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Techno-Economic Analysis of Low Temperature Waste Heat Recovery and Utilization at an Integrated Steel Plant in Sweden

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Energy consumption and CO_2 emissions is an ever-present issue for energy intensive industries, such as the steel industry. The work for reducing the environmental impact is a strong interest among the governments in Europe and the 20-20-20 targets, decided by the EU, set the targets for the year 2020 to increase energy efficiency by 20 %, reduce greenhouse gas emissions by 20 %, and increase the use of renewable energy to 20 %. It is therefore important for the steel industry, and other industries, to continuously be working on development of concepts for decreasing the environmental impact, which are also financially viable.
This paper presents the work that has been conducted in order to evaluate the potential benefits regarding energy- & cost saving and CO_2 mitigation, when recovering and utilizing low temperature waste heat at an integrated steel plant in Sweden, SSAB EMEA Luleå. In order to achieve a holistic overview of the plant a process integration approach is applied to evaluate the effects that occur when applying technologies for waste heat recovery. The results indicate a potential for energy saving of 1.9 %, and a corresponding CO_2 mitigation potential of 1.5 %. The calculated payback time for the applied waste heat recovery concepts, which is based on specific methods and economic assumptions, range between 1.5 – 7.0 y.

1. Introduction

Steel production is an energy intensive industry; in Sweden, the steel industry is the second largest energy consuming industry, and accounts for 18 % of the energy use by the industry sector. According to the World Steel Association, the specific energy consumption for steel production has been reduced by 50% since 1975. The increased development and energy efficiency improvement has resulted in that many steel sites are operating with high energy awareness and close to the limits of which the production is possible to be conducted, and further energy efficiency improvements would thus require new technology implementation, which often is associated with high development and investment costs. The concept of reusing low temperature waste heat (LTH) is therefore a concept which might be an economically viable alternative to further decrease the steel industry’s primary energy consumption and environmental impact.
The concept of reusing by-products is not new to the steel industry in Sweden, as the integrated steel plants are utilizing energy rich process gases for producing electrical power and district heating for nearby municipalities, and recycling by-product materials in order to decrease landfill. However, the utilization of LTH is not of frequent occurrence.
The concept of utilization of waste heat stream occurring in different industries has previously been presented in several papers: low grade heat recovery within the food industry Ireland was presented by Semkov et al. (2013), Bendig et al. (2012) presented an approach to defining the potential of useable waste heat in industrial processes using exergy pinch methods, Etemoglu (2012) examines a procedure in order to assess the performance of a combined heat and power plant (CHP) when utilizing low temperature waste heat, electrical power production through industrial waste heat recovery was presented by Karellas et al. (2012).

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1.1 SSAB EMEA Luleå

SSAB Luleå is an integrated steel plant situated in the municipality of Luleå, in the north of Sweden. The production is 100% pellet based and the main process product chain consist of coke plant, blast furnace, steel shop and continuous casting, with auxiliary process such as lime kiln, oxygen plant and power plant. The final product from the site is steel slabs, which are either sold or sent for further treatment at other SSAB EMEA production sites. The annual production is around 2.0 Mt slabs. During the production of the slabs, energy containing process gases are produced at coke plant (COG), blast furnace (BFG) and steel shop (BOFG). The gases are utilized in various processes at the site, see Figure 1.
The surplus of the process gases is utilized in the CHP, which produces district heating for the municipality, process steam and drying gases for nearby industries, and electrical power.

1.2 Purpose

The purpose of the work presented in this paper is to evaluate the potential for energy saving through recovery and utilization of low temperature waste heat occurring at a Swedish steel plant. The evaluation is carried out through techno-economic system analysis of the effects and benefits from utilization of low temperature waste heat.

2. Method

2.1 Approach

The work is based on mathematical programming and utilizes a Mixed Integer Linear Programming (MILP) approach to create the system model for the steel plant and process units. The system model is created in the in-house software reMIND, which is a graphical modelling interface and based on the MIND method (Method for analysis of INDustrial systems). The reMIND software has previously been used in order to describe and perform system analysis at industries such as steel sites (Ryman et al., 2008), kraft and pulp mills (Jönsson et al., 2008), and district heating systems (Olofsson et al., 2013). A commercial solver, CPLEX, is used to optimize the results from the system model; Microsoft Excel is then used for post processing of the results. Calculation and determination of blast furnace properties are carried out in a spreadsheet based blast furnace model, which has been presented by Hooey et al. (2010).

2.2 Low temperature waste heat

The included waste heat in the work is in the form of flue gases, liquid streams, and radiation. The low temperature heat streams (flue gas and liquid streams) included is limited to a maximum temperature of 350 °C. The minimum temperature limits for the waste heat streams, to which it can be lowered when recovering the sensible heat are 130 °C for flue gas and 70 °C for liquid streams. These are the temperature limits which are deemed feasible due to dew point limitations and technical limitations for current available technologies. The minimum temperature levels thus limit the amount of potentially recoverable waste heat.

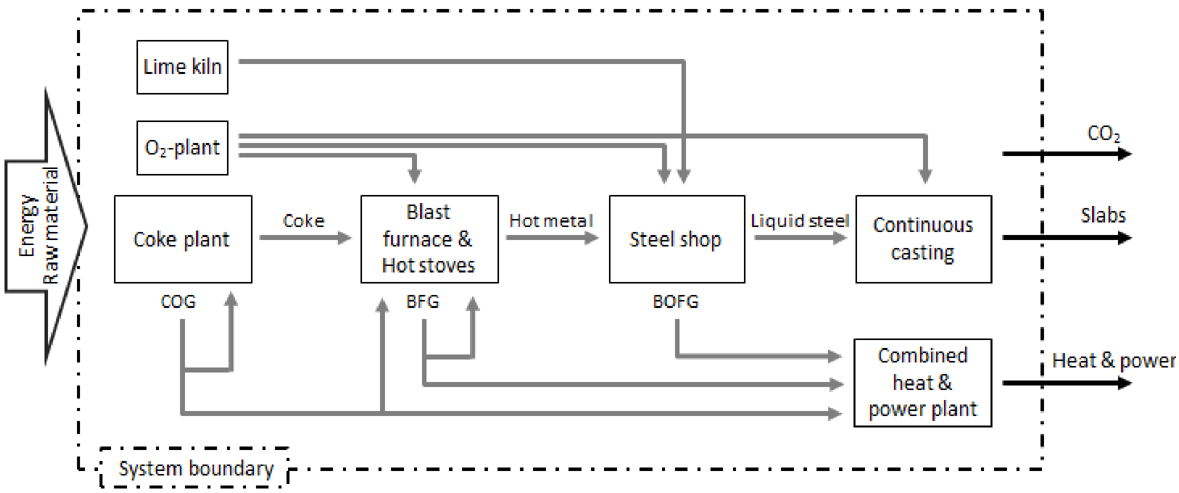

Figure 1: Systematic overview of main energy and material flows at SSAB EMEA Luleå

2.3 System boundaries

The system model of the steel site includes all the major process units as well as the auxiliary units. The process units are modelled with ingoing raw material and fuels, which are associated with energy content and corresponding CO_2 emission, see Table 1.

As previously mentioned, the steel site includes a CHP, which exports district heating and electrical power. For the work presented herein, the export of electrical power surplus to the power grid is viewed as a decrease of the total ingoing energy to the steel plant. The CO_2 emission factor for electric power is based on a Swedish power production mixture, which is heavily based on hydropower and nuclear power, and thus low in emissions.

2.4 Waste heat recovery technologies

The technologies considered in the system model are current best available technologies (BATs) for low temperature heat recovery, such as Organic Rankine Cycle (ORC), Wet Steam Turbine (WST), Coal Moisture Control (CMC), scrap preheating at steel shop, preheating of combustion air and gases, see Table 2. Hot water production from flue gases is included as a way of decreasing the amount of steam and hot water that is extracted from the steam turbine at the CHP, and thus allowing for a higher rate of electrical power production. The concept of extended steam recovery is applied when recovering sensible heat from hot process gases, which is generated at the steel shop during oxygen blowing.

2.5 Economic evaluation principle

The economic benefits when applying the waste heat recovery technologies are evaluated by assessing the energy and raw material savings when implementing the technology. The economic assessment is performed according to Net Present Value NPV method, with an assumed installation fee of 20 % of equipment cost and a yearly maintenance cost of 2 % of total investment cost, and a payback time for the investment can then be calculated.

3. Results

The objective of the system analysis is to minimize the energy use at the steel site by recovering and utilizing available LTH in the most efficient way. The presented economic evaluation is based on the energy optimization.

3.1 Inventory of low temperature waste heat

In order to be able to evaluate the potential for minimizing the energy consumption at the site, an inventory of the occurring low temperature waste heat streams was performed, see Figure 2.

Table 1: Energy content and corresponding CO_2 emission factors for included raw material and fuels

Fuel/Raw material	CO_2 emission (t/GJ)	Energy content (GJ/t)	CO_2 emission (t/t)
Iron ore pellet	-	-	-
Coking coal	2.64	0.089	29.8
External coke	3.74	0.092	40.9
Pulverized coal (PC)	2.92	0.103	28.2
Limestone	0.428	-	-
Oil	3.21	0.076	42.1
Electricity	-	0.020 t/MWh	-
By-products			
- Benzene	3.29	-	-
- Tar	3.35	-	-
- Sulphur	-	-	-

Table 2: Waste heat reuse technology options included at each process unit

Process unit	LTH reuse technologies included in the model
Coke plant	CMC, WST, ORC, Hot water production
Blast furnace	ORC, Preheating of combustion air & gases, Hot water production
Steel shop	Scrap preheating, Extended steam recovery

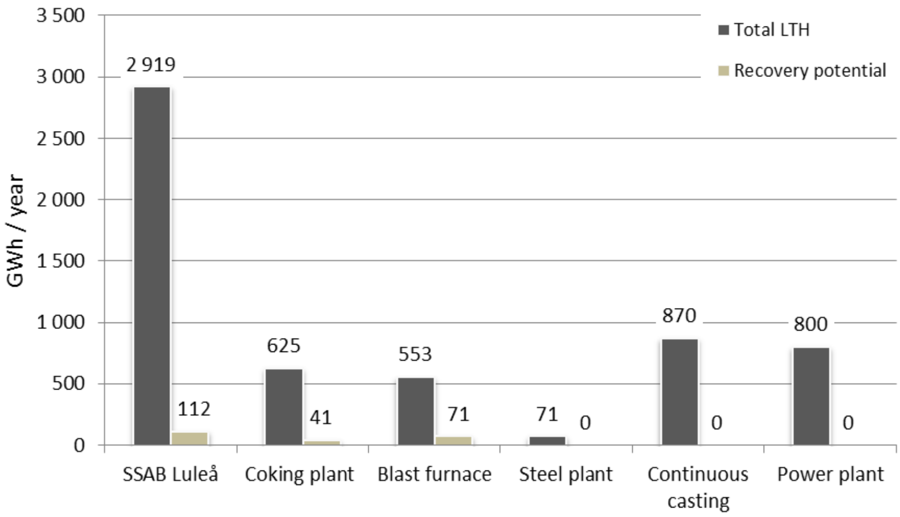

Figure 2: Inventory of low temperature heat at annual basis

As can be seen in Figure 2, two amounts of low temperature heat are presented. The amount labelled 'Total LTH' is calculated as the sensible heat present in the heat stream, with a reference temperature of 5 °C during winter periods and 15 °C during summer periods. The amount labelled 'Recovery potential' is the available sensible heat in the stream when considering the restricting temperature limits previously mentioned, 130 °C for gas and 70 °C for liquid streams. Radiation is included in 'Total LTH' but is deemed not possible to recover with commercially available BATs, and thus not included in 'Recovery potential'.

3.2 Energy optimization

The optimized results with the objective to minimize the energy consumption can be seen in Figure 3. As can be seen, the potential for energy saving amounts to 221 GWh/y (2.0 %). The majority of the potential energy saving (196 GWh/y) is attributed to reduced COG consumption at coke plant and hot stoves at blast furnace.

For a fully integrated steel plant, with hot rolling mill and other finishing processes, an increased availability of COG is usually used to replace consumption of external fossil fuel, such as oil, LPG, or natural gas. However for the case of SSAB EMEA Luleå, with a production route absent of rolling mill, the consumption of external fossil fuel is concentrated to the CHP, where oil is used to cover the demand of district heating to the municipality during cold winter periods. The saved amount of coke oven gas exceeds the yearly average oil consumption and thus there is still available coke oven gas to be utilized even when the oil consumption has been replaced; one alternative for utilization of the excess coke oven gas is to inject it in the blast furnace in order to reduce the consumption of reducing agents and fuel. For this work, two

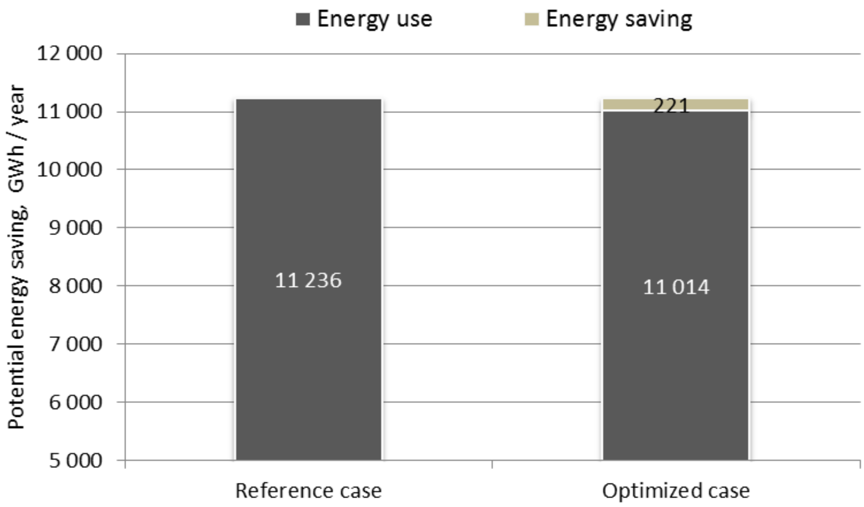

Figure 3: Potential energy saving from recovery of low temperature waste heat

objectives for injection of the excess coke oven gas in the blast furnace have been calculated: reducing coke consumption and reducing PC injection. The result of the calculation can be seen in Table 3. For both objectives, the injected amount of coke oven gas is calculated as the excess amount of gas when the oil consumption at the CHP has been replaced. The injection of coke oven gas will result in an increased generation of blast furnace gas, which is assumed to be utilized for increased electricity production at the CHP.

As can be seen the potential for reduced energy consumption for the two objective amounts to 213 GWh/y (1.9 %) and 191 GWh/y (1.7 %), with a corresponding CO_2 abatement potential of 55 kt/y (1.5 %) and 50 kt/y (1.3 %). The objectives present process-controlling challenges which affect the possibility for implementation of the concept; for instance, permeability of the reducing gases in the blast furnace is a factor which limits the possible reduction of coke rate. In this work, the concept of reducing coke rate at the blast furnace is not evaluated for economic feasibility.

3.3 Economic evaluation

As previously mentioned, the economic feasibility evaluation is based on the net present value-method. No cost information for scrap preheating is available and will thus not be included in the economic evaluation. The evaluated waste heat reuse concept can be seen in Table 4. For Alternative no. 2-4, it is implied that the saved amount of coke oven gas is first to be used for replacement of oil at the CHP. The calculated payback time can be seen in Figure 4.

As can be seen, the payback time ranges between 1.5 to 4.5 y with the highest payback time for the alternative which presents the highest energy saving potential, alternative no. 4, see Table 4.

4. Conclusions

As can be seen in Figure 2, there are considerable amounts of low temperature heat streams present at the steel site. However, the majority of streams occur in such a form (radiation) or in a temperature range that there are few, or none, commercially available technologies for recovery and utilization. For most steel

Table 3: Alternative for coke oven gas utilization in blast furnace

Objective	Reduced coke consumption	Reduced PC injection
Coke saving, kg/t hot metal	2.5	-
PC saving, kg/t hot metal	-	2.5
BFG generation increase, GJ/h	24.8	22.6
Total energy saving, GWh/y	213 (1.9 %)	191 (1.7 %)
Corresponding CO_2 abatement	55 (1.5 %)	50 (1.3 %)

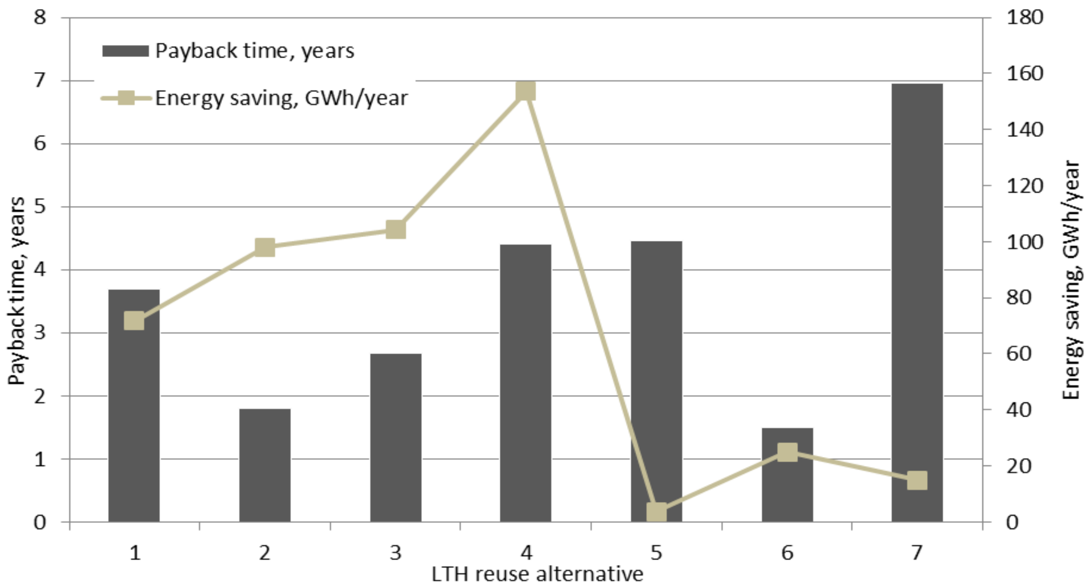

Figure 4: Calculated payback time for evaluated waste heat reuse concepts

Table 4: Evaluated waste heat reuse concepts

Waste heat reuse concept	Description
Alternative no. 1	Implementation of CMC at coke plant and replacement of oil with saved COG
Alternative no. 2	Implementation of combustion air and gas preheating at hot stoves. Excess COG is used for increased electricity production at power plant.
Alternative no. 3	Implementation of combustion air and gas preheating at hot stoves. Excess COG is injected in blast furnace for PC saving
Alternative no. 4	Implementation of CMC at coke plant and preheating of combustion air and gases at hot stoves. Excess COG is injected in blast furnace for PC saving
Alternative no. 5	Implementation of wet steam turbine at coke plant
Alternative no. 6	Increased recovery of steam at steel shop
Alternative no. 7	Implementation of ORC for utilization of all available LTH

plants, there are few streams that need to be heated with external fossil fuel and thus the possibility for extended heat exchangers network for the reduction of primary fuel is relatively small. However, the study shows that by focusing on reusing LTH internally and utilizing flue gases for heating and drying purposes there is a potential for reducing consumption of ingoing primary fuel. The utilization of heat-to-power technologies should only be considered as a final option, due to low efficiencies and high investment costs. The economic evaluation in this study is based on some assumptions and general simplifications; more in-depth evaluation needs to be performed before investments are made, as specific retrofitting cost and fluctuating fuel prices highly affect the economic feasibility of the LTH concepts.

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