CHEMICAL ENGINEERING TRANSACTIONS Volume 21, 2010
Editor J. J. Klemeš, H. L. Lam, P. S. Varbanov
 ISBN 978-88-95608-05-1 ISSN 1974-9791
DOI: 10.3303/CET1021230

Possibility to Combine Exergy with other Process Integration Methods for a Steelmaking Case

Erik Elfgren[1]*, Carl-Erik Grip[1,2], Chuan Wang[3], Jonny Karlsson[4]
[1]Luleå University of Technology Dept. Energy Engineering, 971 87 Luleå, Sweden
Erik.Elfgren@ltu.se
[2]SSAB until 2007, [3]Swerea MEFOS, [4]SSAB

The energy system of Luleå consists of the steel plant, a local CHP using process gases from the plant and the district heating system. Process integration work to improve the efficiency of the system is presently carried out by mathematical programming using a MILP tool (reMIND). Further improvements would need an improved possibility of the tool to consider the thermodynamic quality of the energy flows. This project aims to include exergy parameters in the node equations and object functions. This has been carried out for a test case, including a part of the system. Programming principles and some results are described.

1. Introduction

1.1 The energy system in Luleå

The Luleå energy system consists of three major parts: the SSAB steel plant, the LuleKraft CHP (combined heat and power) plant and the local district heating system (Luleå Energi), see Figure 1.

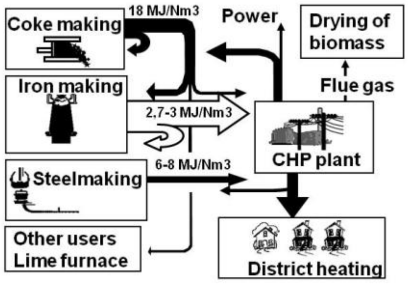


Figure 1: Overview of the energy system in Luleå.

The process gases, coke oven gas (COG), blast furnace gas (BFG) and basic oxygen furnace gas (BOFG) are generated at SSAB. These energy rich processes gases are partly used within SSAB and partly sent to the CHP plant, where they are combusted in the boiler, creating 520 °C steam that goes to a turbine system. The output from the turbine system is sequentially 300 °C process steam, 95 °C steam, 80 °C steam and 30

Please cite this article as: Elfgren E., Grip C-E., Wang C. and Karlsson J., (2010), Possibility to combine exergy with other process integration methods for a steelmaking case, Chemical Engineering Transactions, 21, 1375-1380 DOI: 10.3303/CET1021230

°C steam. It also generates about 80 MW of power. The 300 °C steam is process steam, which is used in SSAB. The 95 °C steam and the 80 °C steam are used for district heat production via a two-steps heat exchanger, for example to preheat the hot water from 50°C to 90 °C before delivering to the district heating system. The district heating system then provides heating to the whole municipality of Luleå, around 700 GWh per year. The remaining steam is condensed at the end of turbine. All temperatures are approximate but represent winter conditions.

1.2 Process integration on the Luleå system

The energy system is complicated and a global approach is needed to reach energy efficiency. Process integration studies on the Luleå system (SSAB Steel plant- CHP plant of the LuleKraft-district heating) have been practiced for several years. Most studies are carried out by mathematical programming, using a MILP method (Mixed Integer Linear Programming) tool. The tool itself is a software shell, the thermodynamics, energy and material balances are inherent in the equations and data put in the nodes and connections of that shell. The method and tool is used to analyze and improve the system(s) for several parameters, e.g., energy use, emissions, material efficiency, cost etc, see for example (Larsson and Dahl, 2003), (Ryman et al., 2007), (Ryman and Larsson, 2006) and (Wang et al., 2008). The process integration techniques are further developed within the excellence centre PRISMA. The standard procedure used for process integration at LTU and PRISMA is mathematical programming using the MILP based tool reMIND. The tool was initially developed by Linköping Universty (LiU). Further development was carried out in cooperation between LiU, LTU and PRISMA. The programming language is Java. In reMIND the cases are modeled in a graphical interface showing the process units as nodes and the flows as arrows between them. The nodes can be raw materials, energy, process units or product. They are linked by flows based on mass and energy balance in between. The equations expressed in the relevant nodes are linear as the MILP programming use linear equations. The flows have a magnitude e.g. unit/s. They also carry properties, e.g. energy/unit, kg/unit, content of chemical elements etc. They are included as a matrix of several properties. This is because of the multiproperty characters of steelmaking flows. The properties are constant values, not variables. Once again, this is because of linearity demand, otherwise (flow*property) would be a 2nd degree expression. The reMIND tool converts the node and flow parameters into an equation matrix, which is treated by a commercial solver, CPLEX, for optimization work. The output data from the solver is then converted into practically useful results in an evaluation model, which in the reMIND case is in Excel format.

Process integration often involves optimization of energy systems. A solution has to be found that optimizes the system within the frame stipulated by first and second law of thermodynamics. The 2nd law criteria could be exergy or even entropy. Exergy is chosen as criteria in this study, mainly because SSAB and LTU have a long experience and ongoing work in using exergy for mapping and evaluating the steel plant energy system. The exergy of a system can usually be described as

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

where E is the exergy content, ΔH and ΔS are the change in enthalpy and entropy from the reference state in J/kg and T_0 is the temperature of the reference state. For a temperature change of solids and liquids without chemical reactions ΔS can be described as

$$\Delta S = m \cdot C_p \cdot \ln(T / T_0), \tag{2}$$

while for an ideal gas

$$\Delta S = m \cdot C_p \cdot \ln(T / T_0) + m \cdot R \cdot \ln(p_0 / p), \tag{3}$$

where m is the weight in kg, C_p is the heat capacity at constant pressure in J/(kg·K), T is the temperature in K and p is the pressure in Pascal.

1.3 Previous use of exergy at SSAB

Combined energy and exergy studies have been practiced intermittently at SSAB since 1989. Principally the studies have given two types of useful answers, see Figure 2.

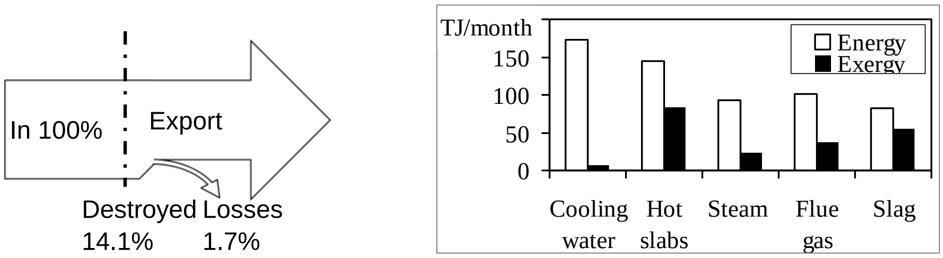


Figure 2: Exergy balance for blast furnace (left) and exergy content in different energy Media (right).

The general balance for a unit or the whole system gives efficiency, losses and destroyed exergy. The destroyed exergy is the part that is irreversibly destroyed in the process. It is an expression of the efficiency of the process itself. The exergy loss is an expression of the remaining exergy in the waste flows. It can give an indication of the possibility to use it elsewhere. The right diagram in Figure 2 shows the energy- and exergy contents in some flows. The cooling water represents the highest amount of rest energy but it is hardly recoverable because of the low exergy quality. Hot slabs seems most promising from an exergy point of view. Further details see (Grip et al., 2009).

1.4 Scope of paper

The scope of this paper is to present the ongoing work on including exergy criteria in reMIND along with some preliminary results.

2. Creating a "thermodynamic MILP"

The reMIND model consists of nodes interacting through their in- and outputs and their transport flows.

2.1 Node equations and flows

The nodes contain equations describing process units. These equations are based on mass, energy and exergy balance. Sometimes existing knowledge, experiences and models used in process computers and in offline evaluations by plant or institute engineers are also needed. The steel industry is based on thermo-chemical processes, and thus these process models are also based on thermodynamic. The interaction is taken care of by in- and outputs that are transported by flows. These flows are described by their magnitude and by content properties, e.g. energy in J/unit.

2.2 Formulating thermal exergy expressions for a linear equation matrix

The node calculations can be expected to give output consisting of mass flows combined with accompanying energy flows. In a normal excel sheet the exergy flow could easily be calculated from these data by using the temperature and material properties. In a MILP model this cannot be done directly because of the non-linearity. The calculation of temperature involves a division of energy flow with mass flow and C_p, and the determination of exergy from those data is definitely non-linear. In this work an interpolation technique has been chosen, based on splitting one flow into two (or more) virtual flows. Take as an example a case where water with a certain content of mass and thermal energy leaves the node. Chose one virtual flow of "cold water" and one of "hot water", both having a precalculated enthalpy and exergy per mass unit. Use a mass-heat balance to calculate the amount of the two virtual waters that would give a mix with the mass- and enthalpy content of the real water. Make a weighed mean of the "cold" and "hot" water precalculated exergies to get the exergy of the "real" water. As the exergy curve is non-linear this is applicable only if the interpolation area is of limited width (see Figure 3).

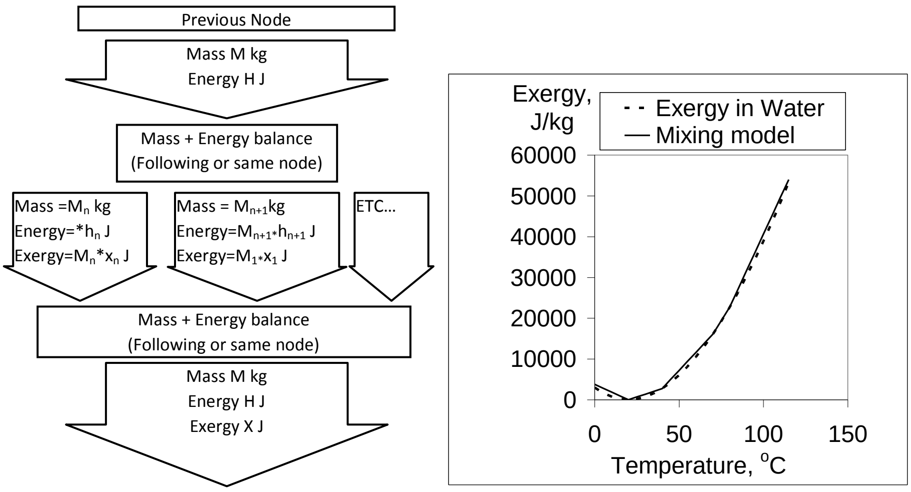


Figure 3: Linear approximation of thermal exergy. Left: virtual mixing method. Right: comparison of modelled and real exergy for a six-component case.

If the width is more large the problem can be solved by choosing several virtual waters and letting the program chose the two closest (see Figure 3). Such a choice can be made using the integer facility in the MILP tool. An example using six components is shown in Figure 3. The choice and interpolation were simulated in excel. The calculation was made for a reference temperature of 20 °C. Like any interpolation of non-linear functions it is not perfect, there is always a difference between the calculated and real exergy. In our case the difference is principally a function of the entropy when mixing the two components.

3. Exergy reMIND model for the Luleå system

3.1 Model

The Luleå energy system has been partly modeled, focusing on the CHP plant, shown in Figure 4. The CHP plant is interesting both from an exergy point of view (the water temperature is the dominant exergy term) and also from the point of view of the industry, since cost can be reduced at Luleå Energi by lowering the flow line temperature.

Each node (the boiler, the turbine system and the heat exchangers) has mass, energy and exergy balance. The destroyed exergy is also calculated (flows F17, F18 and F19 in Figure 4) in each of these nodes.

The water flows passing through the condensers (called heat exchangers in Figure 4) from the turbines (F13 and F16 in Figure 4) do not change their temperatures significantly but transfer energy by changing from steam phase to water phase.

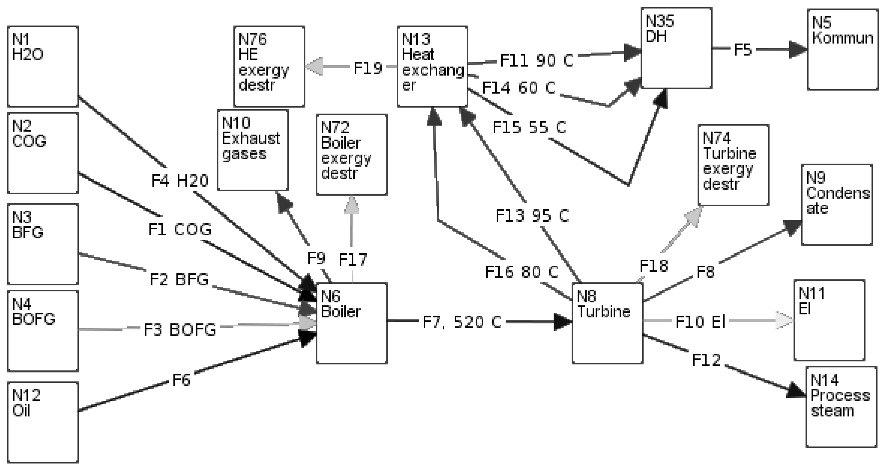


Figure 4: Model of the CHP plant, showing the different nodes and flows.

3.2 Preliminary results

Currently, all parts of the CHP plant are not included in the prototype model but some encouraging preliminary results can still be obtained. When exergy destruction is minimized, it is found that the 80 °C (F16 in Figure 4) steam only destroys roughly a third of the exergy in the heat exchanger as compared to the 95 °C steam (F13 in Figure 4). In consequence, more electricity can be generated in the turbine instead. This result can be understood from the higher exergy content in high temperature steam compared to steam with lower temperature.

Furthermore, when exergy destruction is minimized and the optimizer can choose between the three different flow line temperatures, 55, 60 and 90 °C (F15, F14 and F11 in Figure 4), it chooses the 90 °C water. The reason for this is that the higher the temperature, the more exergy can be transported away, thereby reducing the exergy destruction. The 55 and 60 °C flows give roughly three times higher exergy destruction as compared to the 90 °C flow. Obviously, the major part (about 90 %) of the exergy destruction always occurs in the boiler since that is where the combustion occurs.

4. Discussion

4.1 Exergy in reMIND

Including exergy calculations in the reMIND program can give valuable insights into the possibilities of optimizing an industrial system. Furthermore, including it does not seem to require any significant extra effort. With exergy included, both the exergy waste and the exergy destruction can be monitored and optimized. Different cases can easily be studied and the most beneficial selected.

4.2 Other combination methods

Gong and Karlsson (2004) proposed a coordination of exergy analysis and MILP method for the pulp and paper industry. In their work, some process improvements from the exergy analysis have been used as different investment alternatives in the optimization model, therefore, the cost optimization can be made to find out the cost-efficient alternatives.

Acknowledgements

We wish to thank the Swedish Energy Agency for funding this research.

References

Gong M. and Karlsson M., 2004, Coordination of exergy analysis and the MIND method - applied to a pulp and board mill, International Journal of Exergy 1, 289-302.

Grip C .E., Dahl J and Söderström M, 2009, Exergy as a means for process integration in integrated steel plants and process industries, Stahl und Eisen 129, S2–S8

Larsson M. and Dahl J., 2003, Reduction of the specific energy use in an integrated steel plant – The effect of an optimization model, ISIJ International 40, 1664-1673.

Ryman C, Grip C.E. and Larsson M, 2007, Model based evaluation of sustainability indicators in integrated steelmaking: A Swedish case study, AISTech 2007, The Iron & Steel Technology Conference and Exposition, May 7-10, Indianapolis, Ind., USA.

Ryman C. and Larsson M., 2006, Reduction of CO2 emissions from integrated steel-making by optimised scrap strategies: Application of process integration models on the BF-BOF system, ISIJ International 46, 1752-1758.

Wang C., Larsson M., Ryman C., Grip C-E., Wikström J-O., Johnsson A. and Engdahl J., 2008, A model on CO2 emission reduction in integrated steelmaking by optimization methods, International Journal of Energy Research 32, 1092-1106.

Possibilities and problems in using exergy expressions in process integration

Carl-Erik Grip [1,*], Erik Elfgren[1], Mats Söderström[2], Patrik Thollander[2], Thore Berntsson[3], Anders Åsblad[4], Chuan Wang[5]

[1] LTU (Luleå University of Technology) Division Energy Technology, Luleå, Sweden
[2] LIU (Linköping University), Division Energy Systems, Linköping, Sweden
[3] Chalmers University of Technology, Division Heat and Power Technology, Gothenburg, Sweden
[4] CIT Industriell Energi, Gothenburg, Sweden
[5] Swerea MEFOS, Luleå Sweden
** Corresponding author. Tel: +46 920 49 14 72, Fax: 46 920 49 10 74, E-mail: carl-erik.grip@ltu.se*

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:

$$E = \Delta H - T_0 * \Delta S \qquad (1)$$

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

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

And for an ideal gas as

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

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

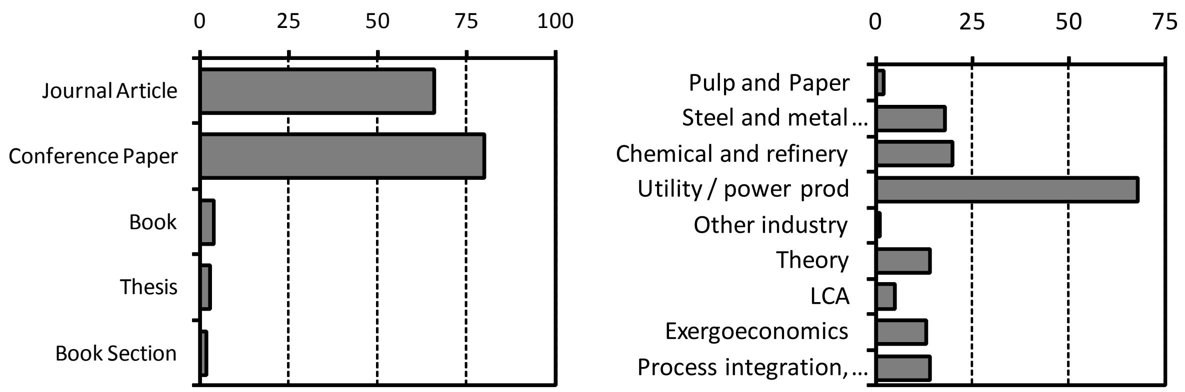
Step 4. A case study to demonstrate the practical application on an industrial system. The case chosen was the Luleå Energy: The SSAB steel plant, CHP (combined heat and power plant) and district heating. Collected production data were used for exergy calculations both for the total system and some subsystems

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”.

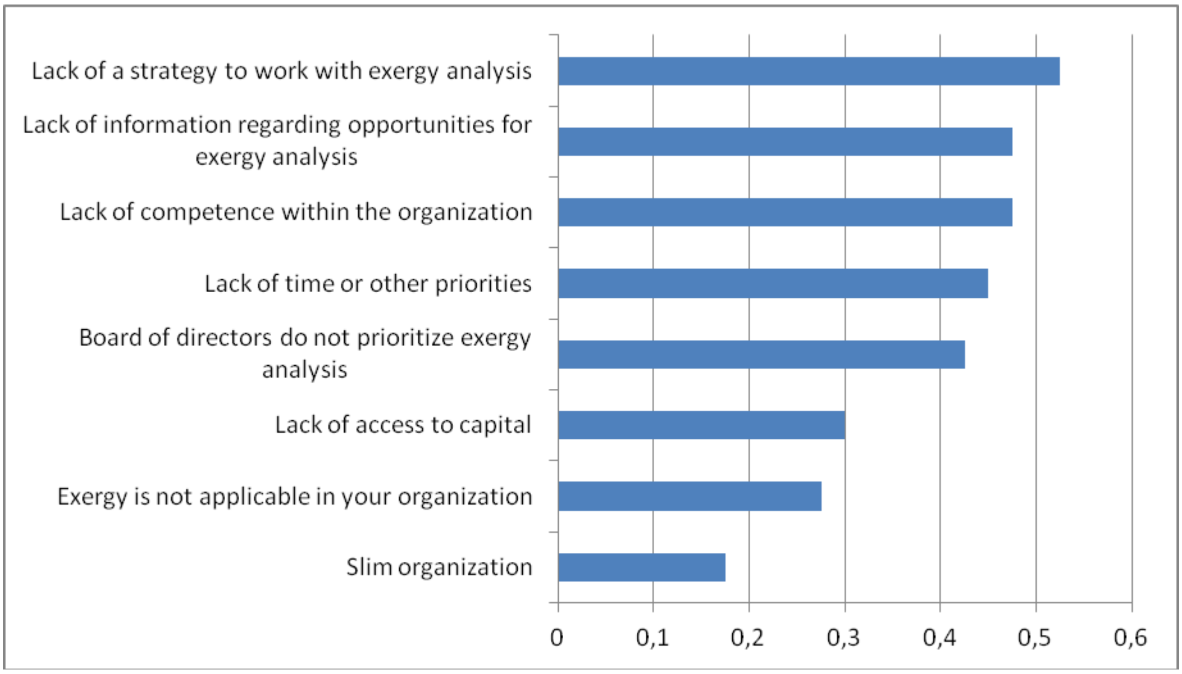


Fig. 2 Weighted summary of obstacles for exergy analysis. Often important =1, sometimes important =0.5, seldom Important = 0.

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.

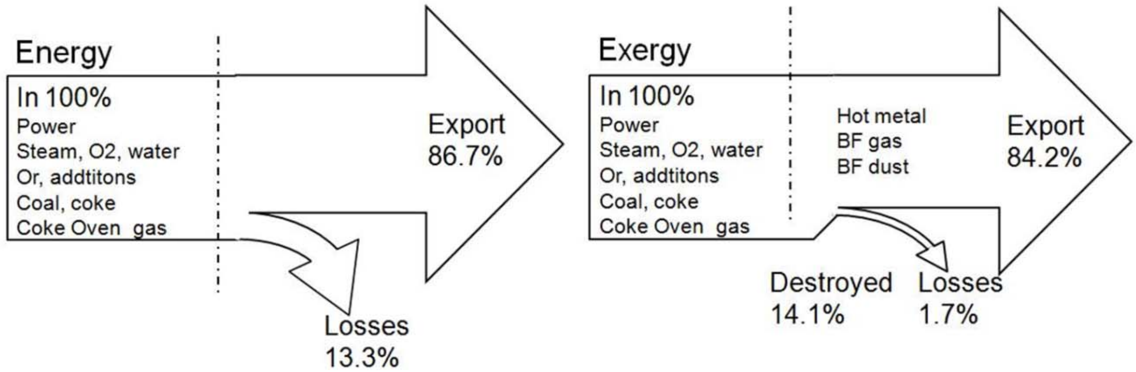


Fig. 3 SSAB Study 2005, Example on Energy-Exergy Diagrams for the blast furnace [12].

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.

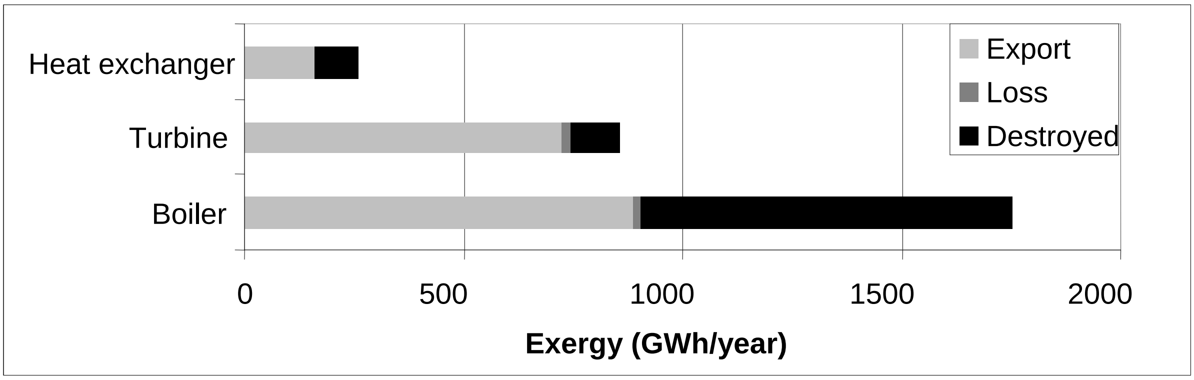


Fig. 4 Example on Exergy balances for the heat and power plant.

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.

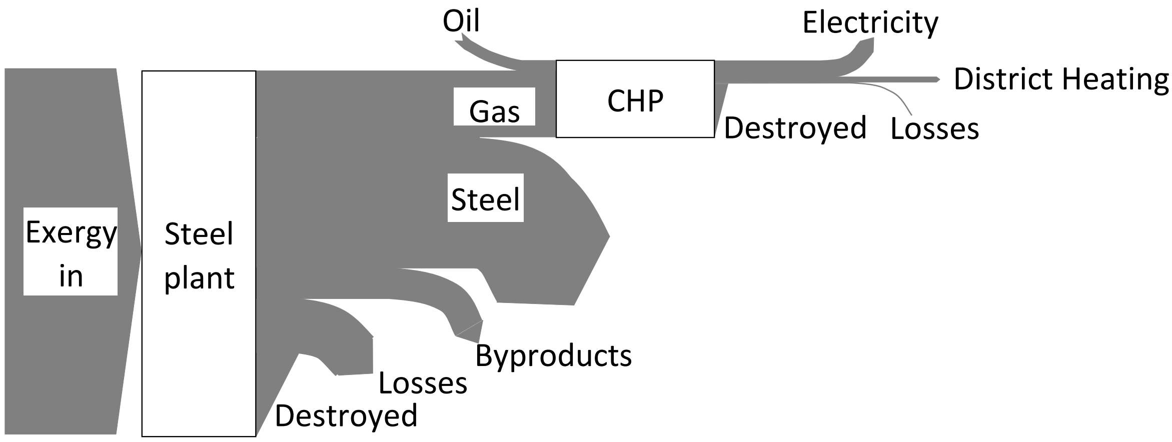


Fig. 5 Exergy flows through the total system

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

Acknowledgements

The authors would like to thank the Swedish Energy Agency for financing the project. We would also like to thank the many interviewees who kindly answered our questions and the people at SSAB, Lulekraft and Luleå Energi who have helped with data collection.

References

[1] Linnhoff B. & Flower J.R., “Synthesis of Heat exchanger Networks I. Systematic generation of energy optimal networks”, Aiche Journal 24 (4), 1978, pp. 633-64

[2] G. Wall, "Exergy Flows in a Pulp and Paper Mill and in a Steel Plant and Rolling Mill", The Fourth International Symposium on Second Law Analysis of Thermal Systems, Rome, 25-29 May, 1987, pp. 131-140, ASME.

[3] Nilsson K. and Söderström M., “Optimising the operation Strategy of a pulp and paper mill using the MIND Method”, Energy, vol. 17 (10), 1992, pp. 945-953

[4] Grip C.-E. and Thorsell A., “Swedish national research program for energy saving by means of process integration”, Scanmet II, 2nd International Conference on Process Development in Iron and Steelmaking, June 6-9, 2004, Luleå, Sweden

[5] Grip C.-E., Söderström M., Berntsson T., “Process integration as a general tool for energy intensive process industry. Development and practical applications in Sweden”, SCANMET III (3rd International Conference on Process Development in Iron and Steelmaking), June 8-11, 2008, Luleå, Sweden

[6] Larsson M., Doctoral thesis, Luleå University of Technology, 2004, No.:2004:63, ISSN: 1402-1544

[7] Larsson M., Sandberg P., Söderström M., Vuorinen H., “System gains from widening the system boundaries: analysis of the material and energy balance during renovation of a coke oven battery”, Int J Energy Res., 2004, pp. 1051-1064

[8] Larsson M., Grip C.-E., Ohlsson H., Rutqvist S., Wikström J.-O., Ångström, S., “Comprehensive study regarding greenhouse gas emission from iron ore based production at the integrated steel plant SSAB TUNNPLAT AB”, International journal of green energy. vol. 3, nr. 2, 2006, pp. 171-183

[9] Wang C., Doctoral thesis, Luleå University of Technology, 2007, No:2007:28, ISSN print):1402-1544

[10] Thollander P., Trygg, L., Svensson, I.-L., ”Analyzing variables for district heating collaborations between energy utilities and industries”, Energy 35 (9), 2010, pp. 3649-3656

[11] Zetterberg L., “Flows of Energy and Exergy in the Steelmaking process at SSAB Luleå”, Master Thesis SSAB and Chalmers, Gothenburg, 1989

[12] Verbova M., “Energy and Exergy flows in Steelmaking Processes at SSAB Strip Products Division in Luleå”, Master Thesis SSAB and LTU, 2007:080

[13] Grip, C., Dahl, J., Söderström, M., “Exergy as a means for process integration in integrated steel plants and process industry”. Stahl und Eisen, 129, 2009, pp. S2–S8

[14] Malmström, S., “Efficient use of waste energy in the steel industry”, Luleå University of Technology, Master Thesis SSAB and LTU, 2009:110

[15] Elfgren E, Grip C, Wang C and Karlsson J. Possibility to combine exergy with other process integration methods for a steelmaking case. 13th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES’10), 28 August – 1 September 2010, Prague, Czech Republic

Exergy as a means for Process integration in an integrated Steel plant

Erik Elfgren[1*] Carl-Erik Grip[1,2],Jonny Karlsson[3] Chuan Wang[4]

[1]Luleå University of Technology, SE-97187, Luleå, Sweden, [2]SSAB Tunnplåt AB until 2007
[3]SSAB EMEA, SE-971 88 Luleå, Sweden [4]Swerea MEFOS, SE-971 25 Luleå, Sweden

*Corresponding author: erik.elfgren@ltu.se
Key Words: Exergy, Process integration, Energy system, Optimisation, Energy efficiency

Abstract

The Luleå energy system consists of SSAB (an integrated steel plant) – LuleKraft (the heat and power plant) – Luleå Energi (the district heating network). The exergy flows in the whole system have been studied and some possibilities on how to reduce the exergy losses are discussed. The exergy thermal efficiency of SSAB, LuleKraft and Luleå Energi are 70 %, 40 % and 30 % respectively. The relatively low exergy thermal efficiencies is a natural consequence of converting high-value chemical energy into heating water. In the integrated steel plant, the exergy losses are caused by the cooling of the steel prior to transport. In the heat and power plant, exergy is destroyed mainly in the furnace. In the district heating, exergy is destroyed mainly by the customer. A preliminary conclusion is that a lot of exergy is destroyed and lost in order to produce hot water, which doesn't really need so much exergy. By lowering the water temperature of the district heating, a larger portion of the exergy can be converted to high-value electricity. Mapping by combined Exergy/energy analysis is important to find ways to improve energy efficiency. It can also be important to initiate regional energy collaboration.

1 Introduction

1.1 Process integration

An industrial system consists of several components. If these are optimised individually, the overall result can be worse due to interdependencies between the components. Process integration is a method to take into account the whole system while optimizing so a global energy saving can be achieved. There are several tools available to do process integreation such as pinch analysis [1-3], exergy analysis [4-6] and Multiple Integer Linear Problem (MILP) tools [7]. Pinch analysis is useful when dealing with many different temperature flows, exergy analysis is useful when chemical energy is involved. MILP-tools are useful and can be used to optimise many different objectives.

1.2 Exergy

In this study exergy was chosen as a process integration tool since there are chemical energies involved and also plenty of exergy data were available.

Different flows of energy have different value and different usability. E.g. the energy in cooling water with some degrees over temperature will get a high value in the energy balance but is practically useless. On the other hand the energy in electrical power can be used with very high efficiency and converted into other energy types. For this reason, energy balances where the energy content of different streams is summed up are an insufficient measure in the evaluation of measures for energy saving in industrial systems. One possibility to overcome this is to include exergy balances. Exergy is the part of the energy that according to the second law of thermodynamics can be converted into work. A combined energy-exergy study gives information on both the amount and the quality of the energy.

Process integration often involves optimization of energy systems. A solution has to be found that optimizes the system within the frame stipulated by first and second law of thermodynamics. The 2nd law criteria could be exergy or even entropy. Contrary to energy, exergy can be destroyed and the continuity equation for exergy reads:

$$E_{\text{import}} = E_{\text{export}} + E_{\text{loss}} + E_{\text{destroyed}}.$$

Lost exergy is defined as the exergy that is lost due to cooling, flue gases etc, i.e. exergy that could be recovered. Destroyed exergy cannot be recovered but could possibly be reduced using more efficient components. The exergy of a system can usually be described as

$$E = \Delta H - T_0 \cdot \Delta S,$$

where E is the exergy content, ΔH and ΔS are the change in enthalpy and entropy from the reference state in J/kg and T_0 is the temperature of the reference state. For a temperature change of solids and liquids without chemical reactions ΔS can be described as

$$\Delta S = m \cdot C_p \cdot \ln(T/T_0),$$

while for an ideal gas

$$\Delta S = m \cdot C_p \cdot \ln(T/T_0) + m \cdot R \cdot \ln(p_0/p),$$

where m is the weight in kg, C_p is the heat capacity at constant pressure in J/(kg·K), T is the temperature in K and p is the pressure in pascal. In this work, we have used T_0 = 15 °C and p_0 = 1 bar.

1.3 The system SSAB – CHP – District heating

The Luleå energy system consists of SSAB (an integrated steel plant), LuleKraft (the heat and power plant) and Luleå Energi (the district heating network), see Figure 1 and Figure 2.

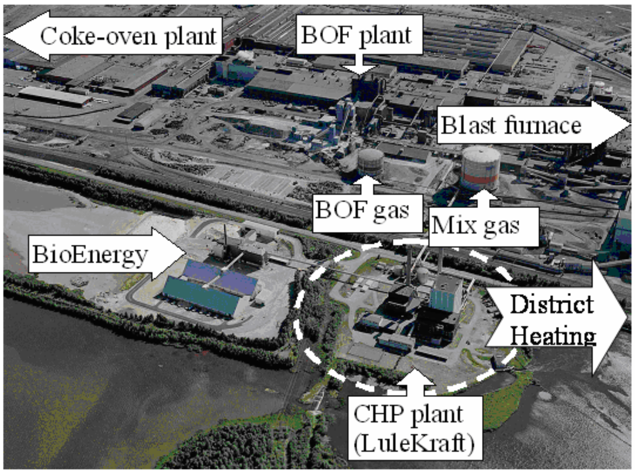


Figure 1: Air-view of the Luleå energy system (Photo: METRIA).

In the steel plant, natural resources (mainly ore and coal) are used to produce steel. The primary by-product from the steel process is energy gases: coke-oven gas (COG), blast furnace gas (BFG) and basic oxygen furnace gas (BOFG). These gases are partly recycled within the steel plant and the surplus is sent to the CHP (combined heat and power) plant LuleKraft. LuleKraft produces electricity and hot water for the district heating. The flue gases from the furnace are used to dry bio mass in the wood pelletizing plant Bioenergi Luleå (not included in this study, the energy content is not significant). The hot water from the CHP plant is used for district heating (important in the north of Sweden) in the whole Luleå area.

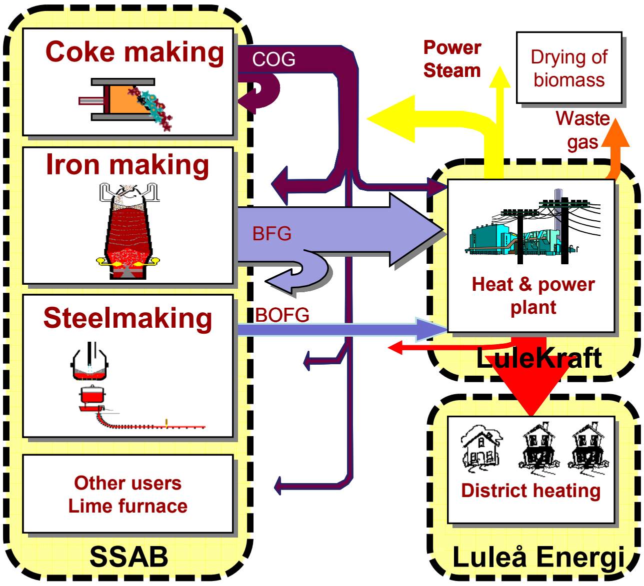


Figure 2: Energy flows in the Luleå energy system.

1.4 Scope

Over the years, a number of exergy studies have been carried out on the energy system of the integrated steel plant at SSAB Luleå [8-10]. These have given useful information on the efficiency of the units, possibilities and limitations for recovery of low value energies etc. An extended study has now been carried out, where the CHP plant and the district heating are included. The different studies and their results are described and the consequences of a reduced hot water temperature are evaluated.

1.5 Time frames

The studies covered in this article have been made during different time periods. When comparing them, care has been taken to scale the inputs/outputs between the systems so the results of the studies are compatible.

2 Case study

2.1 Exergy for SSAB

The energy flows in SSAB are shown schematically in Figure 3. In the products flow, most of the energy is chemically bound within the steel, the rest is contained in the energy gases going to the CHP plant.

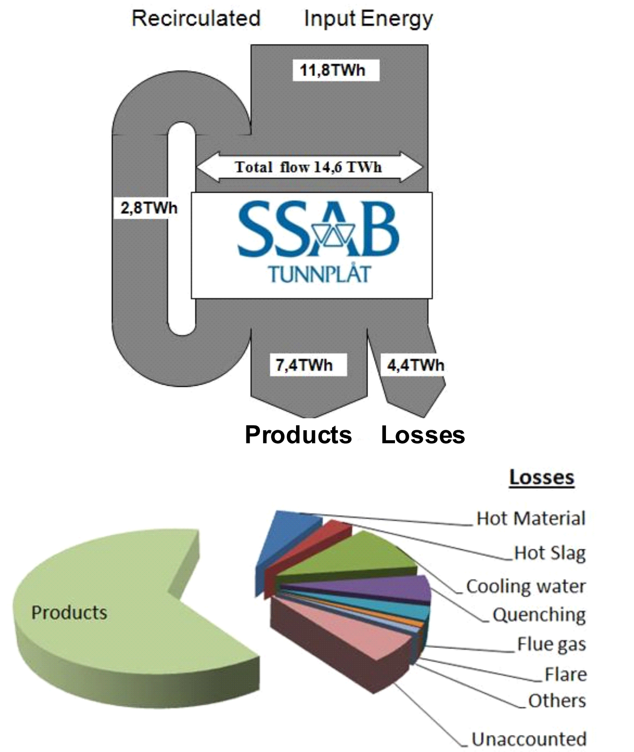
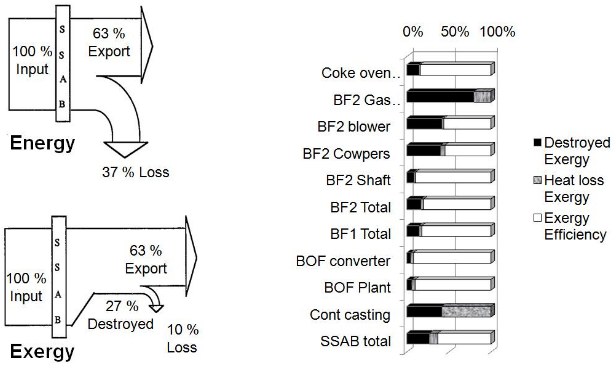


Figure 3: Energy flows and losses in SSAB 2007 [8,11].

The energy and exergy balance of the steel plant is shown in Figure 4 [8]. The reason why the losses are equal in terms of exergy and energy is that the incoming resources are mostly pure exergy (chemical and electrical energy) and so are the outgoing energies (except for the losses). The partial losses 1989 were 37,2 %, which is on par with the losses 2009, 37,7 % calculated in the current project. In Figure 4b we see that the principal components; the coke oven, the blast furnace and the basic oxygen furnace are fairly efficient, since they basically transform chemical energy into other chemical energy. The continuous casting only has losses since the excess heat from the steel is cooled off. The chemical energy was not included in that bar since it is unchanged by the process.



a) Energy and Exergy Balance of the total system

b) Exergy efficiency of individual units

Figure 4: a) Energy and exergy balances for SSAB b) exergy efficiency of individual units in SSAB [8].

The exergy loss and destruction for the steel and coke making were also calculated for the year 2005 [9]. The results were similar to those in Figure 4.

Figure 5 shows the energy and exergy contents of different components of SSAB. This can be used to evaluate where energy recovery is possible. The cooling water contains large amounts of energy but small amounts of exergy due to its low temperature. This energy is basically useless. The surface losses are caused by the cooling of the slabs and here is a good potential for energy recovery. This is also the case for the slag and the flue gases and to some extent for the steam.

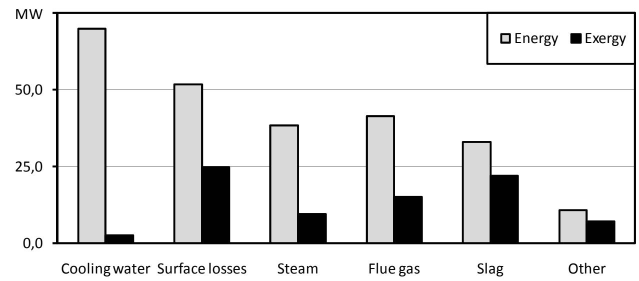


Figure 5: Energy and exergy losses for different components of SSAB based on data from [10].

2.2 Exergy for LuleKraft

LuleKraft is a combined heat and power (CHP) plant that converts the energy gases from SSAB to hot water and electricity, see Figure 6 . The hot water is used for district heating. The energy gases (COG, BGF and BOFG) are mixed and the result is called BLG ("blandgas" in Swedish). This BLG is used, sometimes enhanced by some high-energy COG. Some oil is used to supplement the combustion and if a lot of heat is needed (on cold days) some extra oil is used. The oil and the energy gases are combusted in the boiler and the flue gases are used to pre-heat the water. Some of the flue gases also go to Bioenergi Luleå to dry biomass. Part of the steam is exported back to SSAB, some is used to generate electricity and the remaining steam is used to heat the water in the district heating trough two heat exchangers. The steam remaining at the end of the turbine system has very low energy-content and is condensed to water using water from the nearby bay.

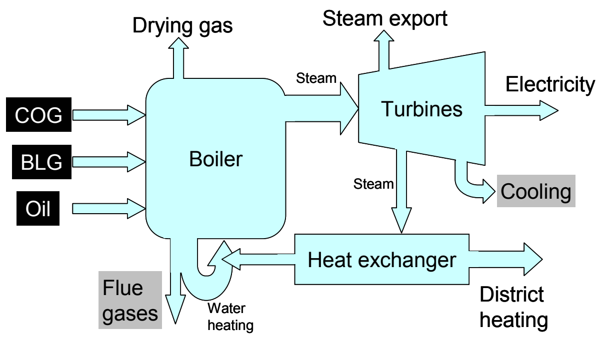


Figure 6: Schematic overview of the energy/exergy flows in the CHP plant LuleKraft. Black background signifies imported energy/exergy and grey background signifies exergy losses. Internal flows have small text and the remaining arrows are energy/exergy export.

In this project, the period March 2009 – February 2010 was studied since we had access to detailed process data for this period.

In Figure 7 the monthly imported exergy (which is equal to the imported energy since it is chemical energy) is shown. During part of June and entire July, there was no production at SSAB, which is reflected in the figure. There is a correlation between low temperature (NB, inverted axis) and high energy usage and particularly with high oil consumption.

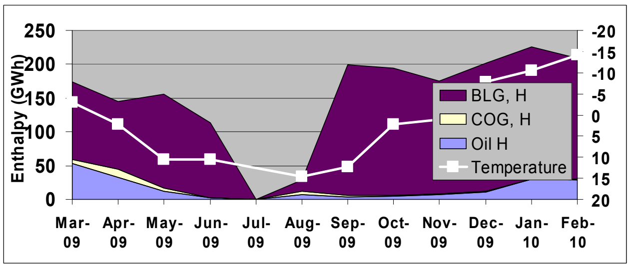


Figure 7: Left y-axis, energy used in LuleKraft, right y-axis, mean temperature during the period March 2009 – February 2010.

Figure 8 shows the three principal components of LuleKraft: the boiler, the turbines and the heat exchangers. In the boiler, much exergy is destroyed since the energy gases contain almost pure exergy, which is converted into superheated steam and hot flue gases, both of which have much lower energy quality. The only thing that might be done is to change the boiler but this is an important investment. A comparison between the efficiencies of some industrial boilers can be found in [12]. A large portion of the energy in the flue gases is recycled, in the preheating and in the drying of bio-mass but the remaining exergy is lost since it has not seemed profitable to recycle it. In the turbine system, exergy is lost in the low-value steam that is condensed to water by the sea water. Exergy is destroyed since the superheated steam from the boiler has much higher exergy than the resulting condense steam. In the heat exchangers, exergy is destroyed when the steam transfers energy to heat the water, which has lower entropy than steam of the same temperature.

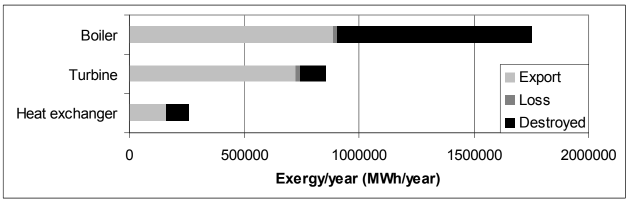


Figure 8: Total exergy exported, lost and destroyed in the boiler, the turbines and the heat exchangers in LuleKraft per year.

The annual loss and destruction of exergy is presented in Figure 1. During the summer, when most of the energy is used to make electricity, a lot of exergy is destroyed because the plant is not optimized for pure electricity production. On the right axis the exergy thermal efficiency is show, defined as

$$\eta = \frac{E_{export}}{E_{import}}.$$

The exergy thermal efficiency seems to correlate with the total amount of used exergy.

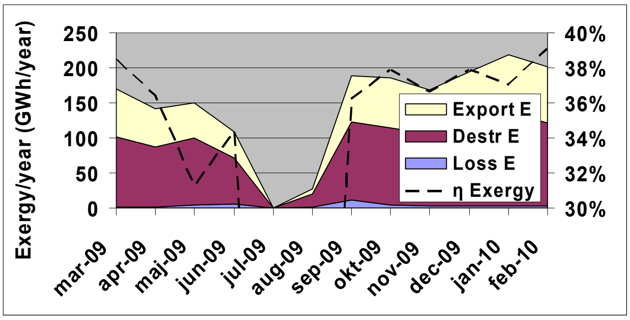


Figure 9: Monthly exported, lost and destroyed exergy along with the exergy thermal efficiency for LuleKraft during the period March 2009 – February 2010.

Figure 10 shows the correlation between the exergy thermal efficiency and the heat water consumption. At higher heat water consumptions, the efficiency is also somewhat higher. The reason for this is that LuleKraft is optimized for heat water production, not for electricity production. The data in the figure has been filtered to exclude missing data and transient data at start/stop.

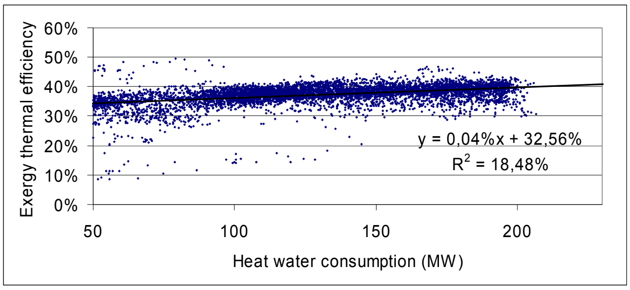


Figure 10: Exergy thermal efficiency as a function of the heat water energy consumption at LuleKraft during the period March 2009 – February 2010.

2.3 Exergy for Luleå Energi

The principal parts of the energy and exergy flows can be seen in Figure 1. The first pair of bars shows the total imported energy/exergy to LuleKraft from the energy gases and the oil. This is almost purely chemical energy and hence the exergy is equal to the energy. The second pair of bars is the heat and power delivered to the district heating system Luleå Energi. Some of the exergy is destroyed in the boiler and the heat exchangers and some is lost in flue gases and cooling. Part of the exergy is also exported to Bioenergi Luleå and to SSAB. The exergy losses and destruction in these exports have not been included. The third pair of bars is the heat delivered to the district heating network. Both the exergy and the energy is reduced compared to the previous pair of bars because the power output (that is pure exergy) is not included. In the fourth and last pair of bars, the energy and exergy used by the customers is shown. The customers only need warm water (about 50 °C) which has a very low exergy value. An interesting possibility is to develop the use of low value energy, e.g. industrial rest energy.

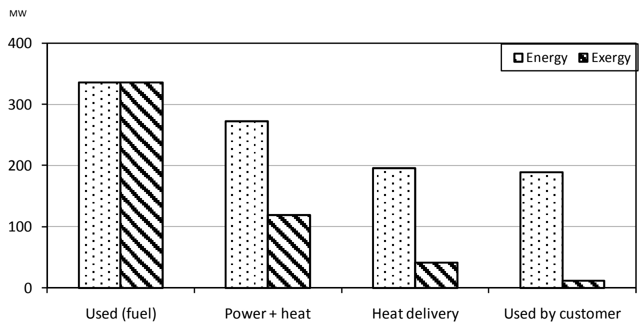


Figure 11: Total exergy flows from the energy gases produced at SSAB imported into the CHP plant LuleKraft and finally to the customers in the district heating Luleå Energi.

2.4 Exergy for the Luleå energy system

Figure 12 shows a Sankey diagram of all the different exergy flows in the Luleå energy system.

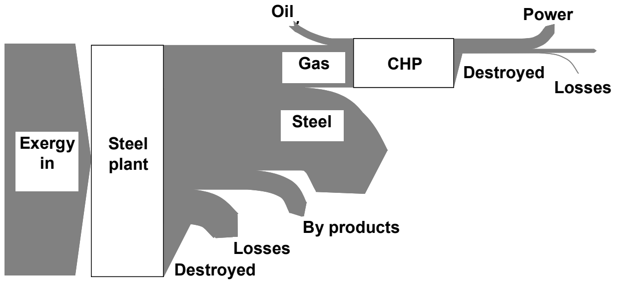


Figure 12: Sankey diagram of the exergy flows within the Luleå energy system.

The box "CHP" includes both production and distribution of heat and power. The high value of destruction in this box is because of the production of hot water with low exergy and high energy content. This is not inefficiency as it is delivered to a customer needing that product.

2.5 Sensitivity analysis

In Figure 13, we show how the reference state affects the exergy in the district heating system Luleå Energi. We compare having a constant reference temperature of 15 °C with a reference temperature equal to the outdoor temperature. During the cold period of the year, we see a somewhat larger difference between the two sets. At maximum, the difference is about 30 %. However, when making use of the exergy, the temperature would probably not be the outdoor temperature but probably rather 15-20 °C.

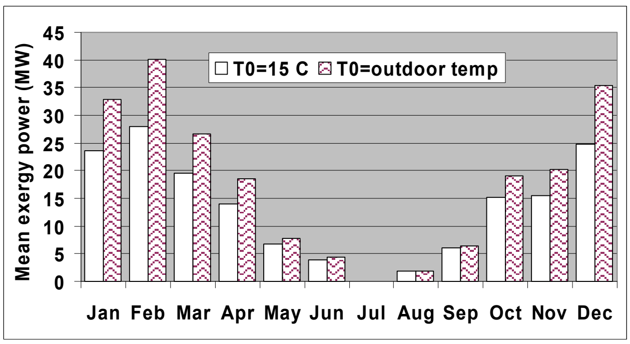


Figure 13: Sensitivity analysis for the district heating of the reference state taken at 15 °C as compared to using a reference state that is the outdoor temperature.

3 Conclusion

As can be seen in Figure 1, large amounts of exergy are used to produce products that mainly only need a moderate amount of exergy. This means that it would be interesting to find ways of making more high-value energy, such as electricity. This can be achieved by lowering the hot water temperature in the district heating system, using the released energy to produce more power. A more detailed study on this topic is planned.

4 Abbreviations

Symbol	Meaning	Unit
C_p	Spec. heat capacity, const. pressure	J
E	Exergy	J
E_{export}	Exported exergy	J
E_{import}	Imported exergy	J
E_{loss}	Lost exergy (leaves the system)	J
$E_{\text{destroyed}}$	Destroyed exergy	J
m	Mass	kg
η	Exergy thermal efficiency	
p	Pressure	Pa
p_0	Reference pressure	Pa
R	Specific gas constant	J/kg.K
ΔS	Entropy change	J/kg
T	Temperature	K
T_0	Reference temperature	K

5 Acknowledgements

We thank the Swedish energy agency for financing the project. We also acknowledge the students Erik Zetterberg, Marina Verbova and Sebastian Malmström for data collections and contributions during their master thesis work at SSAB. We also thank the companies involved for their help and collaboration: Luleå Energi, LuleKraft, and SSAB EMEA.

6 References

[1] Linnhoff, B.; Hindmarsh, E.: The Pinch Design Method for Heat-Exchanger Networks; Chemical Engineering Science 38 (1983) 745-763

[2] Linnhoff, B.; Smith, R.: The Pinch Principle; Mech. Eng. 110 (1988) 70-73

[3] Linnhoff, B.: Pinch Analysis - a State-Of-The-Art Overview; Chemical Engineering Research & Design 71 (1993) 503-522

[4] Gibbs, J. W.: On the Equilibrium of Heterogeneous Substances; Trans. Conn. Acad. III (1873)

[5] Wall, G.: Exergy - A Useful Concept; PhD Thesis, (1986)

[6] Wall, G.: Exergy tools; Proceedings of the Institution of Mechanical Engineers Part A-Journal of Power and Energy 217 (2003) 125-136

[7] Nilsson, K.; Söderström, M.: Optimizing the Operating Strategy of a Pulp and Paper-Mill using the Mind Method; Energy 17 (1992) 945-953

[8] Zetterberg, L.: Flows of Energy and Exergy in the Steelmaking process at SSAB Luleå; Master's Thesis, Göteborg, (1989)

[9] Verbova, M.: Energy and Exergy flows in Steelmaking Processes at SSAB Strip Products Division in Luleå; Master Thesis 2007:080, (2007)

[10] Malmström, S.: Efficient use of waste energy in the steel industry; Master thesis 2009:110, Luleå, (2009)

[11] Grip, C.; Dahl, J.; Söderström, M.: Exergy as a means for process integration in integrated steel plants and process industries; Stahl Und Eisen 129 (2009) S2-S8

[12] Saidur, R.; Ahamed, J. U.; Masjuki, H. H.: Energy, exergy and economic analysis of industrial boilers; Energy Policy 38 (2010) 2188-2197