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Options for the Swedish Steel Industry – Energy Efficiency Measures and Fuel Conversion

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ABSTRACT

The processes of iron and steel making are energy intensive and consume large quantities of electricity and fossil fuels. In order to meet future climate targets and energy prices, the iron and steel industry has to improve its energy and resource efficiency. For the iron and steel industry to utilize its energy resources more efficiently and at the same time reduce its CO_2 emissions a number of options are available. In this paper, opportunities for both integrated and scrap-based steel plants are presented and some of the options are electricity production, fuel conversion, methane reforming of coke oven gas and partnership in industrial symbiosis. The options are evaluated from a system perspective and more specific measures are reported for two Swedish case companies: SSAB Strip Products and Sandvik AB. The survey shows that both case companies have great potentials to reduce their CO_2 emissions.

Nomenclature

AOD	Argon Oxygen Decarburization
BOF	Basic Oxygen Furnace
CCS	Carbon Capture and Storage
CDQ	Coke Dry Quenching
CHP	Combined Heat and Power
DRI	Direct Reduced Iron

EAF Electric Arc Furnace

LHV Lower Heating Value

LPG Liquefied Petroleum Gas

ORC Organic Rankine Cycle

SNG Synthetic Natural Gas

TES Thermal Energy Storage

TPV Thermophotovoltaic

TRT Top Pressure Recovery Turbine

1 Introduction

The threat of rising energy prices, increased competition for raw materials and the environmental problem of global warming, are major concerns for industry today. The challenge is to mitigate the greenhouse gas emissions and to improve the energy and resource efficiency without reducing competitiveness. In Sweden in 2008, the total industrial energy use was 151 TWh or about 38% of the total Swedish energy demand. The iron and steel industry is the second largest industrial energy user, accounting for 15 % of the total industrial energy use in Sweden. [1] Furthermore, the iron and steel industry consumes large quantities of fossil coal as a reducing agent and as fuel, which result in significant CO_2 emissions. In 2008, carbon dioxide emissions from the iron and steel industry in Sweden totalled 6.6 million tonnes or 33% of the total industrial CO_2 emissions [2]. Consequently, it is of great concern that the steel producing sector reviews its energy use in order to meet future climate targets and energy prices.

Though the best performing steel plants in the world are energy-efficient with regard to the production process, there are still opportunities to improve the reuse of excess energy flows. Several authors claim that a promising prospect for today’s industry, not least the iron and steel industry, is to utilize unexploited energy and material flows, for internal reuse or for external use [3, 4, 5].

Previous research has investigated options for the iron and steel industry with regard to energy efficiency measures and CO_2 emissions mitigation [6, 7, 8, 9]. However, there is a need to put these measures into a system perspective thus making it possible to evaluate the options in relation to each other.

2 Aim and limitations

The aim of this paper is to present opportunities for the iron and steel industry in Sweden to utilize its energy flows more efficiently and to substitute fossil fuels with renewable ones and hence become more climate neutral. Furthermore, the proposed measures are evaluated in relation to each other. Potential measures include the utilisation of outgoing energy-flows, changes in the composition of the incoming energy-flows and energy-related changes in the steelmaking process. Opportunities are presented for both integrated steel plants and scrap-based steel plants and more specified measures are reported for two Swedish case-companies; SSAB Strip Products which is an integrated steel plant, and Sandvik AB which is a scrap-based steel plant. This paper focuses on the iron and steel industry's energy-flows and possibilities to reuse excess energy and does not investigate the material flows and possibilities to utilize waste material. Moreover, economic aspects are not considered in the measures proposed.

In this paper, production of electricity from excess energy is considered to reduce the global CO_2 emissions by 918 $g/kWh_{electricity}$, with the assumption that this electricity would otherwise have been generated in coal condensing power plants.

3 Iron and steel industry

There are basically two paths for steelmaking: the iron ore based process (integrated steelmaking) and the scrap-based process (secondary steelmaking). In integrated steelmaking, iron ore, coke and limestone are charged into the blast furnace and heated. Due to the high temperature, iron oxides in the ore are converted into iron when carbon atoms from the coke combine with the oxygen atoms in the iron oxide. The liquid iron is then transported to a Basic Oxygen Furnace converter (BOF converter) where the carbon content is reduced and the iron becomes steel. This is performed by blowing oxygen under high pressure onto the surface of the molten iron. Thereafter, the crude steel is processed, with the addition of for example alloys. [10]

In secondary steelmaking, recycled steel is charged into an electric arc furnace (EAF) and melted. The liquid iron is then transported to a converter and principally, the process then follows the same route as the integrated steelmaking but the converter is often an Argon Oxygen Decarburization converter (AOD converter).

An alternative route for the production of iron from iron ore is a process called direct reduction. In this process, the iron oxides are reduced to iron in solid form at lower temperatures. Here, the reducing agent is a gas mixture comprising mainly hydrogen gas and carbon monoxide produced from natural gas or coal. Direct Reduced Iron (DRI) can replace scrap in scrap-based steelmaking. [11] Figure 1 shows a simplified process chart for the steelmaking processes.

4 Energy use in the iron and steel industry

In Sweden, the iron and steel industry’s primary energy sources are coal, coke and electricity. Coke is used in the reduction process, i.e. the blast furnace, and some of the coke can be substituted with pulverised coal, oil, tar etc. Electricity is used for melting scrap in the EAF, heating and heat-treatment in the rolling mill and running the rolling mill's engines. Besides electricity, liquefied petroleum gas (LPG) and oil are used in the steel industry's heating furnaces. On the Swedish west coast, where natural gas is available, a few steel producers use natural gas instead of oil. [11]

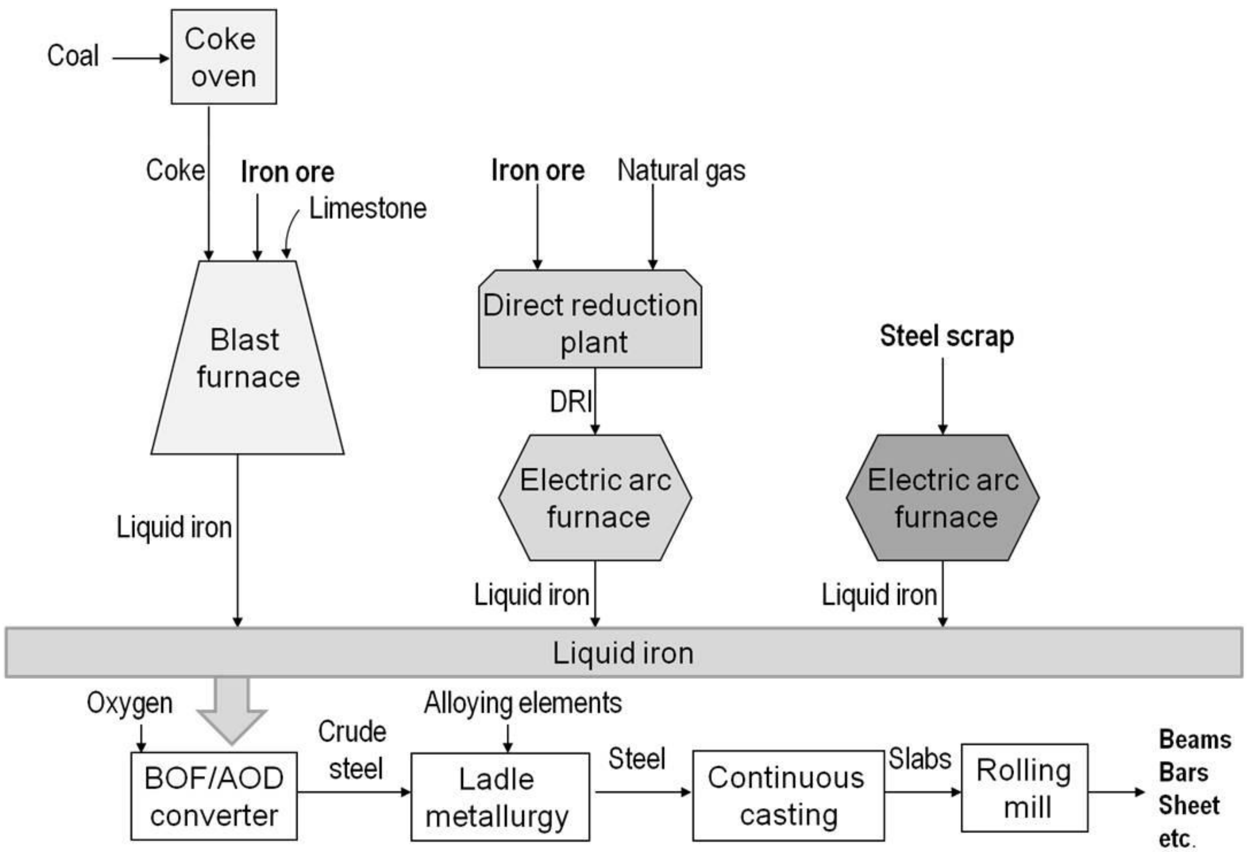

Figure 1 *A simplified process chart for the steelmaking processes. Iron-ore-based steelmaking converts iron oxides into metallic iron in the blast furnace process, which is the most conventional method, or in the direct reduction process. Secondary steelmaking produces steel from scrap and the melting process is most often carried out in an electric arc furnace.*

When iron oxide is converted into metallic iron, chemical energy is stored in the product and the reducing agent is therefore included in the energy-balance. Hence, an integrated steel plant's specific energy-use, i.e. energy used per tonne of produced steel, is five times that of a scrap-based steel plant. [11]

The processes of steelmaking generate large quantities of surplus energy; the integrated steel plant generates energy-rich process gases (blast furnace gas, BOF gas, coke oven gas) and heat of different energy qualities. The excess heat generated from the processes are for example hot material, hot flue gases, steam from cooling processes and cooling water of low temperature [12]. In contrast to integrated steelmaking, secondary steelmaking does not generate considerable amounts of energy-rich process gases, but merely excess heat.

5 Case companies

The case companies in this study are SSAB Strip Products and Sandvik AB. SSAB Strip Products is an integrated steel plant and has operations in Luleå, Borlänge and Finspång in Sweden. In Luleå there are a coking plant, a blast furnace and steelworks. Slabs are shipped every day from Luleå to Borlänge where the company's rolling mills and coating plants are located. In 2008, SSAB Strip Products produced around 2.2 million tonnes of steel slabs and 750,000 tonnes of coke [13].

SSAB Strip Products is the largest producer of sheet steel in Scandinavia and has a leading position in Europe in the development and manufacturing of high-strength steel grades.

Sandvik AB has its production facilities in Sandviken in central Sweden. Sandvik is a scrap-based steel plant and the steel production is conducted in an electric arc furnace, an AOD converter and a ladle furnace, each with a charge-weight of 75 tonnes. In 2008, the company produced 258,000 tonnes of steel slabs and 87,000 tonnes of refined steel products. Sandvik has a world-leading position in three core areas: i) cemented-carbide and high-speed steel tools for metalworking applications and blanks and components made of cemented carbide and other hard materials, ii) machinery, equipment and tools for rock-excavation and iii) stainless and high-alloy steels, special metals, resistance materials and process systems. [14]

In 2008, the CO_2 emissions from SSAB Strip Products and Sandvik AB totalled 1.3 million tonnes[1] and 113,000 tonnes respectively [13, 14].

6 Energy efficiency and fuel conversion options

6.1 Electricity production

Surplus combustible process gases from the integrated steel plant are potential fuels in a combined heat and power (CHP) plant for the generation of electricity and district heating. However, the low heating value of blast furnace gas infers that the gas is mixed with for example coke oven gas in order to get a sufficient energy content for power production.

Another power generating application is Top Pressure Recovery Turbine (TRT) technology which uses the heat and pressure from the blast furnace gas to generate electricity in a gas turbine. Without the TRT the blast furnace gas has to go through other processes to decrease its pressure and temperature. Approximately 40 to 60 kWh electricity/tonne of iron can be generated by TRT [15]. Using the TRT with a dry dedusting method, the generated electricity may supply 30 % of the electricity used by the air blowers of the blast furnace [5]. Currently, there are installations of TRT equipment at major steel mills worldwide.

Furthermore, low-grade excess heat generated from integrated and secondary steelmaking can be used to produce electricity. The Organic Rankine Cycle (ORC) and the Kalina Cycle are

[1] CO_2 emissions originating from process gases exported from SSAB Strip Products to external users are subtracted.

thermodynamic cycles, based on the Rankine cycle, for converting thermal energy to electrical energy. The ORC uses an organic working fluid and the Kalina cycle uses a mixture of water and ammonia. Vaporisation temperatures for suitable working fluids range between 30 and 300°C. Reported electricity efficiencies for the ORC and the Kalina cycle are 8.1% and 12.8% respectively. Both the ORC and the Kalina cycle are commercial technologies and used for geothermal and waste heat electricity production worldwide. [3]

The steelmaking process generates heat radiation, which can be recovered by Thermophotovoltaic (TPV) methods. Principally, the heat radiation is absorbed by photovoltaic diode cells which convert it to electricity. The operation temperature range from 1000 to 1800°C and potential waste heat recovery applications are product, flue gas and wall heat recovery. Products from the iron and steel industry suitable for TPV conversion are blast furnace slag and slabs from the continuous casting. TPV conversion of hot flue gases from for example a blast furnace can utilize temperatures down to 1000°C and the remaining heat is subsequently availably for other heat recovery methods. Potential applications for wall heat recovery with TPV systems are on water cooled areas in a blast furnace or a reactor for ladle metallurgy and the water cooled panels on the roof and sides of an EAF. A case study of an 80 tonne EAF showed that about 4% of the total energy input could be recovered as electricity by implementation of a TPV heat recovery system. [16]

6.2 Coke Dry Quenching (CDQ)

In a coke plant, coal is heated to approximately 1,000°C in a battery of airtight ovens and converted to coke. Conventionally, the coke is then cooled with water, which is sprayed over the coke in quenching towers. Unfortunately there are considerable CO_2 emissions and thermal energy is lost in the quenching process. However, there are alternative cooling procedures where the coke is cooled with an inert gas in dry cooling plants. The coke dry quenching (CDQ) process allows recovery of the thermal energy in the quenching gas by production of steam and electricity, district heating and preheating of coking coal [17]. A CDQ installation can recover approximately 400-500 kg of high pressure and high temperature steam per tonne of coke. This is equivalent to 220-330 kWh steam/tonne of coke [15]. About 35% of the total energy input in the coke ovens can be reused by introducing the dry quenching technology [5]. In addition to the energy savings, the dry quenching of coke reduces the CO_2 emissions.

6.3 Methane reforming of coke oven gas

Syngas is a gas mixture of CO and H_2 and a valuable feedstock for production of e.g. Fischer Tropsch diesel, methanol and ammonia. The main route for syngas production is the methane reforming process, where methane is converted into CO and H_2. Traditionally, syngas is produced from reformed natural gas, but theoretically, coke oven gas could be a complementary feedstock, as it consists of approximately 25vol% CH_4 and 60vol% H_2 [18, 19]. Implementation of this technology could reduce the emissions of CH_4 and CO_2 from the integrated steel mills. Reported conversion efficiencies for the production of methanol from coke oven gas, via methane reforming, are between 56.2% and 67.2% [19].

6.4 Fuel conversion

Coke is the primary reducing agent and fuel in the integrated steel plant. In addition, coke acts as a physical support material in the blast furnace and ensures correct gas permeability, the correct process temperature and correct process drainage. Due to its physical properties it is not possible to replace all the coke in large blast furnaces [20]. However, smaller blast furnaces can be charged entirely with charcoal and in Brazil, there are four large companies that produce steel in blast furnaces using mainly charcoal as reducing agent. [21]

In large blast furnaces, some of the coke can be substituted with an alternative reducing agent, and there are several iron and steel companies that replace some of the coke in the blast furnace with the injection of, for example, pulverised coal[2], fuel oil[3], natural gas[4] or plastics[5]. If biomass is considered to be carbon dioxide-neutral, the replacement of some of the coke with charcoal, methane, carbon monoxide, hydrogen, ethanol and methanol produced from biomass would decrease the carbon dioxide load from the blast furnace processes. However, caution has to be taken when injecting alternative reducing agents, as this may result in a lower flame temperature and could lead to increased coke consumption if proper process temperatures are to be maintained [22]. Unfortunately, biomass has a low mass and energy density and consequently, the amount of biomass required to replace the coke is high.

Today, the steelmaking industry uses fossil fuels, such as oil, LPG and natural gas in the heating furnaces. In order to reduce the CO_2 emissions, these fossil fuels can be substituted with biomass. However, in order to improve the heating value of the biomass it has to be converted into for example synthetic natural gas (SNG) or biogas before it is burned in the furnaces. This conversion step can be performed through gasification [23] or anaerobic digestion by microorganisms [24]. Researchers believe that it will be possible to substitute 10% of the LPG in the Swedish heating furnaces with gas from high temperature gasification of biomass and waste by 2020 [25].

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[2] SSAB Strip Products
[3] Rautauruukki
[4] Donetsk Metallurgical Plant
[5] NKK Keihin Works

6.5 DRI plant as a complement

The EAF at the secondary steel plant can be charged with steel scrap or DRI or a mixture of both. Where steel scrap is on shortage, an option is to integrate a DRI plant with the secondary steel plant. MIDREX® presents an industrial concept where a secondary steel plant, an oxygen plant, a gasification plant, a DRI plant and an electric power plant are combined [26], see Figure 2. This concept provides opportunities for installations of CCS.

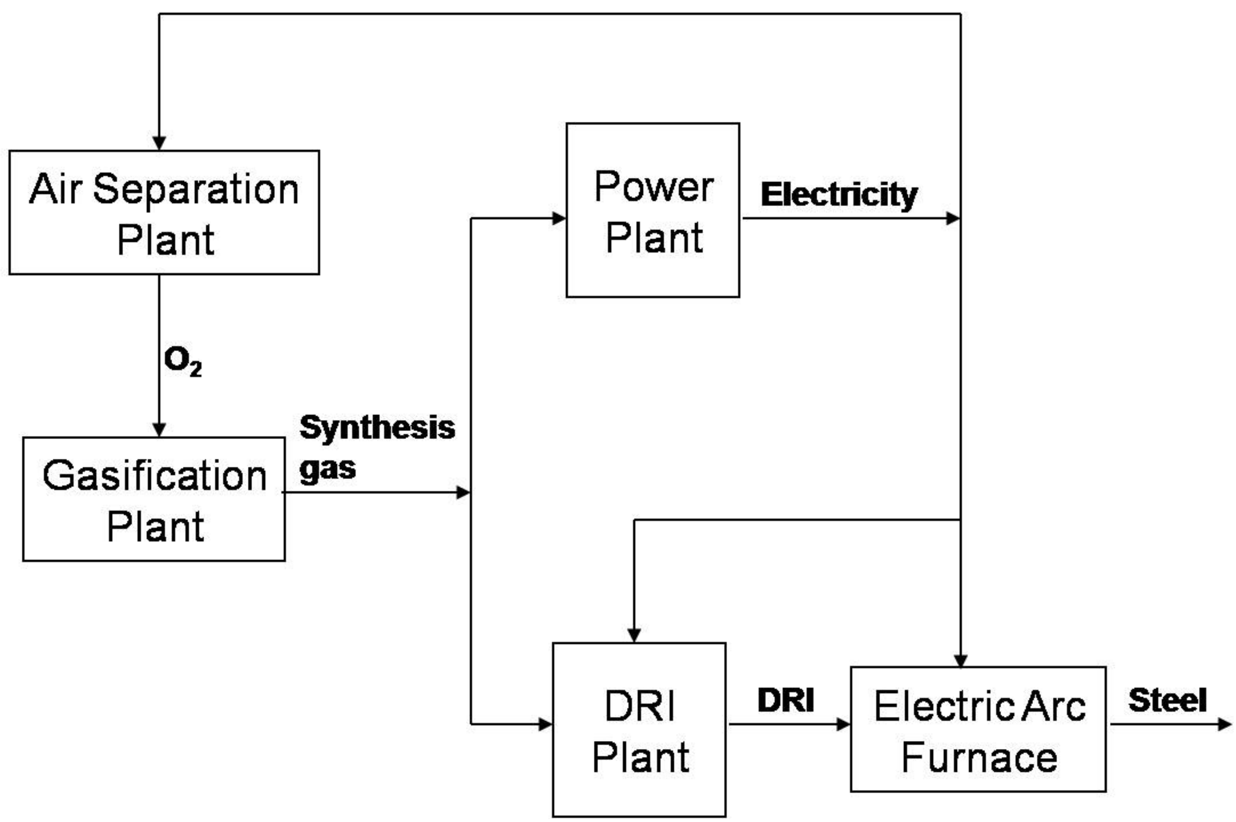

Figure 2 *Integration of a gasification plant with a DRI plant and a power plant [26].*

Furthermore, an integrated steel plant can use a DRI plant as a complement to the blast furnace process. The DRI can be charged into the blast furnace in order to improve the iron content or into the BOF substituting the scrap conventionally used as cooling agent. Additionally, coke oven gas from the existing coke ovens can be used as a reducing agent in the DRI process.

With an annual production of less than one million tonnes of steel, the investment costs are less for a DRI plant than for a blast furnace. Moreover, a natural gas-based DRI/EAF steelmaking process has approximately 40% less total CO_2 emissions compared to a blast furnace/BOF process [27]. Today, DRI plants are built where there are low prices on natural gas.

6.6 Hot water from cooling beds

Convective heat and radiation heat from cooling beds can be recovered and utilized to produce hot water. The hot water can be used as hot tap water and for space heating at the steel mill or sold to a district heating company. Convective heat can be recovered in a heat-exchanger and radiation heat can be recovered by collectors such as water-filled copper pipes or solar-heat panels. A study indicated that about 40% of the heat in processed steel can be recovered as hot water, if convective and radiation heat recovery are combined at the same cooling bed [28].

6.7 Industrial symbiosis

An industrial symbiosis is defined as a relationship in which at least two unrelated industries exchange materials, water, energy or information in a mutually beneficial way. The goal of the co-operation is a collective benefit greater than the sum of the individual benefits that could be achieved without any symbiotic co-operation. [29]

There is great potential for the iron and steel industry to collaborate in an industrial symbiosis in which excess energy and materials from the steel industry can be utilized by other facilities and the steel plant can import for example fuel and reducing agents. As mentioned before, the excess energy flows from the steel industry consist of a large range of energy qualities. Hence, there are options for a variety of energy-related symbiotic partnerships.

6.8 *Thermal Energy Storage (TES)*

One barrier for the utilization of industrial excess heat is a long distance between the producer and the consumer. One solution to this is to use Thermal Energy Storage (TES) systems and transport the heat by train, truck or boat. TES systems are currently under development and the energy storage technologies being investigated are [30, 31]:

- Sorption technology, where the energy is stored as sensible heat in a liquid or solid medium. The storage capacity is 180-400 kWh/tonne.
- Latent heat storage, where a Phase Change Material (PCM) undergoes a phase change, for example from solid to liquid phase, when energy is stored in the material. The potential storage capacity is 80-160 kWh/m^3.
- Storage as chemical energy or products in a reversible chemical reaction with a storage capacity of 30-1000 kWh/tonne.

To date, the research on storage materials has focused mainly on sensible and latent heat storage systems. Comparative studies on PCM and sensible heat storage have shown that storage in PCM results in a significantly reduced storage volume compared to sensible heat storage. Moreover, most of the studies have been performed within a temperature range of 0-60°C, suitable for domestic heating and cooling. However, there are several PCM that are suitable for applications at higher temperatures and currently there are over 100 commercial PCM, available with melting/solidifying temperature range from -118°C to 164°C. [30]

7 Summary and evaluation of proposed measures

The list of energy efficiency measures and fuel conversion options for the iron and steel industry is long and this paper does not investigate all of them. Table 1 summarises the energy efficiency and fuel conversion options described in this paper and their applicability in integrated and secondary steelmaking.

Table 1 Energy efficiency and fuel conversion options for integrated and scrap-based steel plants.

Measure	Integrated steel plant	Scrap-based steel plant	Resource	Product/Effect	Conversion efficiency
Process gases for CHP production	X		COG, BFG, BOFG[a]	Electricity/Steam/District heating	28% electricity efficiency, 71% total efficiency, α=0.66 [b]
ORC/Kalina cycle	X	X	Heat	Electricity	8.1% / 12.8%
TPV	X	X	Infrared radiation	Electricity	4%
TRT	X		Heat and pressure	Electricity	40-60 kWh electricity/tonne of iron
CDQ	X		Heat	CO_2 emission mitigation, heat recovery	35% heat recovery
Methane reforming of coke oven gas	X		COG[a]	Syngas (Methanol)	56.2-67.2% methanol conversion efficiency
Biomass as reducing agent	X		Charcoal, biomethane etc.	CO_2 emission mitigation	N/A
Biomass as fuel in heating furnaces	X	X	SNG from biomass	CO_2 emission mitigation	N/A
DRI production	X	X	Iron ore, syngas/COG[a]	DRI	N/A
TES	X	X	Heat	Heat	N/A
Hot water from cooling beds	X	X	Heat	Hot tap water/District heating	40% of the heat in processed steel
Industrial symbiosis	X	X	Energy, materials, water, information	Efficient use of resources	N/A

[a]COG=Coke oven gas, BFG= Blast furnace gas, BOFG= Basic oxygen furnace gas.
[b]Energy in-put in this example is 12% COG, 68% BFG, 17% BOFG and 3% oil [34].

Even if the conversion efficiencies of ORC and Kalina cycle methods are low, the incentive for implementation is high due to their potential of converting vast amounts of low-grade energy into high-grade energy. Similarly, the low conversion efficiency of TPV methods is not a barrier for implementation and the technology is currently under development, indicating that the conversion efficiency may be improved.

The implementation of one technology may affect the implementation potential of another. For example, the methane reforming of coke oven gas implies that there is less coke oven gas for in-plant use, CHP production or use as reducing agent in a DRI plant. However, a DRI plant with syngas as reducing agent does not affect the potential of the other options. Moreover, installations of TPV systems on the roofs and walls of furnaces reduce the amounts of cooling water which can be used for power production in an ORC or a Kalina cycle or delivered to district heating systems. Furthermore, power production from low-grade heat with an ORC/Kalina cycle reduces the load of heat available for district heating, TES storage technologies and industrial symbiosis. Table 2 summarises how the potential of one option is affected by the implementation of another. However, methane reforming of coke oven gas, conversion of heat radiation from industrial processes into electricity by TPV methods, gasification of biomass into SNG, TES systems and production of hot water from cooling beds are technologies still under development and not yet commercially available. Therefore, measures which have a high compatibility and a high probability for near future implementation in integrated steel plants are CDQ with heat recovery, process gases for CHP production and electricity production with ORC and TRT. Secondary steel plants have great near future potentials to produce electricity with ORC installations. Additionally, the delivery of excess heat to district heating systems and taking up partnerships in an industrial symbiosis are at present interesting opportunities for both integrated and secondary steel plants.

Table 2 A summary of how the potential of an option is affected by the implementation of another. + The potential is increased or not affected. - The potential is reduced. ± The potential is reduced or not affected depending on the implementation configuration.

	Process gases for CHP production	ORC/Kalina cycle	TPV	TRT	CDQ	Methane reforming of coke oven gas	Biomass as reducing agent	Biomass in heating furnaces	DRI production	TES	Hot water from cooling beds	Industrial symbiosis
Process gases for CHP production		+	+	+	+	-	+	+	±	+	+	+
ORC/Kalina cycle	+		±	+	+	+	+	+	+	-	±	±
TPV	+	±		+	+	+	+	+	+	-	-	+
TRT	+	+	+		+	+	+	+	+	+	+	+
CDQ	+	+	+	+		+	+	+	+	+	+	+
Methane reforming of coke oven gas	-	+	+	+	+		+	+	±	+	+	+
Biomass as reducing agent	+	+	+	+	+	+		+	+	+	+	+
Biomass in heating furnaces	+	+	+	+	+	+	+		+	+	+	+
DRI production	±	+	+	+	+	±	+	+		+	+	+
TES	+	-	-	+	+	+	+	+	+		±	+
Hot water from cooling beds	+	±	-	+	+	+	+	+	+	±		+
Industrial symbiosis	+	±	+	+	+	+	+	+	+	+	+	

8 Opportunities for the studied cases

8.1 SSAB Strip Products

At SSAB Strip Products 93% of the ingoing energy is provided by coal and 20% of the total energy demand is covered by the recirculation of process gases [12]. Because the company is not equipped with a rolling mill at the site, where the process gases can be fired as fuel in heating furnaces, there is an additional surplus of these gases. Today, some of the excess gases are used as fuel for the production of electricity, steam and district heating at the CHP plant LuleKraft AB. The CHP plant has 71% total efficiency and 28% electricity efficiency[6]. In 2008, 4,670 GWh of process gases were produced at SSAB Strip Products; 43% of this energy was reused for in-house processes, 50% was sold to external consumers and the rest was flared [13].

A promising option for SSAB Strip Products is to generate electricity and in addition to burning process gases in a CHP plant for heat and power production, there are several technologies that can be used; ORC/Kalina cycle, TRT and TPV. Installation of TRT at SSAB Strip Products would generate approximately 90-130 GWh electricity/year[7]. This corresponds to a reduction in global CO_2 emissions by approximately 80,000-120,000 tonnes/year. Moreover, SSAB in Luleå uses a traditional wet quenching method in the coke production, but by switching to a CDQ method approximately 300,000-370,000 tonnes/year of high pressure and high temperature steam could be recovered. Connection of a steam turbine could generate approximately 90-110 GWh/year of electricity [32, 33], which would lead to a reduction in global emissions of CO_2 by approximately 80,000-100,000 tonnes/year.

[6] Energy in-put is 12% coke oven gas, 68% blast furnace gas, 17% BOF gas and 3% oil [34].
[7] The estimation is based on the production rate in 2008.

Another option for SSAB Strip Products is to reform coke oven gas into syngas. A case study of the steel mill in Luleå analysed the potential of methanol production from reformed coke oven gas. The study concluded that in the future, approximately 400 GWh of coke oven gas per year would be available for methanol production at SSAB Strip Products, yielding 300 GWh of methanol; with the prerequisite that the CHP plant operates on a gas-mixture of BOF gas and blast furnace gas. The methanol can be used as transportation fuel or be sent to Borlänge and used as fuel in the company's rolling mill. [19] Edberg and Kärsrud [35, 36] believe however, that it is more energy-efficient to use the energy-rich process gases from steel production in-house at SSAB Strip Products, than to export the gases. They regard the ULCOS' Top Gas Recycling Blast Furnace[8] as a future option for steelmaking at SSAB Strip Products. This blast furnace produces less excess energy, since the off-gases are recycled back to the blast furnace. Moreover, this kind of blast furnace in combination with CCS has a great potential to reduce the CO_2 emissions from the steel plant.

Several options for industrial symbiosis are possible for SSAB Strip Products. There is for example, an option for collaboration between SSAB Strip Products and pulp and paper industries, where gasified biomass residues from the pulp mill and reformed coke oven gas can be jointly used as feedstock for the production of transportation fuel. Alternatively, the syngas can be used as a reducing agent in the blast furnace or in a future DRI plant. Furthermore, excess heat from SSAB Strip products can be recovered and utilized to produce district heating. There is a large heat capacity but unfortunately, the development of the district heating network in Luleå is limited by municipal borders, and none of the neighbouring municipalities have shown any interest in district heating co-operations [35]. Therefore, one option is to use TES technologies

[8] For more information about the Top Gas Recycling Blast Furnace visit http://www.ulcos.org/en/index.php.

and transport some of the heat to district heating consumers where conventional district heating is not available.

Another option is to use steam produced at the CHP plant in facilities where there is a demand for medium- and high-pressure steam, such as an ethanol plant[9]. This increases the CHP plant's underlying heat load and is most favourable in the summertime when the demand for district heating is low.

In order to reduce its CO_2 emissions, SSAB Strip Products can substitute some of its fossil fuels with biomass. SSAB Strip Products uses approximately 0.3 million tonnes of injection coal per year in the blast furnace process and substitution of the injection coal with pulverised charcoal would require about 0.9 million[10] tonnes of dry wood per year. If the charcoal is considered carbon neutral, a total replacement of the fossil injection coal with charcoal would reduce the emissions of CO_2 from SSAB Strip Products by approximately 760,000 tonnes/year. Another fuel conversion option is to substitute some of the injection coal with biomethane. According to Edberg [35] it is possible to replace approximately one-third of the weight of the injection coal with methane without adding more coke. Accordingly, SSAB Strip Products would demand approximately 134 million[11] Nm^3 of methane to substitute one-third of the weight of the injection coal with methane. The production of this amount of methane, would require mesophilic

[9] Information about ethanol production can be found in [37].
[10] Calculations were based upon a biomass-carbonisation kiln with a weight-basis yield of about 37%,
[11] The coke replacement ratios of natural gas and coal powder are 0.8 kg coke/Nm^3 CH_4 [38] and between 0.5 and 0.99 kg coke/kg coal [22] respectively.

anaerobic digestion of about 1.1 million[12] tonnes of organic waste per year or gasification of 0.5 million[13] tonnes of dry wood per year.

In summary, measures that can be implemented concurrently at SSAB Strip products are methanol production from coke oven gas, CHP production with blast furnace and BOF gas as fuel, CDQ with heat recovery, electricity production with TRT, substitution of injection coal with charcoal, export of steam to other facilities and recovery of heat for district heating.

8.2 Sandvik AB

Sixty-two percent of Sandvik's ingoing energy is electricity and around 26% is LPG. The electricity is mainly used for steel production and rolling processes and the LPG is chiefly used as fuel in heating furnaces. Moreover, heat in flue gases from some of the heating furnaces is recovered in waste-heat boilers. [14]

Today, Sandvik is not a supplier of heat to the district heating system in Sandviken, but imports district heating from the system for some of its space heating. The remaining demand for space heating is covered by steam from steam-boilers at Sandvik. It would be advantageous for Sandvik to deliver excess heat to SEAB, the district heating distributer in Sandviken, and at the same time convert all of its space heating to district heating.

In a longer time perspective, the LPG, which is used as fuel in the heating furnaces, can be substituted with synthetic natural gas (SNG) produced from gasified biomass. In 2008, Sandvik used 290 GWh of LPG, whereof approximately 98% was used in heating and heat-treatment

[12] In this calculation, the biogas production capacity of the mesophilic reactor at Linköping Biogas in Linköping has been used. Linköping Biogas treats 55,000 tonnes of organic waste per year and has a production of 10 million Nm^3 of raw biogas with a methane concentration of 60-70%. [39]

[13] In this calculation synthetic natural gas (SNG) is equalised with methane. A gasification plants with a biomass to SNG conversion efficiency of 60% is used. LHV of methane and dry wood are 11.04 kWh/Nm^3 and 5 MWh/tonne respectively.

furnaces. A substitution of the LPG used in heating and heat-treatment furnaces requires about 26 million Nm^3 of SNG per year, corresponding to an annual biomass input to the gasifier[14] of 473 GWh. This would reduce the CO_2 emissions from Sandvik by approximately 70,000 tonnes/year if the biomass is considered CO_2 neutral. The SNG can be purchased from an external producer or produced in one or several plants owned by Sandvik.

Another opportunity for Sandvik is to generate electricity from excess heat, such as hot cooling-water, hot material and hot flue gases, for example by the use of ORC/Kalina cycle and TPV methods. The electricity produced can be exported to the grid or used for in-house processes. Furthermore, if some of the LPG is substituted with SNG, additional excess heat is generated from the gasification plant and can be used for power production.

In summary, a future feasible combination of measures for Sandvik is substitution of LPG with gasified biomass, hot water production from cooling beds, electricity production with ORC/Kalina cycle and integration with the district heating system.

9 Concluding discussion

There are more options for the recovery of excess energy flows from an integrated steel plant than from a scrap-based steel plant; steelmaking from iron ore is a more complex process than scrap-based steelmaking and hence there is a broader spectrum of energy flows in an integrated plant. The opportunities for Swedish integrated steel plants (IS) and scrap-based steel plants (SS) which are presented in this paper are:

- Electricity production by the use of:
    - Energy-rich process gases as fuel in a CHP plant. (IS)

[14] A gasification plant with a biomass to SNG conversion efficiency of 60% is used.

- Low-grade heat in an ORC or Kalina cycle. (IS, SS)
- Heat radiation converted by TPV technology. (IS, SS)
- Heat and pressure from the blast furnace off-gases in a TRT. (IS)

- CDQ with heat recovery. (IS)
- Methane reforming of coke oven gas for production of for example methanol. (IS)
- Biomass as reducing agent. (IS)
- Biomass as fuel in heating furnaces. (IS, SS)
- DRI production as a complement. (IS, SS)
- TES of heat for transport by truck train or boat. (IS, SS)
- Hot water from cooling beds. (IS, SS)
- Industrial symbiosis. (IS, SS)

High electricity prices may be a driving force for installations of technologies for power production in the steel industry. In Sweden, there are discussions about whether electricity generated from industrial excess energy should be regarded as environmentally friendly and hence have an option to qualify for electricity certificates[15]. Receiving electricity certificates would mean an additional economical driving force for power production from industrial excess energy.

Excess heat from integrated and scrap-based steel plants can be used for district heating which is either delivered directly to a district heating distributer by pipes or transported to district heating consumers by the use of TES technology. In recent years, there have been intensive discussions

[15] The Swedish electricity certificate system is a policy instrument to increase electricity production from renewable resources such as solar energy, wind, water and biomass. The producer of electricity from renewable resources receives a certificate for every produced MWh of electricity and then sells it to the electricity distributer. The system was introduced in 2003.

on the subject of the district heating market. There are opinions that demand an increased competition on the market and one way to achieve this is by introducing a third-party access to the district heating system. Third-party access for district heating systems would benefit industries, such as the iron and steel industry, with large amount of low-grade surplus heat suitable for domestic heating via district heating systems. Therefore it is important to consider existing industries when projecting expansion and new-construction of district heating systems. Issues of concern are the viability and the reliability of the industry as the heat supply must be satisfied in a long-term perspective. The situations of the case companies, SSAB Strip Products and Sandvik AB, indicate that even if there is industrial excess heat available for district heating, it is not obvious that the heat is delivered to a district heating distributer. The operation has to be economically favourable and there has to be a marketing possibility; the heat supply can be greater than the district heating demand.

Furthermore, steel plants have the possibility to be part of industrial symbioses where excess energy flows from the steel industry can be utilized by other facilities and products from these facilities can be imported to the steel plant and used for example as reducing agents or fuel. The symbiosis requires secure and long-term co-operation and technologies that are not commercial are more uncertain alternatives than commercial technologies.

Another option for both integrated steel plants and scrap-based steel plants is integration with a DRI plant. The DRI plant can use gasified biomass and/or coke oven gas as a reducing agent and the DRI produced can be charged into the blast furnace or the BOF at the integrated plant or into the EAF at the scrap-based plant and substitute some of the steel scrap.

In order to achieve a substantial reduction of CO_2 emissions, energy efficiency measures must be combined with breakthrough technologies such as fuel conversion and CCS. Heating furnaces can be fired with SNG produced from biomass and charcoal can substitute the fossil injection coal in the blast furnace process. However, bioenergy is considered a limited resource [41] and there are discussions [42] about which sector of application for biomass that is most cost-effective and would result in the largest CO_2 mitigation. Moreover, calculations show that substituting the fossil injection coal with charcoal at SSAB Strip Products would demand 1.6% of the Swedish bioenergy potential[16] in 2020 and substituting the LPG used in heating and heat-treatment furnaces at Sandvik would demand 0.2% of the potential. Hence, it is not obvious that large-scale substitution of fossil fuels with biomass in the Swedish iron and steel industry will occur in the near future. A top gas recycling blast furnace process with fossil fuels combined with CCS is perhaps a more likely development, than the replacement of coke with biomass in the blast furnace. Furthermore, in a longer time perspective breakthrough steel producing technologies, such as electrolysis of iron ore using electrical energy produced from wind, water or solar energy, may be an achieved environment-friendly process of iron ore based steelmaking. On the other hand, there is a realistic option for both integrated and scrap-based steel plants to exchange fossil fuels in heating and heat-treatment furnaces for gasified biomass when the technology is commercialised.

Even if the conversion efficiency of a technology is low the benefit may be high, for example if the source of energy is vast and there are no competing methods for energy-recovery and/or if the technology infers conversion of energy of lower value into energy of higher value.

[16] The Swedish bioenergy potential in 2020 is estimated at 248 TWh/year, including forestry, agriculture, municipal and industrial waste, peat and black liquor [40].

Technologies which utilize the same resource and hence could compete with each other for implementation are:

- CHP production from process gases, methane reforming of coke oven gas, DRI production with coke oven gas as reducing agent.
- TPV, hot water from cooling beds, ORC/Kalina cycle, TES.
- ORC/Kalina cycle, industrial symbiosis where low-grade heat is exported.

Conversion of heat radiation into electricity by the use of TPV, methane reforming of coke oven gas, gasification of biomass to produce SNG, TES systems and production of hot water from cooling beds are not yet commercial technologies, but in a longer time perspective all of the energy efficiency measures proposed in this paper may be realised opportunities for the iron and steel industry. However, installations of technologies with massive investment costs will probably not occur before the technical lifetime of the corresponding existing equipment has expired.

In conclusion, measures with high compatibility and high probability for near future implementation in Swedish integrated steel plants are CDQ with heat recovery, process gases for CHP production and electricity production with ORC and TRT. There is great potential for Swedish secondary steel plants to concurrently convert their fossil fuels with biomass and to produce electricity with ORC installations. Additionally, the delivery of excess heat to district heating systems and partnerships in industrial symbiosis are at present interesting opportunities for both integrated and secondary steel plants.

Further work will be done where energy conservation options for the case companies will be analysed and optimized from a system perspective.

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