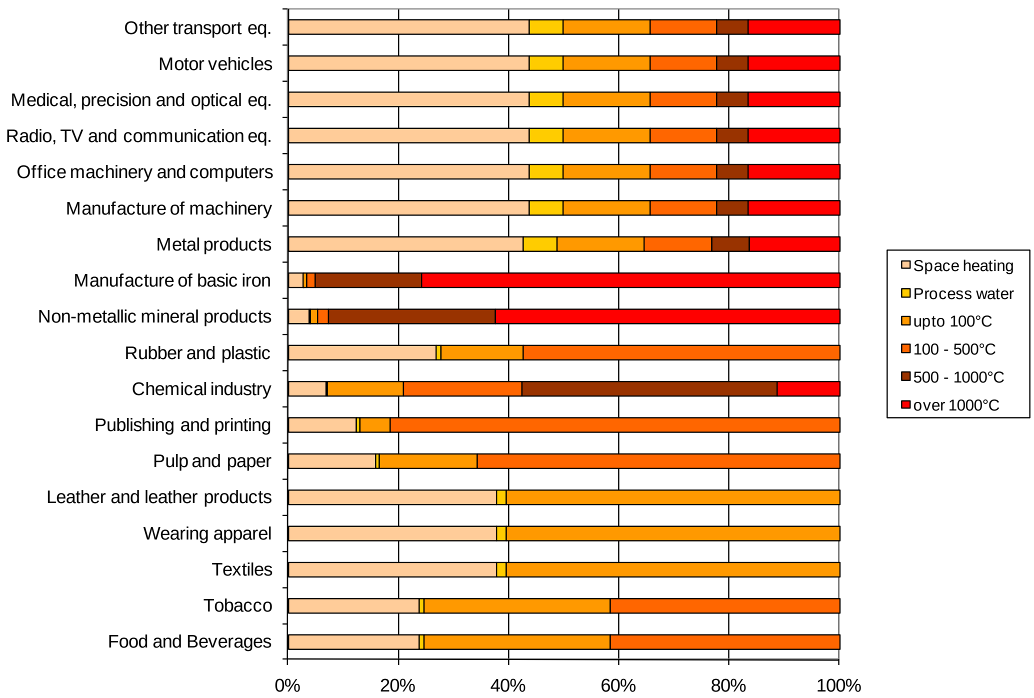


Fig. 2. Distribution of heat demand according to temperature levels and industry sectors in Germany in 2001.

Besides the technical potential also the economic (cost-effective) potential for CHP in the German industry is estimated. The parameters for the technical and economic potentials are defined as follows:

- Technical potential

The technical potential is derived from the useful heat demand applicable for CHP installations (< 500 °C). The conversion from fuel input (final energy) to useful energy is performed with the constant conversion efficiency factor of 90% which corresponds to the boiler efficiency of the separate heat generation. The CHP installation is assumed to apply for 75% of the heat demand. The rest of heat demand will always be generated via a peak load boiler.

- Economic (cost-effective) potential

Economic (cost-effective) potential is defined as a potential that can be supplied more economically attractive via CHP installation than with a separate electricity and heat generation. The base load price on the European Energy Exchange (EEX) served as a reference for electricity generation. The heat generation is considered via a heat bonus. These reference costs were calculated as saved fuel costs in case of separate heat generation. The life cycle of installations was assessed depending on installation type and was defined as 12 years for small installations and up to 20 years for large installations. The interest rate for calculations was set at 10%. Also the financial remuneration of CHP and grid access fees were taken into consideration. In Germany operators of CHP plants get a CHP premium on the electricity production guaranteed by law. The premium is paid to promote new installations of CHP power plants. It is typically between 1.5 and 2 €/MWh and is paid additionally to the revenues for the electricity production. The premium is paid for 4 to 6 years after the installation of the power plant. A comparison of costs and revenues is presented in Table 1.

Table 1. Costs and Revenues for identification of cost-effective CHP potential in the industry.

Costs	Revenues
Investment (life cycle of 12 – 20 years, 10 % real interest rate)	For electricity
Fixed operating costs	For heat
Variable operating costs	CHP premium
Fuel expenses	Avoided grid access fees
CO_2-allowances	

The impacts on the electricity markets are calculated using today's spot market prices from the EEX. Spot market prices for a future scenario with higher RES shares of 40 % have been calculated using the agent based electricity market model PowerACE [8].

2.2. Technical and economic specifications

The spectrum of industrial CHP technologies varies from CHP installations with 1 MW of electric power output to large power plants with several hundred MW of electric power output. In this research the complete spectrum of various CHP technologies available for combined heat and power generation was analysed. For that purpose so called reference installations were defined and their various technical and economic parameters were described. In Table 2 one can see a clear cost decrease with growing power output of an installation.

Table 2: Parameters of CHP installations for output range from 2 to 220 MW (el).)

Parameters	Unit	CC-GT	CC-GT	OC-GT	CC-GT	OC-GT	Gas Engine
Power output [MW]	MW (el)	**220**	**100**	**90**	**20**	**10**	**2**
el. efficiency	%	47.6	47.1	33.0	44.4	31.0	39.0
heat efficiency	%	40.3	41.0	52.4	42.3	49.0	47.6
Efficiency total	%	87.9	88.1	85.4	86.7	80.0	86.5
Investment	€/kW (el)	742	756	722	820	700	800
fixed operating costs	€/kW/a % of Investment	37.1 7 %	37.8 7 %	33.3 6 %	57.4 7 %	42.0 6 %	16.0 2 %
other variable operating costs	€/ MWh_{el}	0.5	0.5	0.5	0.5	0.5	8

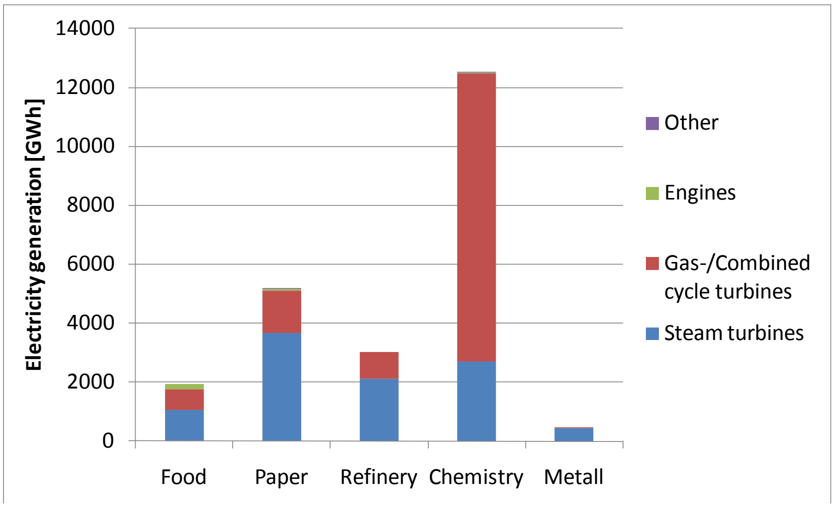
Source: own assumptions based on information from project developers, CC-GT: combined cycle gas turbine, OC-GT: open cycle gas turbine

3. Results

3.1. Additional technical CHP potential

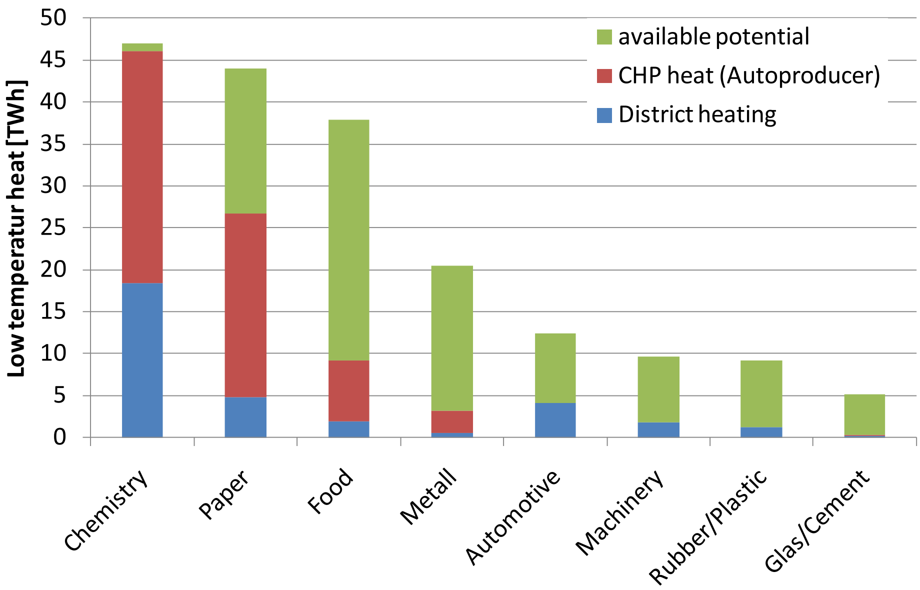
Today the major industry sectors using CHP power plants are the chemical industry, the paper industry and the food industry in Germany (see Fig. 3). They provide around 74 % or more than 19 TWh of the CHP electricity production in the industry sector in 2009 [6]. Additional electricity generation is possible without an increase of the heat generation as the average electricity to heat factor of the CHP installations is only ca. 0.34. The modernization of old CHP devices can increase the electricity to heat ratio above 0.7 and double the electricity generation.

Next to modernization of old CHP generation units, there is also the possibility to find new heat sinks that can be supplied by CHP units. It is found that additional heat potential for CHP heat generation is limited in the chemical industry, some additional potential is found in the paper and food industry (see Fig. 4). Further additional heat potential is found in the manufacturing industry. Final energy demand in the industry sector has been 700 TWh in 2008 with around 214 TWh of low temperature heat. Around 45 % of this low temperature heat is already supplied by district heating or by CHP auto producers. The technical potential to increase CHP heat production is then around 118 TWh. Only a small part of it is a cost-effective and realizable potential. In some sectors like metal or glass industry a lot of high temperature heat is available that could be used first before new CHP units would be installed. In other sectors with small companies the installation of CHP units might not be profitable as only small units with shorter operation times could be used.



Source: [6]

Fig. 3. CHP electricity generation in major industry sectors related to the generation technology in 2009 in Germany



Source: Own figure based on [5, 6, 7]

Fig. 4. Provision of low temperature heat by CHP heat generation, district heating and available CHP heat potential in major industry sectors in 2008

3.2. Renewable fuel use in the industry sector

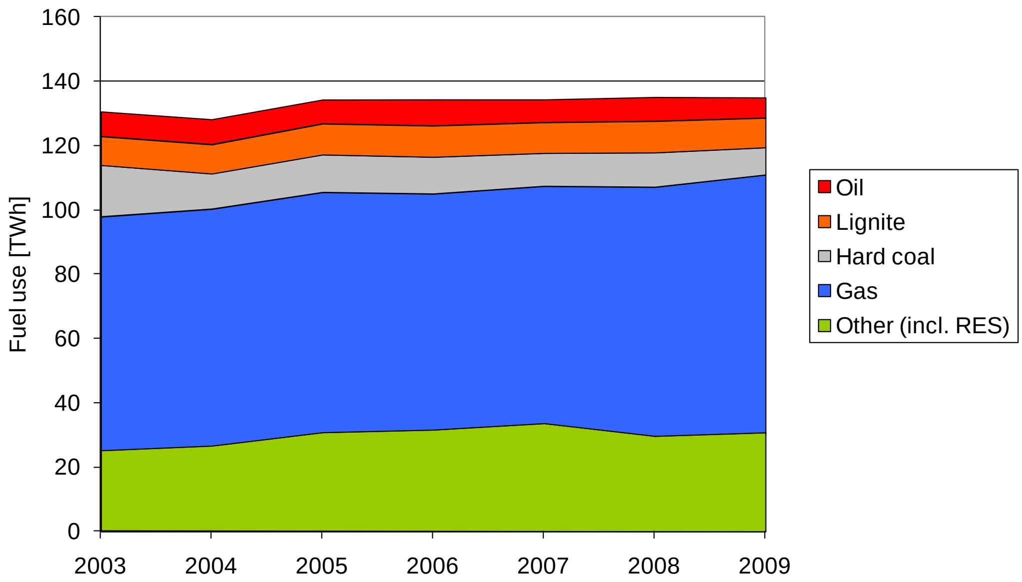
Until now renewable fuels have only a very limited share of 4 % in the industrial sector corresponding to around 27.5 TWh (final energy demand) in 2008 [5]. It increased from 15.5 TWh in 2003. Most of it is used in the wood and furniture industry followed by the pulp and paper industry (see Table 3). In this figure fuel use for heat production in CHP power plants is included. The fuel use for CHP electricity production is covered by the statistics for the power plant sector. The renewable fuel use for electricity production in industrial power plants was 7.8 TWh in 2008 (with 3 TWh in 2003).

Table 3. Distribution of renewable fuel use in major industry sectors in Germany 2008.

Sector	Wood/ furniture	Paper	Chemistry	Cements	Food	Other
Share [%]	37	27	22	8	3	3
Total [TWh]			27.5			

3.3. Renewable CHP generation

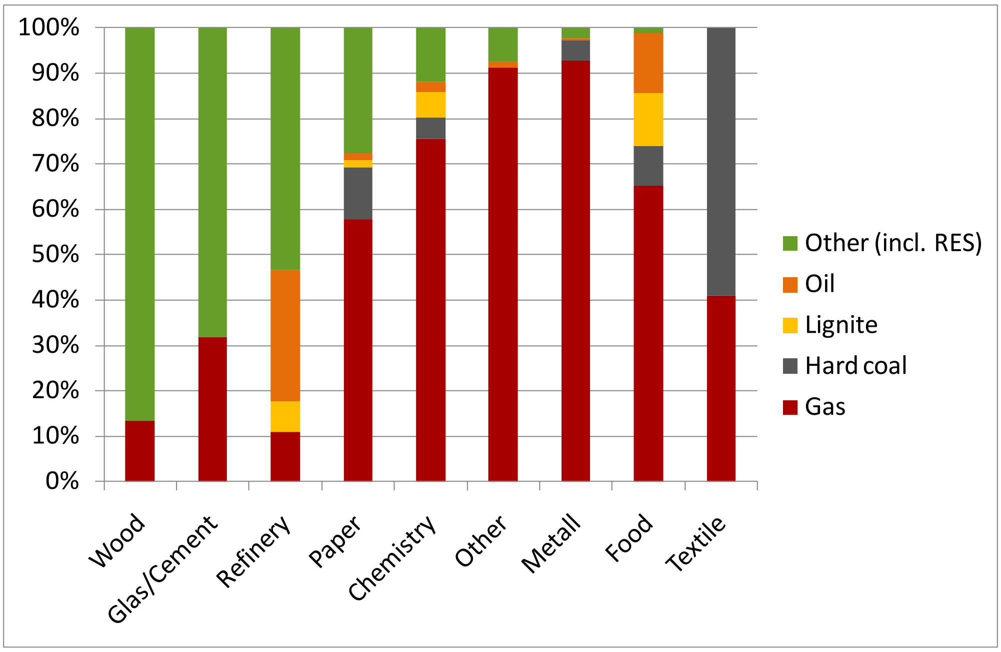
The share of renewable fuels used in CHP power plants is covered in the statistic [6] together with other fuels like waste (refuse-derived fuels, RDF). In the past the use of renewable and RDF fuels has slightly increased from 25.3 TWh in 2003 to 29.8 TWh in 2008 (see Fig. 6). In 2003 around 24 % (6 TWh) of the 25.3 TWh are renewable fuel due to statistics from EUROSTAT [9]. This corresponds to almost 5 % of the fuel used in CHP power plants. For 2008 no statistics are available. Under the assumption that the fuel use in CHP power plants has increased similar to the total renewable fuel use in the industry sector, it should be around 11 TWh in 2008. Progress in the sector is difficult to estimate, but there should have been some in the past.



Source: [6]

Fig. 5. Fuel use in CHP power plants from 2003 until 2008 in the industry sector in Germany

High shares of renewable fuel use in CHP power plants can be found in the wood industry and in the paper industry (see Fig.7). Renewable fuels are also used in the chemical industry. Additional potential in the wood and paper industry is very limited as the major waste material from production processes is already in use [10]. An increase of renewable fuels in CHP power plants can be done with external biomass like wood chips or pellets. Another option is the usage of biogas. Until now this option has not been used as renewable fuel costs were much higher than fossil fuel prices.



Source: [6]

Fig. 6. Share of renewable fuel use in CHP power plants in major industry sectors in Germany 2008

3.4. Economic potential and CO_2 savings

The economic assessment is driven by the size of the CHP units as investment costs typically decreases for larger units. Furthermore utilization decreases costs. Electricity production costs range between 10 Cent/kWh(el) for small CHP units (500 kW) and 6 Cent/kWh for big CHP units (400 MW), when units are in operation for 4000 h/a. If the value of the heat generation is estimated with saved fuel costs then electricity production costs are typically reduced by 2 to 4 Cent/kWh. In this case, CHP units are profitable compared to the electricity purchase. With a higher utilization the benefits typically increase.

Markets can pick up CHP electricity in the short term and installation are profitable when long operating hours can be reached. Profit margins are in the range of 13 to 25 €/MWh for more than 5000 hours per year.

Looking in electricity markets with a higher RES share of 40 %, operation become more restricted making new operation strategies necessary. Times with electricity prices below short term generation costs of CHP installations increase in the future, so that operation will be profitable in fewer hours than today. This is because natural gas and CO_2 allowances will be more expensive. This will be partly compensated by higher revenues for electricity, but the increase of electricity prices will be limited due to wind and solar power production. Typical profit margin increases up to 40 €/MWh, but can be reached only 2500 – 4000 hours per year.

The heat bonus for CO_2 emissions on the CHP heat generation is calculated using a reference heat technology. Assuming gas as fuel and a 90 % efficiency of the heat generation the heat bonus is 223 g CO_2/kWh(heat). Resulting CO_2-Emissions for the electricity generation reach 230 – 280 g CO_2/kWh(el) depending on the CHP technologies. Compared to the German electricity mix with specific emissions of 575 g CO_2/kWh(el) savings up to 60 % can be reached. A comparison with a modern combined cycle power plant, specific emissions are at 340 - 350 g CO_2/kWh(el), leads to a reduction of ca. 35 %.

4. Discussion and conclusions

In short term CHP can bring additional CO_2 reduction in the German industry sector as specific emissions are below the actual electricity mix and also below new combined cycle power plants with no heat or steam generation. As gas is already the dominant fuel source in the industry sector savings in the heat production are limited. Major reductions can be achieved by the substitution of fossil electricity generation outside the industry sector. Renewable fuel use is already done in sectors that have renewable waste from its production process. These potentials within the different sectors are already used today, so that an increase of renewable fuels can be mainly achieved by using additional renewable fuels like wood chips, pellets or biogas from outside the industry sectors. In the medium to long term additional use of RES fuels and adapted operation strategies will be necessary to lead to further CO_2 reductions.

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Energy efficiency opportunities within the powder coating industry

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Abstract: A new challenge to reduce energy usage has emerged in Swedish industry because of increasing energy costs. Energy usage in the Swedish powder coating industry is about 525 GWh annually. This industry has a long and successful record of working towards reduced environmental impact. However, they have not given priority to energy saving investments. Electricity and LPG, for which end-user prices are predicted to increase by as much as 50 – 60% by 2020, are the main energy carriers used in the plants. This paper presents the results of two detailed industrial energy audits conducted with the aim of quantifying the energy efficiency potential for the Swedish powder coating industry. Energy auditing and pinch analysis methods were used to identify possible energy housekeeping measures and heat exchanging opportunities. The biggest users of energy within the plants are the cure oven, drying oven and pre-treatment units. The energy use reduction by the housekeeping measures is 8 – 19% and by thermal heat recovery an additional 8 – 13%. These measures result in an average energy cost saving of 25% and reduction of carbon dioxide emissions of 30%. The results indicate that the powder coating industry has a total energy efficiency potential of at least 20%.

Keywords: *Powder coating, energy audit, pinch analysis, energy efficiency*

1. Introduction

The Swedish electricity market was liberalized 1996 in order to increase competition. The European electricity market deregulation was delayed until 2004 before it was liberalized for industrial consumers, which has led to increased electricity prices in Sweden [1]. Industry accounts for 40% of Sweden's total energy use, which is forecasted to increase due to greater industrial demand. Hopefully new eco-efficient technology as well as increased energy efficiency will reduce the rate of increase of energy usage in industry [2].

The 20-20-20-targets have been formulated by the EU commission in order to achieve their energy policy vision: competitiveness, sustainability and security-of supply. The targets represent 20% reduction in energy use and at least 20% share of renewable energy supply based on the 2005-levels and a 20% reduction in greenhouse gas emissions based on the 1990-level. Key areas of the EU targets are in the electricity and gas markets, renewable energy sources, consumer behavior and closer international cooperation. All EU countries are encouraged to act and coordinate activities in order to try to distribute the burden but also its future dividends. Policy instruments have been introduced in Sweden to achieve these goals and guide the energy use in a sustainable direction, and decrease emissions to reduce climate change. The instruments include energy, carbon and sulfur taxes but also the electricity certificate system, program for Energy Efficiency (PFE), the energy audit program, technology procurement, policy instruments for buildings and transport and information [3]. The end user prices of electricity and liquefied petroleum gas (LPG) is predicted to increase by as much as 50 - 60% by 2020 [4]. This is another driving force in implementing energy efficiency measures. Beside the environmental and economical benefits from making industrial energy usage more efficient there are also marketing benefits as customers begin to require energy-efficient production within the powder coating industry [5].

Experience from Swedish research in industry reveals that the energy saving potential among non energy-intensive companies ranges from 15-50% [6-7]. No figures are available for the energy saving potential in the energy-intensive powder coating industry. The aim of this paper is to quantify energy efficiency potential for the Swedish powder coating industry based on two thorough industrial energy audits. The research was conducted using multiple case study analysis, energy audit as well as pinch analysis.

The Swedish powder coating industry includes approximately 350 plants using more than one metric ton of coating powder. These currently accounts for a combined energy usage of 525 GWh/year, corresponding to 1,5 GWh/year per plant [5]. This sector has successfully implemented eco-technology as a result of legal requirements. However, so far they have not given priority to energy saving investments. A powder coating plant usually includes pre-treatment, drying oven, powder box and cure oven, e.g. see Fig. 6. In the pre-treatment unit, the parts that are to be coated are washed in a degreasing step with alkaline washing solution of around 60°C. The pre-treatment also includes a number of rinsing steps. The parts go through a drying oven that has a temperature of around 120–150°C. Then one layer of powder is applied in the powder box and at the end of the conveyor the parts go through a cure oven that has a temperature of 200°C. After the cure oven some plants have a cooling zone where cold air is blown over the parts to make them cool faster [8].

Two companies were selected for this multiple case study analysis [5]. Company A uses LPG as fuel for firing an immersed heater in order to heat their first pre-treatment bath. Company B uses district heating instead. Direct burners using LPG heat the drying ovens to a temperature of 150^{o}C and 120^{o}C respectively. The cure oven is heated by electricity to 200^{o}C at Company A while Company B uses LPG with direct burners. Company B also has a primer box, primer oven and cooling zone while Company A has a liquid finish box between the drying oven and the powder box. All components besides heating accessories are driven by electricity.

2. Methodology

The electricity use is based on instantaneous measurements for the different units of the process as well as on logging of selected components and it was performed during one week for each company. The values from the logging were used to evaluate how many hours the different parts of the process are in use each day as well as to get an average value for the electricity usage. The calculated energy use of electricity was compared with the electricity invoices. This comparison made it possible to extrapolate the logged and instantaneous measurements to the usage of one year. The usage of district heating and LPG was based on the monthly values for the consumption stated on the invoices. Invoices for one year were compared for all three energy carriers.

Pinch analysis is a tool to analyse industrial process systems and determine how much heat that must be added, how much excess heat must be removed and how much heat that can be recovered within the process. Pinch technology is also a useful tool to investigate how to design a heat exchanger network in order to achieve maximum heat recovery. In this project the heat content in the different streams was estimated based on process data and after this different possible options for heat exchange were investigated. The heat usage depends on the different production schemes, when the processes are used, for how long and the distance between them. In the end the options are weighed against each other based on energy cost savings and capital investment required.
The payoff period and the net present value (NPV) method were used to evaluate the investments. The payoff period quantifies the time period necessary for the investment's

energy cost savings to cover the initial investment cost. The net present value method evaluates the viability of an initial investment by comparing it with all future energy related cash flows. All future cash flows are discounted using the interest rate and a reference period of time. The net present value ratio (NPV divided by initial investment) is used to compare different investments. The investment with the maximum ratio is the most attractive. In the base case, the investments are analyzed assuming constant energy prices over the lifetime of the investment. In a sensitivity analysis, the analysis accounts for the development of energy prices during the years 2010 – 2020.

3. Results

The energy audit showed that 77 – 86% of total energy usage occurs in the core production processes, whereas 14 – 23% is connected to the support processes. The first graphs illustrate the electricity use during an average production day. As can be seen in Fig. 1a, company A has two peaks for the production processes during the day. This is because they operate with two shifts and they have a large variation of products. Company B, e.g. Fig. 1b, has a more homogeneous production and single-shift operation. Significant differences can be seen when analysing how the electrical power load is distributed between the process units during operating hours, e.g. Fig. 2. For Company A the cure oven is the largest consumer of electricity and for Company B it is the powder box. For Company A the cure oven can be used at three different temperatures due to combination of liquid finishing and powder coating. The powder box in Company B has a high ventilation requirement because of a more open construction and employees working inside compared to Company A. Figures 1 and 2 are comparable when production is at its full capacity.

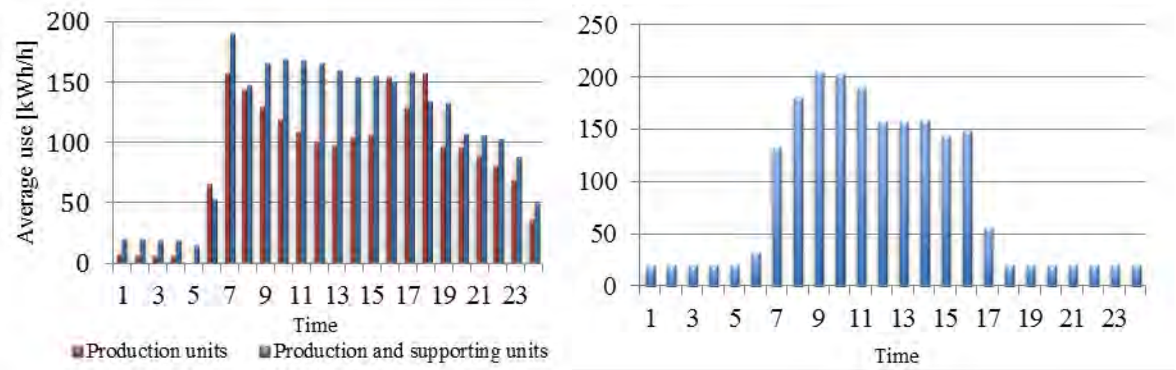

Fig. 1. Electricity use during an average production day for Company A (left) and B (right).

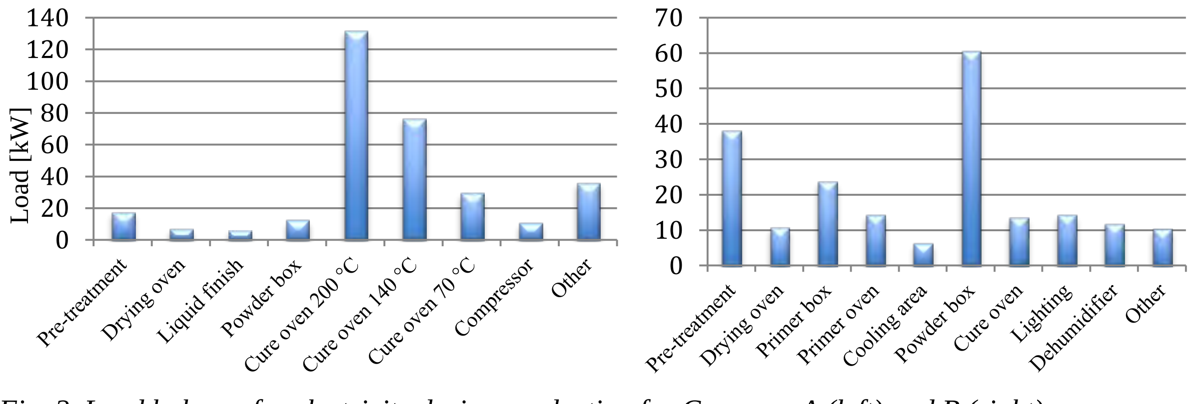

Fig. 2. Load balance for electricity during production for Company A (left) and B (right).

In the energy balance all energy sources are included, i.e. electricity and LPG for Company A and electricity, LPG and district heating for Company B, e.g. Fig. 3. As can be seen it is the pre-treatment, drying oven and cure oven that uses most energy. Together these three units accounts for about 70% of the total energy supply for both companies. When using liquid finishing (65% of the time) the pre-treatment and drying oven are turned off for company A, which leads to a lower demand for LPG for this company. For company B it is the primer box, primer oven and cooling zone that can be turned off during periods.

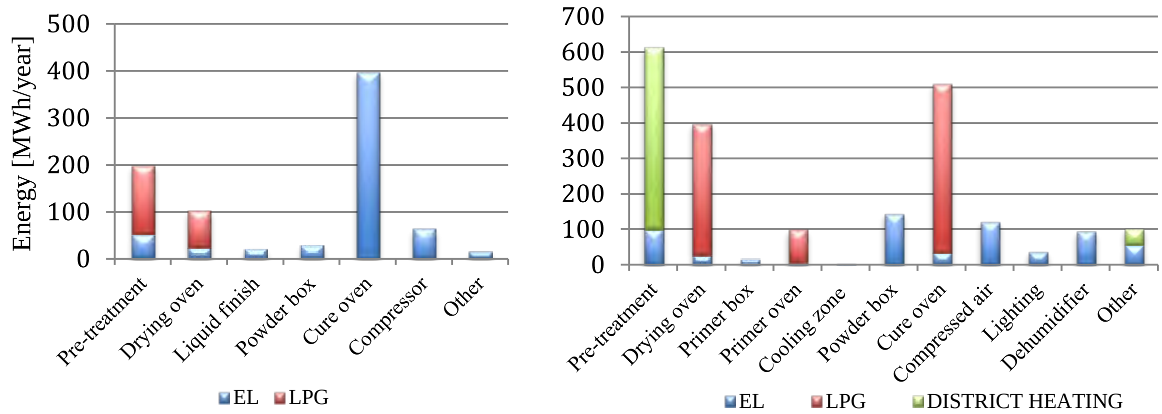

Fig. 3. Energy balance during one year for Company A (left) and B (right).

Figure 4 shows the total energy use for the two companies. Both companies have a significant use of electricity during downtime. This is due to that both have dehumidifiers that are on all the time as well as charging of trucks during the nights.

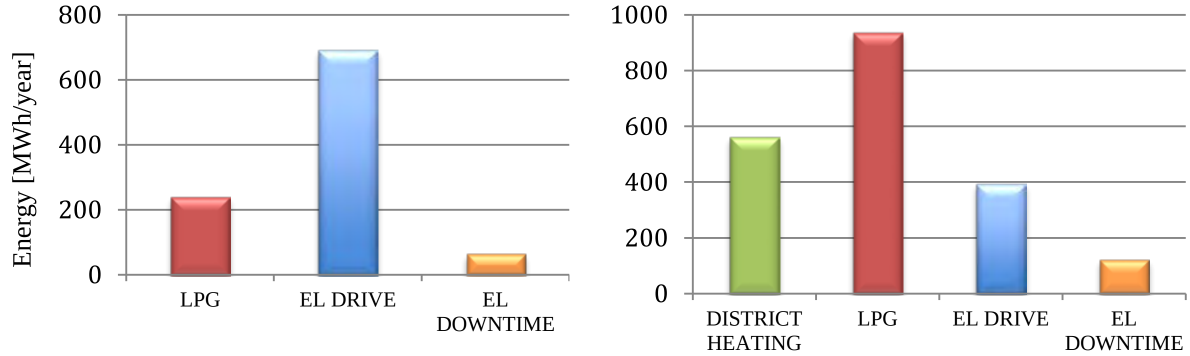

Fig. 4. Total energy use per year for Company A (left) and B (right).

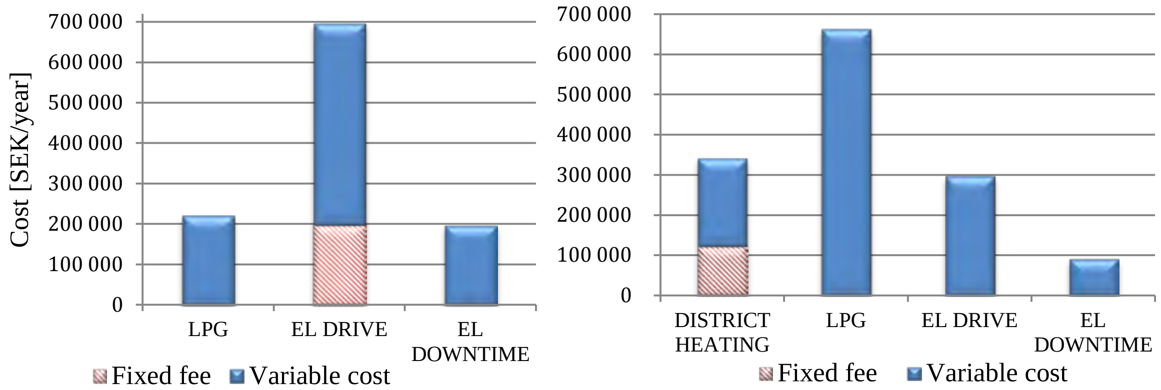

Fig. 5. Energy cost per year for Company A (left) and B (right).

The energy cost can be seen in Figure 5 above. Company A has a fixed fee for electricity but not for LPG. Company B has a fixed fee for district heating but not for the other energy sources. Electricity is the highest energy cost for company A while LPG is the highest cost for company B.

The specific energy usage indicators have been chosen based on a national project within Swedish industry named ENIG (EN in Groups), see Table 1. One main difference between the two companies is that Company A uses half as much energy per year but has twice as much production time. This is because Company A combines other varnishing techniques and offers packing and masking. Company B only uses powder coating technology which is more energy demanding. Since the turnover is similar the second indicator depends mostly on the energy use. The mass flow of parts is more than twice as high for Company B compared to Company A, which affects the third indicator (specific energy usage per ton of product).

Table 1. Specific energy usage indicators.

Company	Energy use per		
	Production time [kWh/h]	Turnover [kWh/kSEK]	Parts [kWh/Ton]
Company A	230	47	185
Company B	973	107	135

The reduction of CO_2-emissions for the suggested measures are based on values of 234 kg CO_2/MWh of LPG, 770 kg CO_2/MWh of electricity and 0 kg CO_2/MWh for district heating. Electricity has a high value due to that it is assumed to be electricity on the margin and district heating has zero emissions due to production from biomass. The energy prices can be seen in Table 2. The prices for 2010 is stated on the companies invoices and the increase until 2020 is expected to be 60% for LPG, 50% for electricity and 30% for biomass [4].

Table 2. Energy prices for 2010 and 2020.

Company	Energy price [SEK/MWh]					
	El. 2010	El. 2020	LPG 2010	LPG 2020	DH 2010	DH 2020
Company A	735	1103	953	1525		
Company B	755	1133	707	1131	391	508

Energy housekeeping measures do not include heat exchanging and are primarily targeted at identifying better operational practices. The potential energy usage reduction, based on such measures was estimated at 8 – 19%, e.g. Table 3.

Table 3. Energy housekeeping measures (compared with the total energy use for each company).

Measure	Reduction potential		
Company A	Energy [MWh/year]	Running cost [SEK/year]	CO_2-emission [Ton/year]
Lighting	22	17 000	17
Standby	65	49 000	50
Production planning	100	74 000	77
Drying oven	8	6 000	2
Total	195 (19%)	147 000 (15%)	146 (23%)
Company B			
Lighting	18	14 000	14
Dehumidifier	31	24 000	24
Powder box’s ventilation	13	10 000	10
Production planning	44	33 000	34
Fans	16	12 000	13
New powder box	44	33 000	34
Total	166 (8%)	176 000 (9%)	129 (26%)

Lighting measures include switching to low energy lighting, removing it in areas where it is not necessary as well as turning off when not in use. Both companies have several applications on standby during nights and weekends, for example compressor and dehumidifier. Complete shut-off of such equipment can lead to substantial energy savings. Company B can turn off the powder box ventilation during breaks. Production planning could reduce the energy usage by having one start per day and process unit. Using a lower temperature in the drying oven for Company A could decrease energy usage but it also generates a risk of lower coating quality. The fans to the drying oven and cure oven are oversized for Company B and changing them could reduce the plant's power load. If Best Available Technology (BAT) is adopted for the powder box, electricity use for the ventilation within the box could be reduced by 30% and the compressed air usage by 45%.

Pinch analysis was used to identify opportunities for heat recovery by heat exchanging. Two possible heat recovery cases were investigated, e.g. Table 4. Case 1 involves heat exchanging incoming and outgoing airflows in the cure oven and drying oven, e.g. Fig. 6.

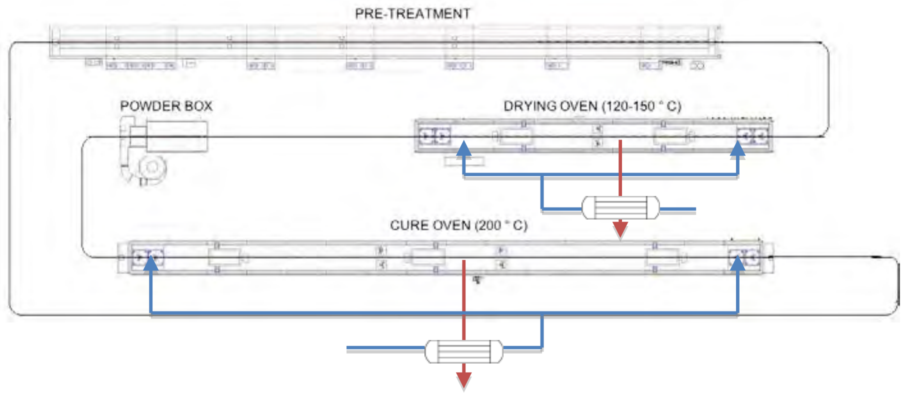

Fig. 6. Case 1 Proposed heat exchanging measures for powder coating process.

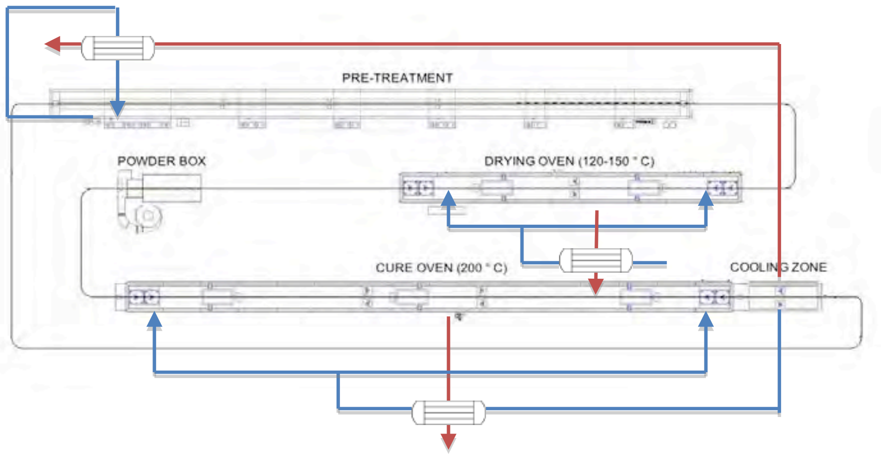

Fig. 7. Case 2 Proposed heat exchanging measures for powder coating process.

Table 4. Saving potentials for heat recovery cases.

Measure	Reduction potential		
	Energy [MWh/year]	Running cost [SEK/year]	CO_2-emission [Ton/year]
Case 1 Company A	121	90 000	76
Case 2 Company A	128	85 000	73
Case 1 Company B	140	100 000	33
Case 2 Company B	251	146 000	28

Case 2 includes a cooling zone after the cure oven. The large airflow from the cooling zone can be divided and used as preheated ingoing air to the cure oven as well as for heat exchanging to heat the pre-treatment bath. For the drying oven the heat exchange is the same as in Case 1, e.g. Fig. 7.

The economic assessment, e.g. Table 5, shows that the two cases for heat recovery are profitable for both companies. However, Case 1 has a much higher NPV and NPVR than Case 2. The total savings are presented in Table 6, showing that Company A has a higher potential for reduction of energy use due to more variations in the production as well as larger hot streams out from the ovens.

Table 5. Economic assessment with expected increased energy prices until 2020 for Company A (interest rate 10%) and Company B (interest rate 15%).

Measure				
Period 10 years	Investment cost [SEK]	Pay off period [year]	NPV [SEK]	NPVR
Case 1 Company A	135 000	0,9	795 000	5,90
Case 2 Company A	450 000	3,1	440 000	1,00
Case 1 Company B	150 000	1,2	460 000	3,08
Case 2 Company B	495 000	2,8	400 000	0,80

Table 6. Total savings for energy housekeeping measures plus thermal heat recovery cases (compared with the total energy use).

Measure	Reduction potential		
	Energy [MWh/year]	Running cost [SEK/year]	CO_2-emission [Ton/year]
EHK+Case 1 Company A	316 (32%)	237 000 (26%)	220 (35%)
EHK+Case 2 Company A	323 (33%)	232 000 (25%)	219 (34%)
EHK+Case 1 Company B	306 (16%)	276 000 (20%)	162 (26%)
EHK+Case 2 Company B	417 (21%)	322 000 (23%)	157 (25%)

4. Concluding discussion

The energy audit shows that the production processes use a substantial amount of energy 77 – 86% whereas the support processes use 14 – 23%. For the two companies investigated the energy usage can be reduced by 8 – 19% with energy housekeeping measures. Thermal heat exchange can reduce the energy use by an additional 8 – 13%. In total this gives energy savings of around 30% for company A and 20% for company B.

Improved production planning will make a large impact on energy usage. For company A this could lead to a reduction of the second electricity use peak, e.g. Fig. 1a. For company B turning on the primer part only once a day could save energy. Another measure for company A is to completely turn off equipment that is not used. For company B the powder box can be turned off during breaks. These are measures that can be implemented by changing the routines etc. within the companies. In this study, energy housekeeping measures have been shown to achieve the same or higher energy savings compared to thermal heat recovery.

Benchmarking shows that the most efficient way of heat exchanging is within the same part in the process. This will reduce the investment costs as well as contribute to a flexible process. Installing a cooling zone after the cure oven will be profitable but there are other investments that are even more profitable. The fact that the cooling zone will give a better working environment should be taken into account. The benchmarking also shows that the airlocks from the ovens usually have too small heat content to be efficiently heat exchanged against ingoing air to the ovens. The contaminations that follow the airlocks also prevent using this air as ingoing air. Another reason is that there is a risk that to much air is pushed into the ovens if airlocks are used. However, there might be a possibility to use them for heat exchanging against facility ventilation air to reduce demand for space heating. To be able to implement thermal heat exchange further study is necessary in order to investigate the impact of contaminants released from the powders when cured in the cure oven. There is a possibility that these contaminants will stick in the heat exchangers and tests must be conducted to see if filters are required upstream from the heat exchangers. It should be noted that companies in Finland have successfully used the airlocks for space heating [5].

The economic results are based on an interest rate of 10% and 15% respectively. A lower interest rate would increase the net present value and the net present value ratio. The results in these projects show that Case 1 is the best investments from an economical perspective for both companies. However, Case 2 has other positive effects that are not accounted for in the calculations. For example a cooling zone would substantially improve the working environment by reducing the heat that is emitted to the facility. Results indicate, based on benchmarking between these two projects, that the powder coating industry may have an energy efficiency potential of 20% which corresponds to total energy savings of at least 105 GWh/year for the sector.

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Case Study and Analysis of the Production Processes in a Steel Factory in Jordan

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Abstract: This work represents a true case study and analysis of the technical and energy managerial aspects of recommended designs of the production lines of a steel factory in Jordan. A modern structure of a control system based on SCADA (Supervisory Control And Data Acquisition) technology is proposed. Furthermore, the mechanical and electrical maintenance sections in the factory were reviewed due to their major effects on the production cost and energy consumption of the factory. This study was performed in two main phases: The first phase contains the collected data and process assessment that were undertaken by traditional direct observation and activity categorization, while the second phase gave details on the proposed control methodology in terms of design and architecture.
Moreover, a proposal on maintenance planning and procedure program was also included in this study in order to reduce the time and accordingly the cost of maintenance. The steel factory studied produces various steel products such as: Concrete Reinforcement Steel Bars (Rebars), Flat & Square Bars Section which includes standard flat bars, standard square bars, and plane round bars, in addition to Wire mesh in different sizes and steel billets. In steel production industries, two automation levels can, in general, be identified. The first level involves the electromechanical actuation of the devices in the production plant; this level of automation is currently available in every plant. The second level involves the supervision of the production process; this level of automation is less frequent and is generally only partial. In fact, steel production involves a variety of complex physical phenomena, described by sophisticated mathematical models which are rarely usable to derive real-time advice for process supervision and control. Most operators' support systems for steel production are represented by simple technologies such as microprocessor-based systems.
Based on the outcomes of this study, the factory purchased a new melting furnace of (60) tons capacity instead of the (30) tons capacity melting furnace used in the factory before the study. The factory is considering also the purchase of a scrap press in its new budget in order to improve scrap quality before melting it; in order to reduce the rate of consuming the furnace electrodes. Also, the maintenance section will be restructured by merging electrical and mechanical maintenance sections into one section headed by the deputy of the factory manager.

Keywords: *Steel Production Line, SCADA System, Maintenance Structure, Efficiency*

1. Introduction

To maintain an efficiently operating unit and avoid failure of critical equipment, especially modern steel industry equipment, the focus has clearly shifted over the years, from Breakdown Maintenance, i.e. repairing the equipment after its malfunctions, to Preventive Maintenance, i.e. fixing the equipment according to planned maintenance schedule. The next trend was Computerized Maintenance Management Systems (CMMS), and the latest trend encompasses asset management and maintenance, supported by various methods of Condition Based Maintenance Systems (CBMS) and in-service inspection processes. CBMS or Predictive Maintenance methods are an extension of preventive maintenance and have been proved to minimize the cost of maintenance, improve operational safety and reduce the frequency and severity of in-service machine failures. The basic theory of condition monitoring is to know the deteriorating condition of a machine component, well in advance of a breakdown, for proactive maintenance. A conventional integrated steel plant has a vast array of equipment. The plant is a conglomeration of smaller units, each in itself complete and self-contained. These constitute Coke Ovens, Coal Chemicals, Sinter Plants, Furnace, Steel Melting Shops, Continuous Casting Machine, Tonnage Oxygen Plants, Plate Mill, Hot Strip Mill, Cold Rolling Mill, other secondary mills, Captive Power Plants and a host of other departments. Every piece of equipment needs special care and attention, characteristic to it. The Coal Chemicals unit has Gas Boosters and Exhausters that handle coke oven gas, a highly inflammable commodity, whereas Sinter Plant Blowers and Waste Gas fans handle air containing highly abrasive sinter dust. The Turbo Alternators of Captive Power Plant require round the clock vigilance involving a variety of parameters. Seemingly innocuous Forced Draft & Induced Draft fans of the Reheating Furnaces also assume significance because of their criticality in application. Failure of these fans may lead to cut down of Hot Strip Mill/ Plate Mill production by 33 - 50 percent. Under the current business environment, cost competitiveness of steelmakers has assumed a priority role. As a global phenomenon, effective maintenance management has been accepted as the key to corporate strategy for reduced costs. This has led to integration of maintenance management function with production and business problems, not just equipment problems. With this realization that maintenance management can cost 35 - 40 percent of revenues and, in most cases up to 15 percent of unit production cost, steel companies are increasingly opting for new maintenance technologies which can be effectively and relatively easily implemented for reduced costs and increased profitability. According to industry estimates, a 10 percent reduction in maintenance costs translates to a 30 percent increase in profitability.

From the previous discussion, the need for introducing new technologies to the steel production is definite. This study provided the factory with some state-of-the-art technologies which can be adopted into the steel production processes in order to improve the product quality, minimize the need for electrical energy and human resources, reduce maintenance time and cost, and increase reliability and real-time data accuracy. The Jordanian factory is located in Zarqa area, and employs (324) technicians, engineers and administration employees. The main function of the factory is to melt Scrap (collected used steel pieces) in an electric furnace of (30) tons capacity, then cast molten iron in moulds to obtain steel billets. The steel billets are then manufactured in a sister company factory to produce concrete reinforcement steel bars (Rebar) in different sizes using rolling and extrusion, flat and square bars, and wire mesh. This factory, which was manufactured by a Turkish company, is a new one that started production in 2008. The current production capacity is around 10,000 tons of steel billets per month.

Employing SCADA system into the melting and casting processes has a good impact on the product quality, minimizing the need for human resources, reducing maintenance time and cost; increasing reliability, and real-time data accuracy. This technology should provide the following:

- Continuous (momentarily) monitoring of the state of the process and of the plant;
- Displaying warnings and alarms, at a sufficiently high level of abstraction;
- Giving advice as needed to the metallurgical management of the process.
- Generating historical reports.

Nowadays, there are two main industrial processes to produce steel: The first one, which is known as integrated steel plant, produces steel by refining iron ore. This ore-based process uses a blast furnace. The other one, which is steel-making from scrap metals, involves melting scrap metal, removing impurities and casting it into the desired shapes. Although, originally the steel production in the electric arc furnaces (EAFs) was applied mainly to the special steel grades, the situation has changed with tap's size increase, and the high productivity that has been reached progressively. This has allowed significant cost reduction, diminishing consumption of energy, electrodes and refractory. At present, electric furnace combined with chemical additives, allows to make a very important part of the worldwide steel production on the basis of the massive recycling of the iron scrap. Under the current business environment, cost competitiveness of steelmakers has assumed a priority role. As a global phenomenon, effective maintenance management has been accepted as the key to corporate strategy for reduced costs. This has led to integration of maintenance management function with production and business problems, not just equipment problems. With this realization that maintenance management can cost 35 - 40 percent of revenues and, in most cases up to 15 percent of unit production cost, steel companies are increasingly opting for new maintenance technologies which can be effectively and relatively easily implemented for reduced costs and increased profitability. According to industry estimates, a 10 percent reduction in maintenance costs translates to a 30 percent increase in profitability [1-3].

2. Methodology

This study reviewed the structure of the maintenance section in the factory in order to improve and develop the existing maintenance processes and reduce running production costs of consumed electrodes and electricity. The current bill of electricity consumption per month by the factory is around $0.5m, which is relatively high for a factory in a developing country. As mentioned above, the automatic control system and measures used to control the process of melting iron and steel scrap, was analyzed and reviewed in order to evaluate its effect on the mechanical and electrical maintenance of the factory. Many machinery parameters can be measured, trended and analyzed to detect imminent failure or onset of problems. Common among them are: Machinery vibration, Lube oil analysis including wear debris analysis, Infrared thermograph, Ultrasonic testing, Motor current analysis, Shock pulse measurement, …,etc. Additionally, operational characteristics such as flow rates, heat, pressure, tension, speed and so on can also be monitored to detect problems. In case of machine tools, product quality in terms of surface finish or dimensional tolerances is often an indication of problems. As all these techniques have value and merit, the application of any particular technique depends on the suitability and ease of implementation [1-4].

The control systems of the Electrical Arc Furnace (EAF) used in the factory need the following improvement and development in order to reduce the final product cost. In order to achieve this aim, analytical methods were followed to improve steel production process in the EAF. In order to do s o, the study was divided into two phases that are sequential yet synergistic. The first phase used traditional methods of work measurement drawn from industrial engineering practice, such as process definition, development of flow charts, and data collection via time-and-motion studies, to obtain a complete, quantitative understanding of current system operational procedures, workflow patterns, and location of productivity constraints. The second phase was built upon the understanding gained during the first phase. In the second phase, opportunities to improve throughput was identified, with particular attention to those opportunities requiring relatively low capital investment. The principal analytical tools to be used for this phase were the operations research techniques of project management, to identify both critical paths within work flow and utilization imbalances among system resources.

2.1. Improving Maintenance Management

A working definition for various types of maintenance actions is as follows:

- Failure Maintenance: This relates to the policy of repair or replacement of a p art or subsystem only upon failure of the named part or assembly.
- Block Maintenance: This relates to the policy of repair or replacement of all parts on subsystems (block) at a predetermined interval of time.

- Preventive Maintenance: This relates to the policy of repair or replacement of a subset of parts or subsystems, when another part of subsystem fails or is repaired/replaced after a certain length of service [5, 6].

Proper maintenance is essential to keep production equipment and capital assets at a state conducive to its output role in maintaining a level of production at a predetermined quality and quantity. Maintenance costs typically average from 5% to 7% of the value of fixed capital assets, hence the economic implications of reducing maintenance costs are very vast. Data can be collected on costs of repair, downtime and availability percent statistics, usage of spares inventory, etc. This information can be used to set budgets, make historic comparisons and in general be used as control information. A sensible combination of failure maintenance and preventive maintenance will ensure that these objectives are met. The equipment failure characteristics often determine the worthwhileness of preventive maintenance activities. Equipment that fail randomly due to unexpected and inexplicable ove rstress, generally do not lend itself to preventive maintenance. Equipment that fails due to wear and tear may lend itself to preventive maintenance. Thus the 1st step in maintenance planning consists of analysis of failure characteristics of the subsystems comprising the total system. Forecasting of equipment failures in a stochastic system (probabilistic) is based on studying the past performance of the equipment and its subsystems, and assuming that these characteristics will hold in the future. Past data of equipment failures like time to fail are analyzed with a view to find a statistical distribution which closely resembles with a confidence limit of 90% or more the actual failure distribution of the subsystem. Once this is determined, methods of statistical sampling can be used to predict times to failure in any analysis. Among the most common failure distribution applicable to electromechanical systems are the Exponential distribution, Normal distribution, Log Normal distribution, Gamma distribution and Weibull distribution.

Maintenance Procedure Program (MPP) system is a s eries of dynamically linked programs, each of which plays an important role in the effectiveness of the maintenance program. The system applies to both electrical and/or mechanical maintenance in the steel production line and provides the process of equipment inspection as well. The MPP is a manner of applying several maintenance concepts into a co mplete program. This program fully utilizes each concept while combining the efforts of all. Each program element can stand alone in its own right, yet together their strength is multiplied. The need of such a program came about after many attempts of installing only one concept of preventive maintenance. It became apparent that no one method would cover all the bases at any one time. Thus, building a structure which would take into account each facet of maintenance and combine the efforts of each into a master program became a reasonable task. In Maintenance Job Order System, information is fed into this system from the crew inspectors, the department inspectors, the nondestructive testing group, the operations department, and the electrical/mechanical maintenance group. This information is in the form of necessary work to be done as a result of inspections from the various sources. The equipment history files are also important inputs into the job order system. This history helps coordinate the jobs to be completed during planned outages. The next step is to open the job order. The job order can be opened or directed to the maintenance foreman or the departmental planner. If the order is directed to the foreman, the work is assigned to a crew for completion. Normally, work assigned to the foreman would be of a nature which could be completed with the line running or which would be done during an unscheduled interruption in the operation. If the job order is opened to the departmental planner, he will coordinate the job order with the central shops crafts department using a shops job priority system, the maintenance foreman, and the maintenance spares man. These people act as a team in organizing the manpower, spares, and other factors necessary to complete the required job during the planned outage. After the completion of the job, the job order is closed.

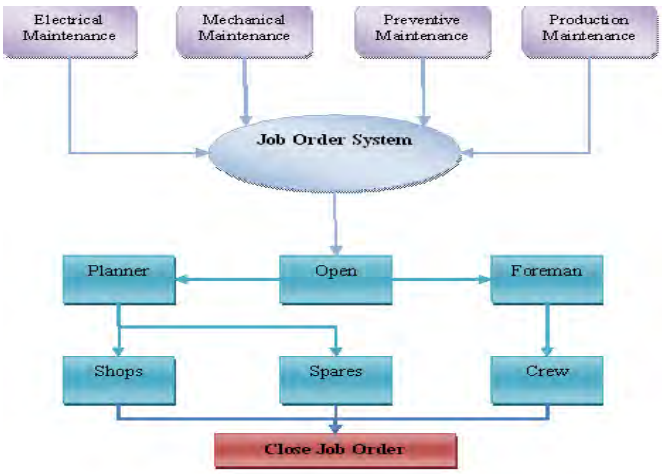

Fig 1: Maintenance Job Order System [5].

2.2. System Modelling

Fig.'s 2 and 3 show physical and electrical models of the existing EAF. In these models, three electrodes are moved vertically up and down with hydraulic actuators. Each of these electrodes weighs 0.4 tons and is 1.5m long. The ore is melted with a huge power surge from the electrodes. The actual product is denser than the scrap and thus falls to the bottom of the furnace creating the matte. Above the matte lies the slag where the electrode tips are dipped. The tremendous heat created by these electrodes causes the ore to liquefy and separate. Thereupon, more raw materials are placed in the furnace and the process repeats itself.

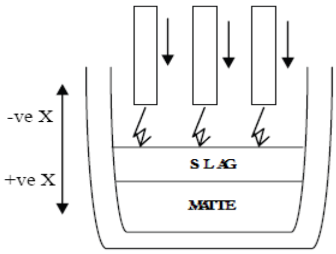

Fig. 2: Physical Model of the EAF [2].

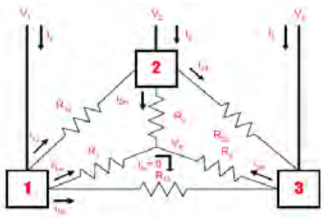

Fig. 3: Electrical Model of the EAF [2].

3. Results

The EAF operates on the principle of direct arc heating. Three graphite electrodes carry the three phase current into the furnace. An electric arc is generated between the electrodes and the metal charge which gives out heat. The charge gets melted by the direct impingement of the arc and also by the radiation from the roof and walls. A proper length of arc is to be maintained throughout the melting cycle. The furnace consists of a cylindrical steel shell mounted on supporting rockets. There is a tapping spout for drawing molten metal and a slag door at the back for slag removal. A removable roof covers the shell. The three electrodes enter the shell through the holes on the roof and are carried by electrode holders on the electrode arm. The position of the electrodes is controlled by moving the mobile carriage over the electrode post which- is done by electrode hydraulic cylinders. The electrodes are water cooled at the point of entry into the furnace. A separate water storage tank with a centrifugal pump is provided for circulating cooling water for the shel1, electrode holder, roof and the slagging door. A control panel is provided for controlling power input to the furnace, for forward and backward tilting, to indicate the currents and voltages and for accurate lifting and lowering of the electrodes. The hydraulic cylinder used for electrode movement is controlled by PLC (S7 400) to maintain the arc impedance a constant for a given voltage, the charging of furnace is done by opening the roof by swinging it to one side. One of the main objectives of the three-electrode control study is to have the electrodes maintain constant power consumption. This is achieved by moving the electrodes to a given depth, obtaining the desired resistances (or conductance), which leads to a constant power consumption. To attain this goal, the open-loop system must be closed in order to create an error signal. The control principle is accomplished by minimizing this error signal with specific controllers. PID controller can be designed and optimized for best performance. For this system, controlling the current will lead to power control; since the power magnitudes are scalar multiples of the electrode currents. Employing SCADA system into the melting and casting processes has a good impact on t he product quality, minimizing the need for human resources, reduction maintenance time and cost, increasing reliability, and real-time data accuracy. This technology should provide the following:

- Continuous (momentarily) monitoring of the state of the process and of the plant;
- Displaying warnings and alarms, at a sufficiently high level of abstraction;
- Giving advice as needed to the metallurgical management of the process.
- Generating historical reports.

4. Discussion and Conclusions

Unfortunately, we found that the SCADA system in the factory is only used for continuous (momentarily) monitoring of the state of the process and of the plant. Therefore; it is highly recommended to activate the other three facilities of the plant. Moreover, the SCADA systems which are employed for the EAF, Ladle Furnace, and the Continuous Casting Machine (CCM) are not networked, which is causing an extra burden and difficulty in the management process [2].

Based on above analysis, great deal of improvements is suggested in order to implement an active control and analysis in order to reduce the cost of production and maintenance in this factory, including scrap management; since economic and competitive pressures force industrial and process engineers to seek continuous improvement in industrial production processes [1]. In a complex industrial system, as in an EAF, the ways to improve this process are diverse, such as selection and treatment of materials, the redesign of the facilities and new kinds of energetic contributions to the process. The evolution of electric furnaces is reflected mainly in the progressive reduction of specific consumption of energy, tap-to-tap times and improvement of the metallic yield [2]. A deep study, comparing energy consumed currently in the production of steel with theoretically needed energy, was made by the Carnegie Mellon University (Pittsburg, USA) for the US Department of Energy [3-8]. The principal analytical tools used for second phase were the operations research techniques of project management and heuristic scheduling [6]. Though the direct comparison of different EAFs is difficult due to the operational differences, the disparity between the theoretical energy and the consumed energy contributes to the idea of potential improvement of these facilities which could be about 25% of the energy consumption. One of the pathways proposed to reach this yield improvement in EAF operation is the optimization of process sequencing by means of Programmable Logic Controllers (PLCs). Important effort has been directed towards further productivity improvements under EAF process. Much of this has focused on de veloping alternative energy sources to reduce the high cost of electrical energy, which means about 10-15% of EAF operation costs. Another two different types of costs that have impact on t he total cost of EAF operation can be identified: the cost of the feed materials and the cost implication of not reaching control objectives. Feed materials are very conditioned by the final quality of steel to obtain (scrap substitutes are mainly used in the production of higher quality products) and the steel cost due to materials is mainly determined by the price of scrap in the world-wide market. Processing control optimization is another very important way for the reduction of the energy consumption. Because of knowledge lack of a suitable plant model, the operations in the furnace are only based on empirical knowledge. There are a large number of traditionally manually controlled variables. The furnace operator, in accordance with his own experience and in his particular way of working, has been taking the decisions. For example, he was deciding if it was necessary to inject more or less oxygen, coal or HBI (hot briquetted iron), or even stopping the process and measuring the steel temperature. The automation of these variables ensures better operation in EAFs [7-13].

Steel scrap is the most important raw material for electric steelmaking, contributing between 60% and 80% of total production costs. In addition, the degree of which the EAF process may be controlled and optimized is limited by fluctuations in scrap quality. Therefore quick estimations of properties of different steel scrap grades are very important for improving the control and optimization of the EAF process. Most countries have national classification systems for steel scrap, but there is also a European classification system that the EU-countries use for international scrap trade [13]. Steel scrap is usually graded in terms of size distribution, chemistry, density, and origin, and processing method. Some melt shops have internal classification systems that further divide the standard scrap grades into subtypes, and also a number of internal scrap grades (scrap produced within the steel plant). However, the scrap grading systems are designed for commercial purposes and the variation in scrap properties within each scrap grade is high. In general, scrap properties may be divided into two main categories, physicochemical properties and process related properties. Physicochemical properties (chemical composition, density, specific surface area, size distribution and melting temperature, specific heat capacity, metallic/ organic/oxidic content) are only dependent on t he particular scrap grade and are best determined by controlled experiments in laboratories. Process related properties (yield coefficients, specific energy consumption, contribution to chemistry of steel and slag, contribution to basket and furnace filling degree, contribution to dust generation and off gas composition) depend on bot h the process conditions and the other materials in the scrap mix. Therefore, the process related properties for the same scrap grade may vary considerably between different melt shops. Chemical analysis, conductivity, metal content and size distribution may be measured or estimated for individual pieces of scrap and/or random samples but the fluctuation in scrap quality is often too large for these measurements to be representative for the whole population of a scrap lot on the scrap yard. Experimental design methods have been proposed to set up a series of experimental heating processes that can then be used to estimate the scrap thermophysical properties. However, because of the variation in process conditions and fluctuations in scrap quality each experiment would have to be repeated several times. The number of experiments needed to get estimations for all scrap grades can therefore be very high, depending on t he number of scrap grades that are used, rendering this approach unsuitable. An alternative to designed experiments is to firstly extract large quantities of data from process databases [3]. Advanced statistical methods can then be used to analyze the combined effect of scrap mix and process conditions on the end conditions, chemical analysis of the liquid steel, energy consumption and metal yield [2- 3, 13].

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Applying process integration methods to target for electricity production from industrial waste heat using Organic Rankine Cycle (ORC) technology

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Abstract: This paper presents the results of an investigation of power production from low temperature excess process heat from a chemical cluster using Organic Rankine Cycle (ORC) technology. Process simulations and process integration methods including Pinch Technology and Total Site Analysis (TSA) are used to estimate the potential for electricity production from excess heat from the cluster. Results of a previous TSA study indicate that ca. 192 MW_{heat} of waste heat are available at 84 °C to 55 °C, a suitable temperature range for ORC applications. Process streams especially suitable for ORC power production are identified. Simulation results indicate that 14 MW_{heat} of waste heat are available from a PE-reactor, which can be used to generate ca. 1 MW_{el}. Costs of electricity production calculated range from 70 to 147 €/MWh depending on the cost for ORC integration. Economic risk evaluation indicates that pay-back periods lower than 4.5 years should not be expected at the electricity price and RES-E support (a European support system for renewable electricity) levels considered in this study. CO_2 emission reductions of up to 5900 tonnes/year were estimated for the analysed case.

Keywords: *Organic Rankine Cycle, Process integration, Total site analysis, Waste heat recovery.*

1. Introduction

1.1. Background

Growing awareness about the greenhouse effect combined with limited fossil fuel resources provide clear incentives for implementing energy savings measures and achieving CO_2 emission reductions in industry. One example to increase energy efficiency is the conversion of low temperature excess process heat into electricity using Organic Rankine Cycle (ORC) technology. The objective of this paper is to assess the potential for electric power generation from low temperature excess process heat at the chemical cluster in Stenungsund, Sweden. Results from a previously performed total site analysis [1] are used to determine the overall amount and the temperature levels of net excess heat from the cluster. Net excess heat is defined as heat that is available after all opportunities for process integration have been exploited and for which no other alternative use is available. Simulation of a selected ORC power cycle was conducted so as to quantify the power output and the overall performance of the system. A preliminary economic evaluation of a selected configuration is presented based on the simulations, supplier/literature data for ORC technology, engineering assumptions for ORC integration and scenarios for assessing profitability and carbon balances of energy investments [2]. The work aims at providing a basis for future projects to optimize energy usage and consequently lower costs and CO_2 emissions from the cluster.

1.2. ORC Technology

ORC is a technology to generate electricity from low temperature heat sources. Unlike in a conventional steam Rankine cycle, a low boiling point organic fluid is used as working fluid. In low temperature applications this technology offers advantages over conventional Rankine Cycles, and a higher heat recovery (efficiency) can be achieved [3]. ORC systems are mainly used in geothermal, solar and industrial waste heat recovery applications. Figure 1 illustrates the working principle of an ORC. The working fluid is pumped from a lower pressure level (state 1) to a higher (state 2). Between states 2 and 3 the fluid exchanges heat with a waste heat stream in a heat exchanger and is evaporated. Contrary to Rankine cycle technology, the working fluid is usually not superheated after the evaporator. The vapour is then expanded in a turbine (state 4), which is connected to a generator to produce electricity. The expanded vapour is condensed by transferring heat to a cooling medium in the condenser (state 1). The cooling can be achieved by air coolers, cooling water or other heat sinks.

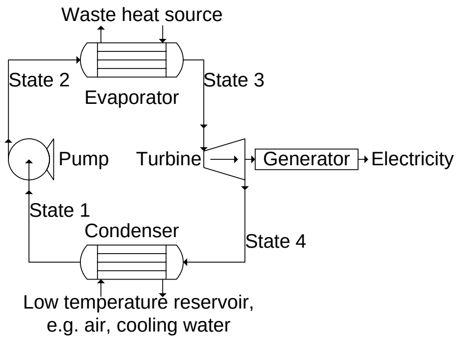

Fig. 1. Working principle of a simple ORC

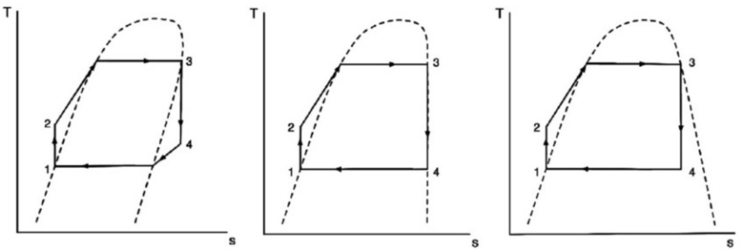

Fig. 2. Characteristic T-S process ORC diagrams for "dry", "isentropic" and "wet"-fluids [4]

The choice of the working fluid strongly influences the efficiency and economy of an ORC system. Working fluids can be divided into three different groups according to their behaviour in the thermodynamic cycle. Figure 2 shows the characteristic T-S diagrams for the three different types of working fluids. "Wet" fluids have a negative slope in the saturation vapour curve. Expansion in the turbine occurs entirely in the two-phase state, and the liquid fraction of "wet" fluids increases. The liquid droplets that form can cause blade erosion damage to the turbine. Condensation is easiest avoided by superheating of "wet" fluids. "Dry"-fluids have a positive slope (left), which means they do not condense during expansion since the degree of superheat increases as the expansion proceeds. Examples of such working fluids include organic substances such as benzene and refrigerants. The third group is "isentropic" fluids with quasi-vertical saturated vapour curves. Since the purpose of an ORC is to recover low temperature heat for electricity production, superheating is not appropriate. Therefore the working fluids used are either "dry" or "isentropic" [5]. Moreover, water has the disadvantage of having a higher specific volume compared to organic working fluids. This increases the size of the turbine, the height of the turbine's last stage blades and pipe diameters [3]. The working fluid should be selected with care so as to achieve a good match with the heat source characteristics and also the available cooling facilities. The following properties should also be considered: high thermal stability at the given operating conditions, low specific volume, low cost, low toxicity, low Ozone Depletion Potential (ODP) and low Global Warming Potential (GWP). The choice has to be based on careful analysis of the given conditions [6].

1.3. Results from total site analysis (TSA)

In a previous work the cluster was analyzed using TSA methodology [1]. The method is based on pinch technology and aims for integration of the heating and cooling demands of the different individual processes at a given site with a common utility system. In this way the amounts of hot utility generated and used by the combined individual processes, the amount of heat recovered in a common hot utility system, and the cogeneration potential can be determined [1]. The previous study [1] showed that the combined heating demand of process plants within the cluster is 442 MW of which 320 MW can be covered by heat recovery within the cluster, assuming that no changes are made to existing process utility levels. The other 122 MW must be covered by hot utility, mostly in the form of boiler steam. Furthermore, the previous TSA study also showed that by making improvements to the overall utility system which enable increased energy collaboration between the companies it is possible to increase the amount of heat recovery at the site from 320 MW to 449 MW. As a result, boiler utility steam is no longer necessary. In addition a net surplus of 7 MW steam is achieved. The cooling demand of the cluster is then 506 MW at temperatures up to 84 °C.

These results are used in the present study to determine the maximum potential for power generation from low temperature excess heat within the cluster, using ORC technology. Because of the relatively low efficiency of low temperature heat-to-electricity conversion it is appropriate to only utilise net excess heat that cannot be utilised in another way [7]. The maximum potential for heat available for power production is estimated using TSA. Within the cluster available heat is estimated at Q_{ORC}=192 MW_{heat} at temperatures between 84°C and 55°C.

2. Methodology

2.1. Heat source selection

From the inventory of the excess process heat available, a selection is made to focus on streams with loads and temperature levels interesting for power generation and for which there is no alternative use. This temperature range was determined in a previous TSA study. The maximum heat source temperature for excess heat from the cluster is 84°C. The minimum allowable heat source temperature was selected as 55°C in order to achieve acceptable Carnot conversion efficiency values. Supplier information also confirmed this value of lower temperature limit [8].

2.2. ORC simulation

Literature data about ORC cycles only provided information about approximate efficiency values. Furthermore, it was necessary to evaluate different working fluids depending on the process conditions in order to achieve maximum efficiency. Therefore a simple ORC cycle was simulated in HYSYS. The cycle includes a pump, an evaporator, a turbine and a condenser. The tested working fluids are R134a, Propane, 1-Butene, Butane and Pentane as they are typical fluids for ORC applications at low temperature levels. The results are used as input for the economic evaluation.

2.3. Cost estimations

To determine the basic investment costs of the unit, the turbine capacity (in kW) is taken as the indicative size of the new unit. The equipment costs of a reference ORC-unit are estimated based on published data for a reference geothermal power plant located in Altheim, Austria with a capacity of 1 MW_{el} [9]. The equipment cost of this reference ORC-unit is 1.58 M€ (in 2000). This cost was updated using the Chemical Engineering Plant Cost Index (CEPCI) for 2010 and 2000, i.e. an update factor of 1.376 [10]. Furthermore, a scaling factor of 0.7 (widely used for electricity production) was used for estimating the investment costs of differently sized units [11]. The <u>installed cost of the ORC unit</u> can thereafter be calculated based on published cost data for an ORC plant in Lienz, Austria with an <u>installation cost factor</u> of 1.32 [12], which covers planning, installation and grid connection costs. Not included are the costs of integration in the considered process plant.

The costs for integrating the ORC into the process plant vary depending on the situation on-site, the process fluid, the location of the ORC-unit and other factors. Three examples of projects presented by the ORC manufacturer Turboden [13] indicate integration cost factors ranging from 1.7 to 2.6. All projects include a thermal oil cycle which collects the heat from the waste heat source and delivers it to the ORC unit. For this reason those systems are more complicated and expensive than systems where the process stream is used directly, which might be the case for integration with a chemical cluster. Therefore integration cost factors from 1.1 to 2.6 were considered in this work. The annuity method is used for determining the annualized investment costs $I_{total\ annualized\ capital\ cost}$) which are used to estimate the net Cost of Electricity (CoE) generation for the ORC plant. The assumed internal interest rate is 11 % (i_r). The economic lifetime (t_e) is assumed to be 15 years, as this is typical for CHP plants based on ORC technology [12]. The corresponding annuity factor is 0.14. Cost data for annual operating costs are assumed to be 3 % of the installed costs of the ORC plus the personnel costs (400 h/yr á 30 €/h) [12]. The CoE are calculated by Eq. (1)

$$\mathrm{CoE} = \frac{I_{\text{total annualized capital cost}} + \text{Annual operating costs}}{\text{Annual electricity production}} \tag{1}$$

CoE can then be compared with scenario values for electricity purchased from the grid. The economic value of the electricity produced is based on avoided costs of purchasing electricity. Five different grid electricity price scenarios are analysed, see Table 1.

In order to discuss the economic risk of investment in an ORC unit, the payback period for a new ORC investment is also calculated. The total annual savings take into account the avoidance of electricity purchased (equal to net power output of ORC) and the electricity saved by less cooling water pumping (2.5 % of net power output of ORC). When producing electricity from waste heat, which otherwise is cooled by cooling water, part of the cooling is saved. The main part of the cooling costs is the pump work in the cooling water system. In this study it is assumed that for each avoided MW of cooling, 0.025 MW_{el} are saved. These cost savings are calculated with the assumed electricity price and included in the annual cash flow to calculate the payback period (see below). An annual running time of 8000 h per year is assumed. The pay-back period for the ORC investment can then be calculated according to Eq. (2).

$$\text{Pay-back period} = \frac{I_{\text{total ORC}}}{(\text{Annual savings - Annual operating costs})} \tag{2}$$

The scenarios were generated using the ENPAC tool, developed with the purpose of evaluating the performance of future or long-term energy investments at industrial sites using consistent scenarios. Scenarios chosen in this study include the current electricity price and two scenarios (high/low) for the years 2020 and 2030. RES-E support is currently not granted in Sweden for electricity production from waste heat with fossil origin. In this study both case (with and without support) will be shown in order to show its influence on the overall economic performance of ORC investments. By using a number of different scenarios that outline possible cornerstones of the future energy market, robust investments can be identified and the climate benefit can be evaluated. To obtain reliable results, it is important that the energy market parameters within a scenario are consistent. Consistent scenarios can be achieved by using a tool in which the energy-market parameters (e.g. energy prices and energy conversion technologies) are related to each other [14]. Table 1 shows the electricity prices, support levels for “green” electricity generation and CO_2 emissions from electricity production from the assumed long term marginal electricity production.

Table 1. Electricity prices, support for green electricity, CO_2 emissions from electricity production and marginal long term electricity production for the five scenarios [2]

Scenario		1	2	3	4	5
Year		2010	2020	2020	2030	2030
Fossil fuel price		2010	Low	High	Low	High
CO_2 charge	[€/ton]	20	15	58	15	58
Electricity price SPOT	[€/MWh_{el}]	51	46	74	45	81
RES-E support[1]	[€/MWh_{el}]	20	20	20	20	20
CO_2 emission from electricity production	[kg/MWh_{el}]	770	722	722	679	129
Long term marginal electricity production		Coal	Coal	Coal	Coal	Coal, CCS

[1]Premium paid to producers of electricity from renewable energy sources [2]

2.4. CO_2 emissions reduction

CO_2 emissions reduction by electricity produced with an ORC unit is calculated from CO_2 emissions data for future long term marginal electricity production in Table 1. It is assumed that electricity from the ORC unit replaces marginal electricity and that the waste heat used for electricity production has no alternative use (in this case the possibility to deliver waste heat to the district heating system close to the cluster is fully exploited).

3. Results

3.1. Heat source selection

One heat source is chosen as an example to carry out further investigations, including simulation of the ORC unit using HYSYS and economic assessment and calculation of CO_2 emissions reduction. The stream chosen is a loop reactor jacket cooling water stream with T_{start} and T_{target} of 78 °C and 68 °C, respectively. This results in a Carnot efficiency of 17 %. The heat load of the stream is 13970 kW.

3.2. ORC simulation

Simulations were carried out with different “dry” fluids appropriate for use in ORC systems. The main results are presented in Table 2. The turbine inlet and outlet pressure is chosen so that the boiling point of the working fluid is matched with the temperature profile of the heat source and the heat sink (cooling water at 20 to 25 °C) respectively. Among the five working fluids investigated, butane shows the best net electrical output and electrical efficiency. R134a and Propane are interesting cases, but the cycle needs to operate at higher pressure than the cycle with butane. Lower operating pressure should be preferred as increased pressure implies higher investment costs. Pentane is not suitable as the minimum pressure in the cycle is set to 0 bar(g), to avoid extra costs for vacuum operation. Pentane is more suitable for higher temperature heat sources. Butane has a slightly higher power output and efficiency compared to 1-Butene. The simulation with a mixture of pentane and butane does not show better results than with a single fluid, even though the temperature profiles of heat source and working media match better, which results in less exergy losses during evaporation. High performance is not reached with the mixture as the pressure difference for expansion in the turbine is not sufficient. Pentane limits the maximum and butane the minimum possible pressure in the given case (ΔT_{min} of 5 K in the evaporator and condenser). Butane was retained as working fluid for the ORC unit. This cycle has a net electricity output of 958 kW_{el} (7.7 GWh/yr for 8000 hours/yr of operation), with 6.85 % electrical efficiency.

Table 2 Results from the simulation in HYSYS for an ORC unit using loop reactor cooling water heat source

	R 134a	Propane	1-Butene	**Butane**	Pentane	Butane +Pentane
$p_{turb,in}$ [bar(g)]	18.5	23	7.6	**6.2**	1.45	3.5
$p_{turb,out}$ [bar(g)]	6.7	9.8	2.5	**1.8**	0	0.6
$Q_{el,out}$ (net) [kW]	923	900	948	**958**	798	950
η_{el} [%]	6.6	6.4	6.8	**6.85**	5.7	6.8

3.3. Cost estimation

The results for the selected heat source stream are presented below. Costs calculations have been performed according to the procedure defined in Section 2.3. Table 3 shows simulation and economic results for the selected waste heat source assuming butane as working fluid

Table 3 Turbine capacity, basic equipment investment costs, installed costs and operating costs

Turbine output [kW]	Net power output [kW]	Equipment investment costs for ORC unit [€]	Investment costs ORC including installation [€]	Operating costs [€/yr]
993	958	2 163 489	2 855 806	97 674

The calculated CoE range from 70 to 147 €/MWh, depending on the integration cost factor, see Figure 3 and Figure 4. The electricity price scenarios in Figure 3 do not include RES-E support. It can be seen that at the current electricity price (Scenario 1: ca. 51 €/MWh) and without RES-E support, investing in an ORC is not profitable.

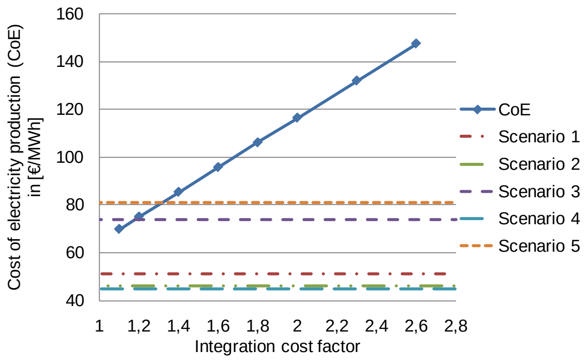

Fig. 3. CoE depending on the integration cost factor (with electricity price scenarios without RES-E support)

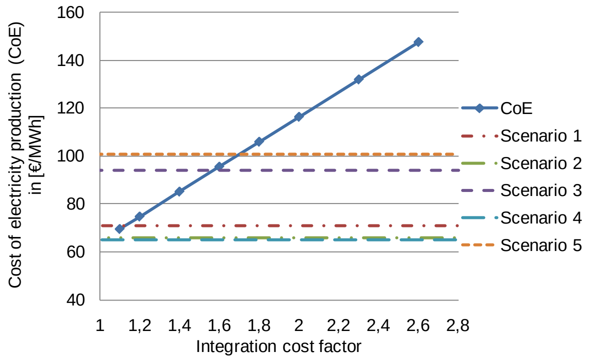

Fig. 4. CoE depending on the integration cost factor (with scenarios including RES-E support)

Without RES-E support, ORC electricity generation is only profitable for the two highest price scenarios (Scenario 3 and 5) considered in this study and at low costs of integration. If RES-E support is granted also more complicated integration is feasible at high electricity prices. At low integration costs even the current electricity price shows a feasible investment. Calculations on the pay-back period of an ORC investment show that without support for electricity production the pay-back period for the lowest costs of integration estimated (10 % of ORC installed costs) ranges from 5.8 to 12.3 years depending on the electricity price scenario. With RES-E support the pay-back period is decreased for the low integration factor case to between 4.5 to 7.7 years. Even if RES-E support is considered, pay-back periods lower than 4.5 years should not be expected for ORC technologies at the electricity price and RES-E support levels considered in this study. On-site electricity production bears lower risks than other investments, as the produced electricity can be used on-site. This might justify longer pay-back periods. The scenarios used in this study include costs for CO_2 emissions from fossil-fuel fired power plants. It can also be seen that in the scenarios with low CO_2 emission charge (scenario 2 and 4) the costs of electricity production and pay-back period are highest, while high CO_2 emissions charge (scenario 3 and 5) shows lower values. Therefore CO_2 emissions charge is seen as an important parameter which has a large influence on the profitability of ORC investments.

3.4. CO_2 emissions reduction

Figure 5 shows the CO_2 emissions reduction in the different scenarios when electricity is produced with an ORC unit. It can be seen that the reduction is high if marginal electricity from coal power plants is replaced by electricity from the ORC unit, 5204-5902 tonnes-CO_2/year. The least reduction is achieved if marginal electricity is produced in coal power plants with carbon capture and storage (CCS) technology (989 tonnes-CO_2/year). This is the case because the electricity produced with an ORC replaces marginal electricity, which in the CCS case already has relatively low CO_2 emissions.

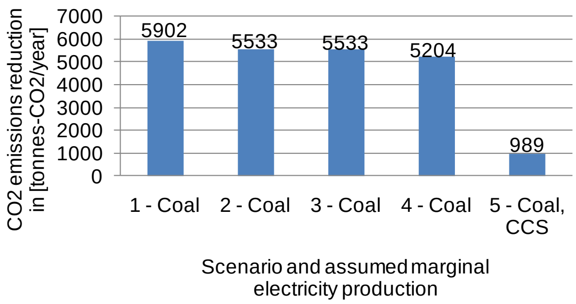

Figure 5 CO_2 emissions reduction associated with electricity production from excess process heat using ORC unit

4. Conclusions and Discussion

In this paper TSA methodology was used to identify the amount of net excess heat from a chemical cluster including the corresponding temperature levels suitable for low temperature heat-to-electricity production by ORC technology. For a more detailed analysis a suitable process stream was selected as heat source. Process simulation was used to determine the best working fluid for the suggested ORC unit, to calculate the net electricity output and the electrical efficiency of the unit. The simulation results were used for preliminary economic assessment and calculation of CO_2 emissions reduction potential based on different future energy market scenarios. From the TSA study it was found that there is 192 MW_{heat} at a temperature range between 84 °C and 55 °C available that can potentially be used for ORC applications. It was shown by process simulation that the selected ORC reaches an electrical efficiency of 6.85 % when converting ca. 14 MW_{heat} into 953 kW_{el}, using butane as working fluid. Economic assessment of the system shows a strong dependence of profitability to the costs for integration of the ORC unit in the process. Production costs were determined in a range between 70 and 147 €/MWh, indicating that at the current prices and without support an ORC project is not feasible and also only two out of seven scenarios showed feasibility without support. Depending on the scenario, pay-back periods between 5.8 to 12.3 years assuming low costs of integration. RES-E support and CO_2 emissions charge were found to have a strong influence on profitability. Pay-back periods lower than 4.5 years should not be expected at the electricity price and RES-E support levels considered in this study, even if in the future support is granted for this kind of electricity production. Standardisation and technology improvements are expected to have a p ositive effect on the costs of ORC technology, leading to lower electricity production costs and pay-back periods in the future.

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Modeling SOFC & GT Integrated-Cycle Power System with Energy Consumption Minimizing Target to Improve Comprehensive cycle Performance (Applied in pulp and paper, case studied)

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Abstract: This study has considered hybrid system SOFC/GT with the new approach. This cycle, as a power plant is designed to reduce losses and improve comprehensive cycle performance. In the first part cycle, fluidized bed system with biomass (wood chips) fuel using gas cleaning mechanism, produce combustible gases which are required fuel combustion chambers of steam reformer and the GT. Second part cycle, required hydrogen for SOFC system is supplied through external SR. In the third part, the treated bio syn-gas from the cleaning unit outlet, in conjunction with recycled exhaust gases of the cell's anode will feed SR and GT combustors. In the fourth part cycle, flue gas would pass through heat recovery steam generator. Thus, high pressure and low pressure steams with values 3.39&0.45 ton/hr, respectively are generated. In this study, SOFC and GT with a capacity of 1000 & 750.81 kW respectively are designed. Overall efficiency of power production 74.4% is obtained. In comparison with similar study done in 2008 at the University of Delft, that overall 47% efficiency, increasing the efficiency of such systems has been viewed.

Keywords: *Solid Oxide Fuel Cell (SOFC), Gas Turbine (GT), Bio syn-gas, Fluidized Bed (FB), Steam Reformer (SR), Comprehensive Cycle Performance*

1. Introduction

Recent studies have indicated that in integrated SOFC/GT cycles which employ natural gas, the overall efficiency of the system is estimated to be 50% to 60%. Burning and gasifying the biomass and combining the result with SOFC/GT system, enables the hybrid system to contribute to an efficient power plant [1], [2]. Generally, in order to generate power in a cost effective way and develop generating systems, distributed power generation has recommended an effective measure [3], [4]. The general prospect of the present study has been the integration of industries which normally generate combustible wastes and plants that consume such wastes. This study mainly focuses on de signing an integerated SOFC/GT power plant based on burning biomass in combustion chambers and reforming the natural gas in a steam reformer. The a-grade wood has been considered as the biomass in the planning and 1.75 MW of the electrical energy is expected to be generated. According to the field available technologies and the studies which have already been conducted in this field, our proposed cycle can be considered as a new approach in designing similar power plants in the future. A thorough analysis of energy in the system will determine and visualize the losses and realize the thermodynamically efficiency.

2. System Approach

2.1. Improving the efficiency

1- Trying to improve energy generation efficiency and enhancing energy transfer and distribution efficiency (utilizing CHP systems and cogeneration to maximize absorption and recovery).
2- Determining the essential fuel and each of the aforementioned units' efficiency.

2.2. Employing renewable form of energy

1- Calculation related to considerable amount of electrical energy by using renewable forms of energy (SOFC/GT).
2- Estimating a portion of required fuel by renewable forms of energy (Biomass gasification system).

2.3. Managing the industrial process products

1- Putting to use the by-products of industrial process (such as pulp and paper industry) to supply the fuel required for SR and GT systems [9].

2- Making use of hot flue gases and generated heat, for consuming in the comprehensive cycle and auxiliary units.

3. System Configuration

As it is illustrated in the figure 1, this system is comprised of different sections which have been pinpointed by the sections' names. These sections are as the following:

Fluidized bed system and gas cleaning, External Reforming SOFC system, GT system, HRSG[1] system, heat exchangers for pre heating fuel and air generating steam required for the reformer. Burning and gasification of the fuel biomass (wood) is usually preformed in the FB system. The gasifier operates at $500^{\circ C}$ and 4 bar. Heat is transferred by circulating the materials. Impurities within the components of the bed are separated from the gases by a C, SiO_2 separator [6], [7]. The gas which is exhausted from FB unit cannot be directly used within SR combustion chamber and GT. This is mainly due to the fact that the gas turbine. Therefore components such as H_2S, SO_2, COS and NH_3 are effectively removed from the exhaust gas [8]. Form chemical prospect, performing gas treatment, within the higher temperature ranges, seem to be able to be really demanding and imposes restriction treatment process. It is generally believed that the hot gas needs to be appropriately cooled down before being treated. Hot gas temperature is diminished to $500^{\circ C}$ in the heat exchanger [9], [10]. The cooled exhaust gas from cooling and treatment units is then mixed with hot exhaust gas from SOFC which mainly contain non-reacted steam and hydrogen. The mixture will then be transferred to GT and SR combustion chambers. The SR units have been employed to supply the fuel required for SOFC. This unit makes use of natural gas reformation to produce the fuel. The operating temperature and pressure of SR are considered to be $800^{\circ C}$ and 1 bar respectively [11]. The treated syn-gas from the cleaning unit outlet, in conjunction with recycled flue/exhaust gases of the cell's anode (off-gas), which contains some combustible remnants; will feed SR and GT combustors. The pressurized air is directed towards the cathode. Fuel cell with an external reformer (SOFC) is able to directly turn hydrogen, which is the product of already reformed natural gas method, in to electricity. The hot exhaust gas from the cathode (off-gas) is recycled to supply the gas turbine. The expanded flue gas has been used to recuperate the incoming air, after it had been pressurized. An air compressor attached to the turbine supplies the essential air for the integrated SOFC/GT system. Connecting the turbine to the generator, the second electrical current in the cycle is generated. HRSG system has been designed based on a dual pressure-mode in which both high and low steam pressures are generated, in order to improve the system performance and enhance steam generation rate. The results of the previous studies took the HRSG planning process into consideration. There is a feed water boiler in the methodology where the water supply after leaving LP (Low Pressure) economizer is split into two parts. One portion is directed

2- Heat Recovery Steam Generator

towards LP evaporator and another one to HP (High Pressure) economizer. Figure 2 illustrates the schematic performance mechanism of HRSG in the cycle [12].

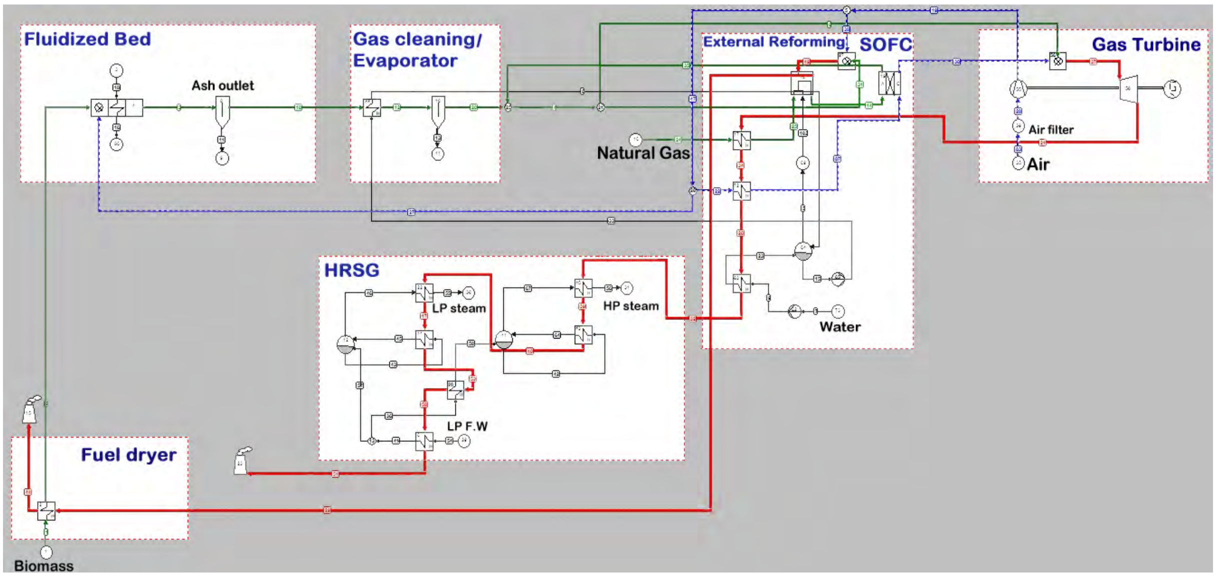


Fig. 1. Schematic of hybrid system

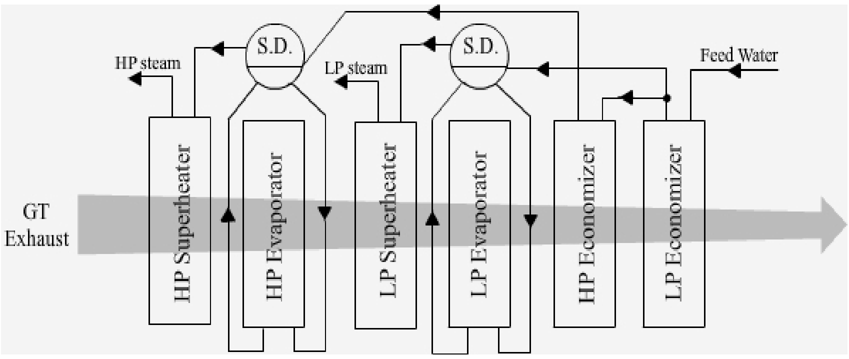


Fig. 2. Schematic of HRSG mechanism

4. System modeling

4.1. Model assumptions

In order to evaluate the system and obtain a balance between mass and energy of the cycle, Cycle-tempo software was employed. The main purpose of using such software was to create a model in the study state. Therefore a model consisting of subsystems has been created. Achieving a consensus on subsystem calculations is the prime objective in creating this model. There are some general assumptions which have been made in creating this model [13], [14].

- The whole system operates at steady state.
- In SR steam generating section, isentropic efficiency of the pump after the steam drum equals 75% and prior to the economizer is 85%.
- Isotopic efficiency of the compressor and gas turbine are 87% and 86% respectively.
- The mechanical efficiency for compressor and gas turbine is set to 99%.
- The generator efficiency is set to 98%.
- The pressure drop within the heat exchanger has been assumed to be zero. Pressure and temperature prior to the system have been listed in table 1.

Table 1. Pressure and temperature of fuels, air and water inlet to the system

Sink name	Pressure(bar)	Temperature(^{oC})
Biomass	4	15
Natural gas	1.18	15
Air	1.013	15
Water*	1.2	20

* Inlet water in SR system

The operational temperature of the fuel cell is 950^{oC} and the pressure is 3.45 bar. The fuel cell area is supposed to be 700 m^2 and the fuel cell resistance 0.75 $\Omega.cm^2$. The efficiency of the DC/AC converter is 96%.

Figure 1 illustrates the SOFC and GT integrated cycle power system schematically. Based on temperature and pressure, two different types of system are generated in HRSG unit. High pressure steam (50 bar) which is as hot as 470$^{\circ C}$ and low presser steam of 15 bar and 270$^{\circ C}$.

4.2. Preliminary discussion

With a view to reach a higher efficiency in SOFC/GT hybrid system, the following points should be considered in planning the cycle.

- The combustible gases which have been produced in FB can be directly used in SR and GT combustors.
- Making use of the released heat while cooling the gas leaving FB and prior to cleaning which can be used to supply the necessary steam for SR unit.
- Employing a portion of the gas turbine flue gas heat in pre heating the fuel (natural gas) and the air entering the SOFC system.
- Using the pressurized air by the gas turbine compressor in the cathode.
- Using a great deal of gas turbine flue gas heat to generate steam in HRSG.
- Making use of the exhaust heat from SR in drying biomass entering the system.

After considering the application of a SOFC system with a constant power of 1MW for reaching such power in GT, the present study adjusted reaction pressure and outlet pressure of the FB unit to 4 bar. The outlet pressure of the compressor was sent to 3.46. Minimizing fuel consumption was one of our other objectives.

Comparing this hybrid system with 1.75MW gas turbine system within similar temperature & pressure states, implies a considerable reduction in fuel consumption. Table 2 shows the comparison of these two systems.

Table 2. Comparison of fuel consumption in hybrid and GT systems with similar capacity

System type	Natural gas consumption (kg/hr)	Biomass consumption (kg/hr)
Hybrid system	159.41	129.6
Gas Turbine system	1396.8	-

In order to substitute the integrated system of heat and power generation, a pulp manufacturing plant which is also capable to be developed to produce pulp and paper (the 22Bahman particle board manufacturing company located in northern city of Behshahr in Iran) was considered. This plant is traditionally supplied by the regional electrical transmission network in tandem with burning fossil fuel, to run its manufacturing process. The main characteristics of this study are presented in table 3. The annual production of the plant has been estimated to be 41438880 kg. The capacity which has been selected for the hybrid system is in congruity with electrical power consumption of the plant.

Table 3. Energy consumption comparison between the Traditional and integrated power generation

	Description	Energy unit
Traditional system	Electric power consumption	52753716 MJ
	Heat consumption	60802100 MJ
	Specific energy consumption (SEC)	5.28 MJ/kg
Hybrid system	Electric power generation capacity	1.75 MW
	Heat consumption	97136501 MJ
	Specific energy consumption (SEC)	2.34 MJ/kg

Based on the results from the study, the specific energy consumption shows a decrease of 2.94 MJ/kg. The first reason for such decrease is electrical power generation in the new system. The second reason to be mentioned is daily generation of 690.65 kg waste product which constitutes the 22% biomass fuel essential for hybrid system.

5. Results and conclusion

5.1. Quantitative approach

In the present model, according to the power generation capacity of the integrated SOFC/GT system which is 1.75 MW the mass flow rate entering biomass is set to be 129.6 kg/hr. The already generated gas leaved FB with 4 bar and 1543.04$^{℃}$. The main ingredients and their mole fractions have been shown in table 4.

Table 4. Mole fractions of FB exhaust gases

Component	Mole fraction (%)
H_2	7.07
N_2	49.72
CH_4	4.34
H_2O	18.45
CO_2	18.42
CO	1.37
AR	0.59

Here, 31.9 kg/hr ash leaves the system as mentioned earlier; the mixture contains some harmful gases which will affect the SR and GT system unless they are controlled. The gas which has undergone cleaning process is mixed with the gas leaving the fuel cell anode under a pressure around 3.45 bar. The hot flue gases (1200$^{℃}$) from the combustor enter SR. SR requires steam with a flow rate of 460.26 kg/hr. In view of the reactions occurred in SR, the convenient fuel with a mass flow rate of 619.67 kg/hr, are generated in SOFC. The fuel cell operating at 950^{oC} produces 1000 kW of electrical energy. Not all fuel is converted in the SOFC stack; the fuel utilization is 85%. The SOFC characteristics for current & power densities are rendered 1963.04 A/m^2 & 1488.1 W/m^2 respectively. The TIT[1] is 1100$^{℃}$. Expansion of the mixture of gases entering the turbine 1276 kJ/kg generates power. Having

1- Turbine Inlet Temperature

preheated the fuel and air in the SOFC system, and also exchanged heat in SR steam generating economizer, the flue gas from the gas turbine enters HRSG; meanwhile its energy content and temperature are 3908.7 kW and 782.94$^{\circ C}$ respectively. Economizer outlet is split into two 183$^{\circ C}$ currents, which enter the LP and HP evaporators. The outlet pressures of HP and LP evaporators reach 15 bar and 50 bar respectively. The flow rate of steam leaving HP and LP super heater outlets are 0.45 ton/hr and 3.39 ton/hr respectively. Energetic HRSG efficiency equal to 92% was obtained. In table 5 the energy inputs and consumptions of the system for the conversion of biomass into electricity are presented.

Table 5. Energy input and consumption of the biomass gasifier and SOFC-GT hybrid system

	Biomass	Natural Gas	Fuel Cell	Gas Turbine
Absorbed power(kW)	670.32	1682.81	_	_
Delivered gross power(kW)	_	_	1000	750.81

5.2. *Qualitative approach and recommendations*

In the Figure 3, the nature of heat recovery and constant output is reasonable. Increase in bio fuel consumption is mainly due to FB system performance as a bottleneck. We have to cross out (as a decrease) in some of the objective to increase Bio. In reality if there is a necessity for increasing the bio fuel, right after that increase ash production rate is maximized to a great extent and puts a restriction on power generation and heat recovery.

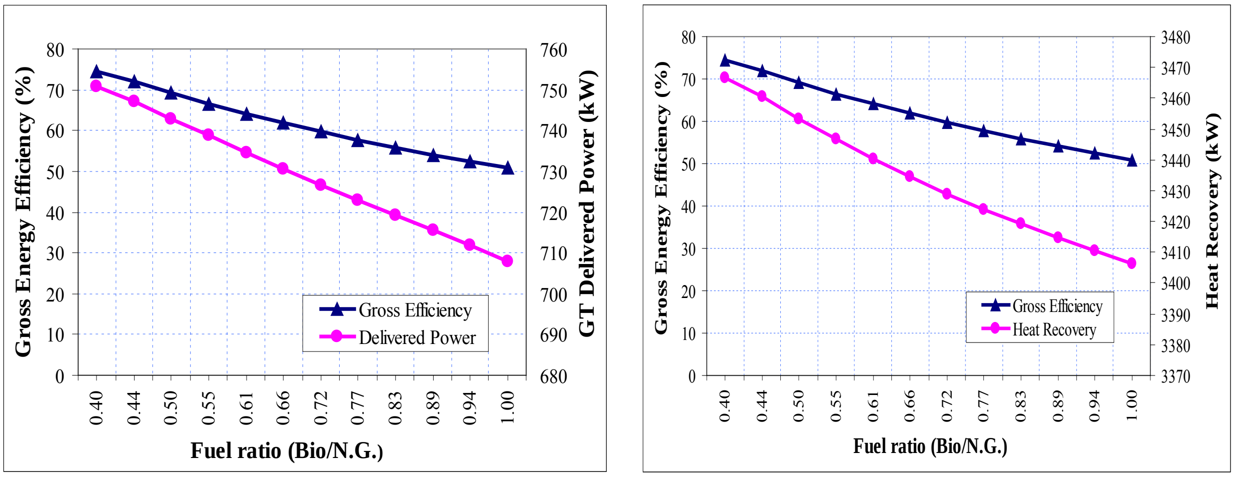
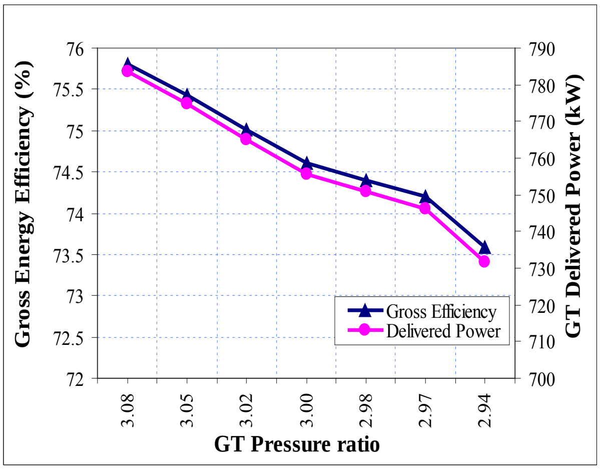
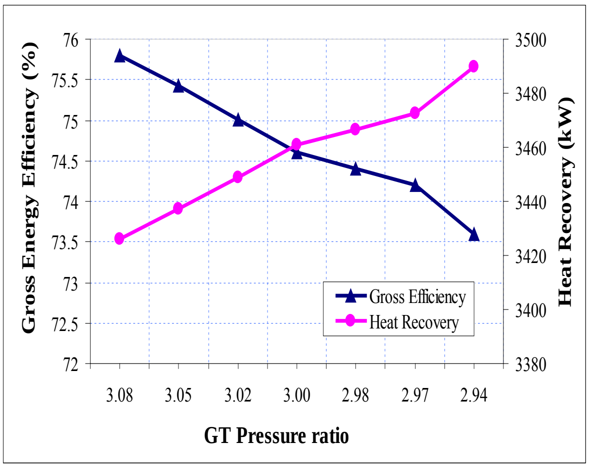


Fig. 3. Fuel ratio variations against hybrid system energy profiles

The point that is worth mentioning is that geometry of the bed and incoming fuel level can be increased but the thermal value and residence time, which is considered to be a more important factor, are limited. In Figure 4(a), the real difference in curves' tails is strongly depends on irreversibilities that taking place by more rated pressure in GT. (As GT's property, sacrificing efficiency against more power production is technically predicted).



(a)



(b)

Fig. 4. GT pressure ratio variations against hybrid system energy profiles

But in Figure 4(b), the pressure ratio in GT is working as a balancing element, which is correlated directly with GT delivered power and inversed with Heat recovery. These explanations are clearly demonstrated in mentioned graphs. In this stage a trade-off point is found at 3 for pressure ratio, which covers all two targets named GT delivered power and heat recovery. This point can be applied as a nominative reference for our designed system called best practice point in our modeling approach. In the comparison of graphs Nos. 4(a), 4(b) it can be observed that mentioned increased irreversibilities based on pr essure decreasing, would be transferred to stack as an increased source for heat recovery. The best proportion for electricity generation in an integrated SOFC/GT system is 60 to 40 [15]. Therefore the power which is expected to be generated by the system is planned in such a way that 1000 kW is generated by SOFC. Likewise according to the assumptions and calculations conducted, the power generated by GT equals 750.81 kW. As it c an be implied from table 5, the gross efficiency of the cycle is 74.4%. This can be compared with the gross efficiency of the similar study which had been conducted in university of Delft [3]. It is thus evident that an increase in gross efficiency has been fulfilled. Such increase can be attributed to the following reasons.

1. Direct burning of FB combustible gases output at GT combustion chambers and SR
2. Using natural gas (with a higher percentage of hydrogen) as fuel input SR system and its sense of more appropriate quality in fuel Sign for SOFC
3. Changes in the recovery position of SOFC gas combustible system, comes from SOFC process recycling by adding them to the purified gas cleaning unit (obviously, internal reforming itself is a part of the energy consumption indeed)

In order to obtain a h igher efficiency and higher steam mass flow rate generated by the system, some changes in heat exchangers' locations were applied. The pinch point which is located between the evaporator's outlet and inlet has been adjusted to be $10^{\circ C}$. LP and HP steam produced in the cycle can be used for steam units placed side-consumer. Also adding a steam cycle power generation, steam production can be used to generate electricity. Thus, the overall efficiency of power production systems will increase.

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Studies of preferences as an extra dimension in system studies

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Abstract: Industrial energy systems are complicated networks where changes in one process influence its neighboring processes. The network complexity increases if production/use of bio fuel is introduced in an existing system. Process integration can be a useful tool to study such systems and thus avoid sub optimization.

However, changes in an industrial complex do not only influence the technical values of energy and material efficiency. The social impact is also important and sometimes is comparable to that of technical factors.
A process integration project has recently been carried out for a paper mill in northern Sweden with a side view on future expansion with a bio refinery. An activity to study the social impacts were included through a Conjoint analysis, a stated preference method that combines statistics and interviewing technique.

The results indicate that the participants are divided in four groups, the largest group focusing on a change in the process towards a bio refinery, the second largest focusing on the local environment. The third and fourth group both look at the local forestry, one group wanting to increase local forest production, and one rejecting an increase.

Keywords: *process integration, bio refinery, conjoint analysis, social values.*

1. Introduction

1.1. Pulp and paper – development of energy efficiency and biofuel production

The Swedish wood industry is an important part of the Swedish economy and is responsible for 12 % of the Swedish export. Totally, it is the world's second largest exporter of total paper, pulp and sawn timber. The forest industry is Sweden's largest user of bio-energy and also the largest producer of bio energy. Presently this energy is used mainly internally [1]. A lot of effort is put on work to improve energy efficiency and sustainability. Also several large projects have been started on conversion of by-product into bio fuel e.g. green motor fuel [2].
A partly conversion of a paper producer into a bio refinery involves a lot of changes which will influence the rest of the mill, the employees, the surrounding society and the interaction with the actors involved in supply of wood raw material. It is important, in order to get a successful practical implementation, to consider also non-technical factors, like ete attitudes and reactions of these actors.

It was decided to test these ideas in a process integration project that was carried 2009-2010 in an existing pulp and paper mill. The project studied changes to improve energy efficiency as well as a hypothetical transformation to also include a bio refinery [3]. The project included several different methods and models. A process integration model of the paper mill was developed using the mathematical programming tool reMIND [4]. The results from this model was compared to a Pinch-analysis. The work also included a study on the effect on the wood suppliers and market prices of raw material, using the tool ReCOM, a regional economic market model. A study using the conjoint method [5] was included to study the effect of a plant conversion on attitudes and popular acceptance. Only plant employees were included as test group to limit the size of the first study.

1.2. What is conjoint

The choices people make are based on many things as previous experiences, training, attitude, habits, ethics etc. A person will choose the product or alternative that is most useful for this person (utility theory). The decision is formed by simultaneously considering multiple factors, a unique quality of the human brain. On a daily basis a person makes hundreds or possibly thousands of choices in this way, and this is what the method of conjoint analysis takes advantage of.

Conjoint analysis is a stated preference method, which can be used to assess people's preferences for a specific product, service or situation. It is used to evaluate the attributes of the product/service/situation and thereby makes it possible to determine which attribute is the most important in the evaluated situation. Individual or group level preferences can be estimated by decomposing the responses into part-worth's, thus the results come in quantitative measures which means that they can potentially be incorporated into other models such as process integration models and/or economic models. Studies have previously been made in which conjoint analysis results has been integrated in a Life Cycle Assessment (LCA) as weights in the environmental valuation phase [6]. There has been some attempts to integrate process integration with economic modeling [7] but to the best of out knowledge studies of social values has never been integrated in a process integration project. Further information on conjoint analysis can be found in [8-11].

The purpose of the study was to study the preferences of the employees when asked to compare local environment, global environment, increased local forest outtake and change of process from paper/pulp to paper/pulp and bio refinery. Another aim of the study was to find methods to integrate the result with the process integration result.

1.3. Scope of paper

The paper describes the conjoint method as such, the possibility to integrate the result with process integration models and economic models, as well as the possible use of the results as a basis for decision-making in the paper mill as well as for community decisions.

2. Methodology

The study was carried out through a web-based questionnaire where employees at a paper mill were asked to rank eight different alternatives where local and global environmental impact, local forestry and change in the process were altered in different ways. From the responses, individual as well ass average preferences have been estimated.

2.1. Conjoint analysis

In a conjoint study, the respondent is asked to evaluate a set of alternatives where the factors are varied in a fractional factorial design (reduced design), with two or three levels of each factor (attribute). The factors must be carefully chosen, and can be identified through group discussions, in depth interviews or expert elicitation. Each factor must be provided with two or more levels (high/low). The number of factors must be limited since respondents will not be able to maintain the same level of concentration if the number of evaluations is too large. Four to six attributes are often considered functional [11].

The alternatives that the respondents are asked to evaluate are created through an experimental plan. In order to keep the workload manageable for the respondents the number of alternatives to evaluate needs to be kept at a reasonable level.

The factors were chosen through discussions with Billerud Karlsborg AB in order to make the study relevant for the paper/pulp mill. Relatively early in the process it was decided that the study should be held internally at Karlsborg in order to avoid rumours and speculations in the surrounding society since a bio refinery is not planned in Karlsborg as of today. In the final design of the study, a fractional factorial design with four factors in two levels (2^4) were used, see table 1. The resolution of the design was IV, and only main effects were studied.

Table 1, The design of the study.

Alternative	Local forestry	Process	Emission of carbon dioxide	Local environmental impact
A	Same as now	Pulp/paper + bio refinery	Same as now	20% increase
B	Same as now	Pulp/paper	Same as now	Same as now
C	Same as now	Pulp/paper + bio refinery	Decrease	Same as now
D	Increased outtake	Pulp/paper + bio refinery	Decrease	20% increase
E	Increased outtake	Pulp/paper	Same as now	20% increase
F	Increased outtake	Pulp/paper + bio refinery	Same as now	Same as now
G	Same as now	Pulp/paper	Decrease	20% increase
H	Increased outtake	Pulp/paper	Decrease	Same as now

The study was distributed as a web questionnaire. A message was posted on the intranet to encourage employees to participate. The questionnaire consisted of three parts, first an introductory letter with information on the study and the factors, then the conjoint analysis where the respondents were asked to rank the alternatives in Table 1 from 1-8, and finally the participants were asked questions on residency, age, gender, educational level, work situation and any training in energy efficiency, environment, work environment and forestry.

All employees hand the opportunity to fill out the questionnaire, it was open for two weeks in order to cover all shifts. In all 61 persons answered the questionnaire and from these six responses had to be removed due to inconsistent answers, leaving 55 responses. There are 425 employees at the mill leaving us with a response rate of 13%.

2.2. Analysis of data

In this study two ways of analysing the data are used, first by calculating the main effects from the experimental plan, and then using partial least squares regression, PLSR.

Partial Least Squares Regression (PLSR) is a bilinear multivariate regression method that can simultaneously handle several response variables. PLSR is based on a linear transformation of the original variables to a limited set of latent variables (orthogonal factors), PLSR also attempts to maximize the covariance between the independent and dependent variables. The main advantage of PLSR is that the results can be presented graphically with all individual responses visible. Further information on this method can be found in [12]. The Unscrambler software was used to perform the PLS regressions in this survey [13].

Cluster analysis has proven useful to find segments among respondents in conjoint analysis studies [14-15]. The cluster analysis forms clusters of the respondents by putting respondents (samples) that are similar to each other into groups, at the same time as respondents that differ in response are kept apart. In this project, a hierarchical cluster analysis was applied to the individual main effects from the experimental plan (cluster method: between-groups linkage and interval measure: squared euclidean distance). The analysis was performed with the classification unit from the SPSS v. 17.0 software package [16].

3. Results

3.1. Respondents

Age and gender of the respondents can be seen in table 2. 22 respondents (40%) worked with operation of the mill, 12 respondents (22%) worked with maintenance, 9 respondents (16%) worked with process- and product development and 11 respondents (20%) worked with administration. 41 of the respondents (75%) worked daytime while 14 (25%) worked shifts.

Table 2, age and gender of the respondents in numbers.

Born	80's	70's	60's	50's	40's	No information	Sum
Men	3	6	9	18	6	2	44
Women	3	3	2	3	0	0	11

37 respondents (67%) lived 6-30 km from Karlsborg, 10 respondents (18%) lived in the vicinity, i.e. closer than 5 km and 8 respondents (15%) had more than 31 km to Karlsborg from their homes. 29 of the respondents (53%) were forest owners (or had someone in their closest family that owned forest), 25 respondents (45%) were not and 1 respondent (2 %) did not give any information on this question. 5 of the respondents (9%) had finished primary school, 27 respondents (49%) had finished secondary school and 23 respondents (42%) had a university degree.

3.2. Preferences

The average results are presented in Figure 1. It must be remembered that the number of respondents is small, only 55 complete responses, which means that the result could probably look different with more respondents.

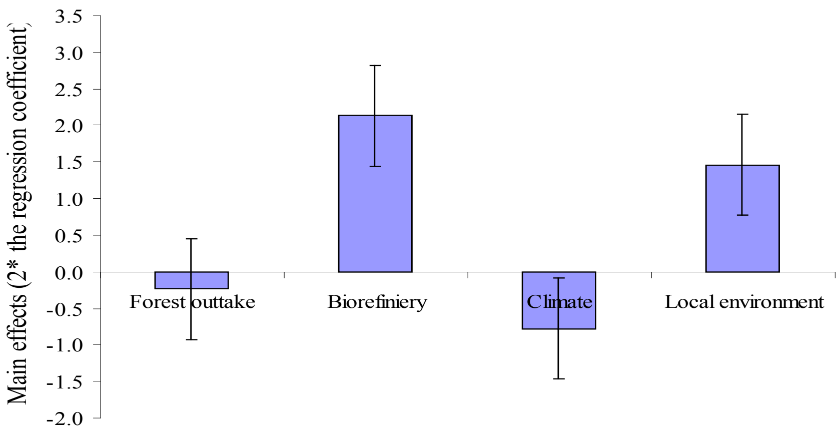

Figure 1. Averaged main effects with standard error for all respondents.

By using a PLSR-plot, individual results can be illustrated, see Figure 2. In the plot, the numbered marks represent individual respondents while the factors are marked with text. The PLSR plot is multi-dimensional, but here, only the first two latent variables are shown, making the graph two-dimensional. The plot can be interpreted like a map, the closer a respondent lies to a factor, the more important the respondent regard the factor. The plot also reveals negative correlations when a respondent lies on the other end of the latent variable (axis) from a factor, she or he has a negative preference for the specific factor.

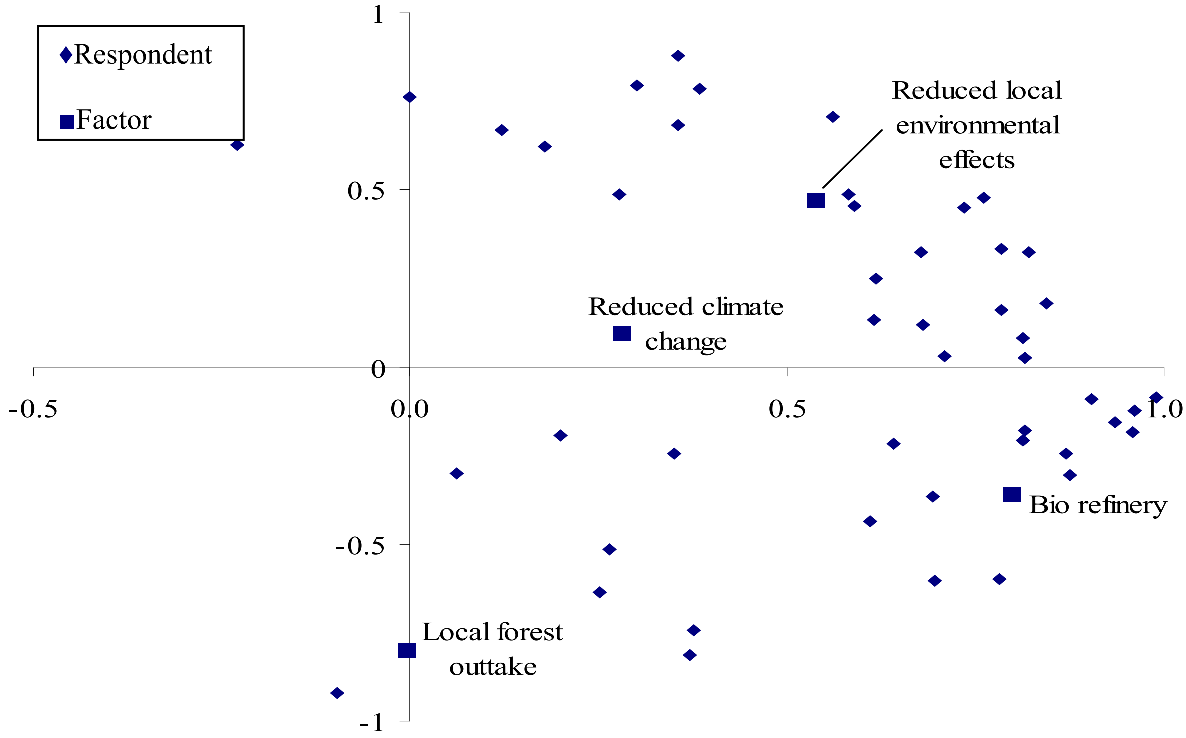

Fig 2. PLSR2. The first two latent variables explaining 65% of the total variance.

If the preferences are compared to the known facts on the respondents, from the information they left in the questionnaire, women are generally more concerned for the local environment than men (p=0.009). Age influence the view on local forestry (p=0.011). Preferences for the local environment are influenced by educational level (p=0.016) and whether or not the respondent or anyone in her/his close family own forest (p=0.010).

If respondents working with maintenance are compared to respondents working with process and product development, there is a significant difference in how they prioritize an increase in forest outtake (p=0.033), see Figure 3.

3.2.1. Training

Respondents with a university degree prioritise increased forest outtake more than respondents with primary and secondary school degrees (p=0.046). 10 respondents had taken part in three or four of the training subjects (forestry, energy, environment or work environment) and for these respondents preferences for forestry differed significantly from the others (p=0.010). The training subjects individually had no influence on the preferences at all. One more thing is interesting to notice, all educations correlate to each other, i.e. if a person has attended one education, she or he is more likely to attend educations in other areas as well.

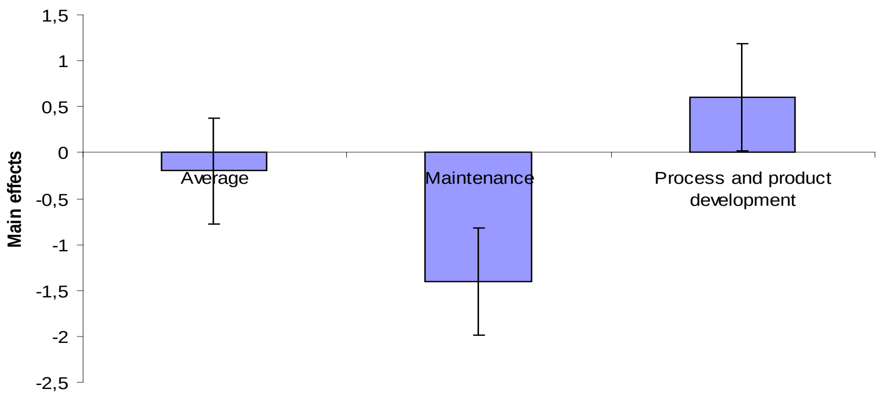

Fig 3. Averaged main effects for respondents working with maintenance (n=12) and process and product development (n=10).

3.2.2. Clusters

Through cluster analysis four clusters (groups) of respondents were formed, see Figure 5.

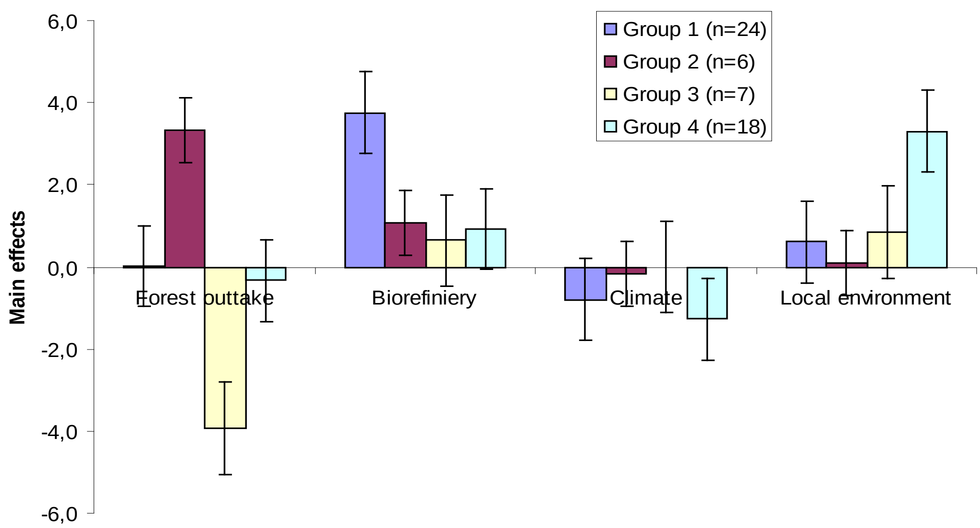

Fig 5. Groups created through cluster analysis.

The number of respondents in this study are to few to draw any further conclusions from the clusters, but in a large-scale study, the clusters could be analyzed for common characteristics such as educational level, occupation, gender etc.

4. Discussion and Conclusions

4.1. Discussion

The number of respondents were fewer than most favorable, probably due to many different reasons. The questionnaire was made available on the Billerud intranet for two weeks, in order to cover all shifts, but it would probably have needed further marketing for more employees to fill out the questionnaire. It would have been preferable to have at least 100 correct responses to the questionnaire.

The results from a conjoint analysis are quantitative. They can be averaged for the whole group or presented individually for each respondent. New groups can also be found through cluster analysis (see Figure 5). Since the number of respondents are so small, it is not possible to draw any further conclusions on c ommon features among the people in the same group (cluster), but with a larger set of samples (respondents) this would be possible. For the industry this means that it could be possible to pinpoint groups of employees that can be especially helpful in implementing new energy efficient processes, or groups that need extra information to be able to carry out new procedures in a correct way.

Conjoint analysis has been used to illustrate and discuss if the results from a conjoint analysis can be used together with a process integration tool such as a remind model and/or an economic model such as the ReCOM model.

The quantitative results can be used in process integration in several ways, see Figure 6.

A It can be used together with en economic model such as ReCOM as a means of choosing scenarios in the model. The factors in the conjoint analysis can be tailored to indicate how the market would respond in a hypothetical situation.

B Conjoint analysis can also be combined with economic theory and used to derive Willingness To Pay (WTP). This implicit pricing can also be used in economic models such as the ReCOM model. The economic model can be used to derive relevant levels to the factors of the conjoint analysis.

C Conjoint analysis can be used to weight different factors in the process integration model. The weighting can possibly also be used in the economic model. The factors will need to bee rather specific, for example emission of NOx from process XX.

D A process integration model can be used to derive relevant levels to the factors of the conjoint analysis.

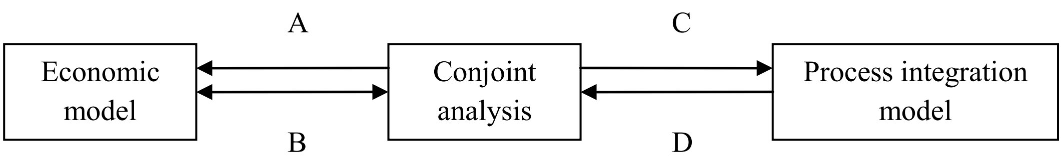

Figure 6. Possible exchanges between conjoint analysis, a process integration model such as a remind model and an economic model such as the ReMIND model.

4.2. Conclusions

Preference studies using Conjoint can be an important tool in studies and actions to improve energy efficiency and sustainability. It can be related in different ways to process integration models and economic models associated with them.

It is also interesting to notice that it is possible to find groups of respondents that were unknown previous to the study, as with the example with two groups of employees working with maintenance and process and product development. If an organisation wants to implement a change in the process conjoint analysis can be used to identify groups of participants with similar preferences and then tailor information to suit these specific groups.

The results of this study leave no clear information on the effect of training. If behaviour and attitudes of the employees are crucial for the full scale implementation of a process integration model, more research needs to be done on the effect of training. In this study, there were no significant connections at all between training and preferences.

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