Energy Efficiency of Metals Production Industry in Finland

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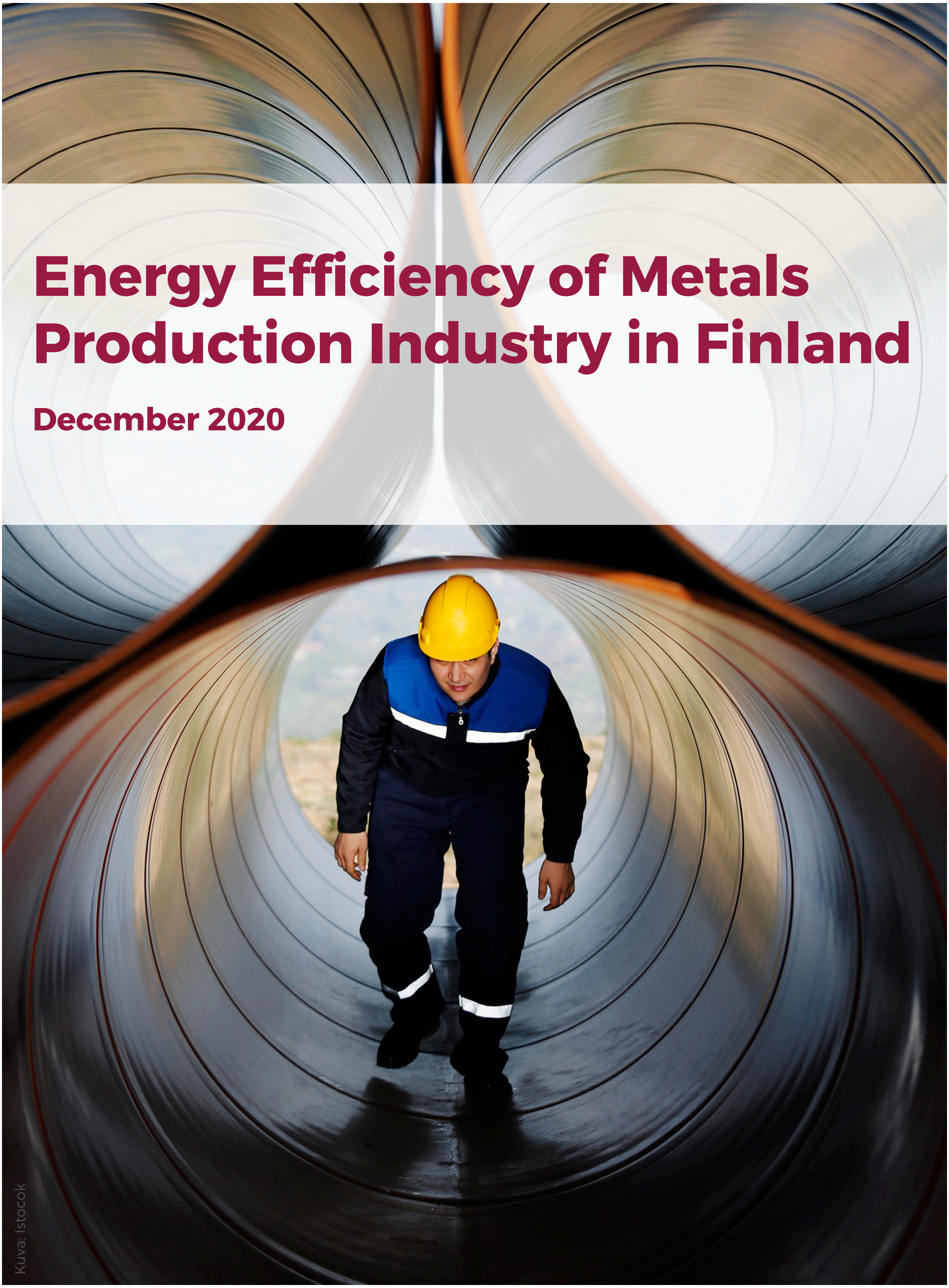

Motiva

Energy Efficiency of Metals Production Industry in Finland

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Preface

The objective of this study is to find out how the energy efficiency of energy-intensive metals production industry in Finland compares to other countries and which factors affect the comparisons of countries and individual plants. Particular focus was on identifying factors which may lead to misinterpretations in any simplified country or plant comparisons based on energy efficiency indicators in metals production industry.

The use of energy indicators and benchmarking of energy efficiency of countries, sectors and sub-sectors is increasing at the international fora. This necessitates a thorough understanding of underlying factors affecting the comparisons and of the limitations to the interpretations which can be made from the data. Some studies have been made in Finland to better understand them. VTT Technical Research Centre of Finland Ltd made a study in 2018 on recently published energy efficiency country comparisons and decomposition analyses as well as ODYSSEE and MURE Scoreboards (Koreneff 2018). In 2019, VTT and Fisher carried out another study on how the energy efficiency of the pulp and paper sector in Finland compares to other countries (Koreneff et al. 2019). This study extends the analyses to another energy intensive industry, metals production industry, which makes a significant contribution to industrial energy consumption in Finland.

The project was financed by the Finnish Energy Authority. The Steering Group of the project was coordinated by Patrick Frostell at the Technology Industries of Finland. Steering Group members were Jarmo Herronen (Boliden), Kimmo Järvinen (Association of Finnish Steel and Metal Producers), Johanna Kirkinen (Finnish Energy Authority), Helena Kumpulainen (Ovako), Martti Kätkä (Technology Industries), Mika Lehtimäki (Boliden), Mikko Lepistö (SSAB), Mia Nores (Outokumpu) and Helena Soimakallio (Technology Industries).

The study was carried out by Lea Gynther and Tomi Kiuru at Motiva Oy in 2020. Significant contribution was made by the Steering Group and technical experts working in the participating industrial companies. Furthermore, Timo Fabritius from University of Oulu, Ari Jokilaakso from Aalto University, Pirjo Virtanen from Metso Outotec as well as Kari Grönfors, Leena Timonen and Anssi Vuorio from Statistics Finland contributed to the report through interviews and reviewing the report.

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1 Introduction

Study Objective

The objective of this study is to find out how the energy efficiency of energy-intensive metals production industry in Finland compares to other countries and which factors affect the comparisons of countries and individual plants. The metals included in the study are steel, stainless steel, copper and zinc, with a few references to nickel. Aluminium production in Finland is based on recycled raw material which is not an energy-intensive process and, therefore, not discussed in the report.

Study Approach

The study was carried out in three steps: data collection, interviews and analysis.

Country level data was acquired from the European Odyssee energy indicator database and plant level data were procured from the international consultant Wood MacKenzie. Plant-specific international data was supplemented by plant-specific data from Finnish metal companies. Plant data covers the specific consumption of oxygen crude steel (BOF), electric crude steel (EAF), copper and zinc. Although Outokumpu produces stainless steel using EAF, the integrate is globally unique with no peers to compare to.

Interviews were conducted among the Finnish metals producers Boliden (copper, zinc and nickel production), Outokumpu (stainless steel and ferrochrome), Ovako (electric steel) and SSAB (oxygen steel). In addition, interviews were made with Statistics Finland, University of Oulu (steel), Aalto University (non-ferrous metals) and Metso Outotec (metal technology company). The objective of the interviews was to identify key factors affecting overall energy efficiency while comparing plant and to get an overview on remaining possibilities for energy efficiency improvements.

Report Structure

Chapter 2 of the report gives and overview of the metals production industry in Finland. The objective of the chapter is to act as a background reference particularly when reading interview findings in Chapter 4 and conclusions in Chapter 5. Chapter 3 demonstrates what comparisons based on international indicators seem to suggest. Chapter 4 summarises the interview results. Chapter 5 provides a summary and conclusions drawn from data and interviews.

2 Metals Production Industry in Finland

This chapter gives an overview of the metals production industry in Finland, briefly introduces the production processes, summarizes the statistical factors affecting country comparisons and explains policies in place to pursue energy efficiency in energy intensive industry. The chapter can be used as a technical reference when reading the results of the industry interviews and conclusions in Chapter 5.

2.1 Metals Production Companies in Finland

The main metals produced in Finland are steel, copper, nickel, zinc and chromium. Finland is also a significant producer of cobalt and produces some aluminium, gold, silver and platinum. Table 1 shows the largest companies producing metals and their characteristics.

Table 1 Metals production companies in Finland

Company	Products and production capacity	Raw material	Processes
SSAB Europe, Raahe	Steel (2 800 kt in 2018)	Imported concentrate	Oxygen
Outokumpu, Tornio	Stainless steel (slab capacity 1 650 kt per year) Ferrochrome (530 kt per year)	Share of recycled steel up to 90%; chrome mine in Keminmaa	Electric
Ovako, Imatra	Steel (on average 240 kt per year)	100% recycled steel	Electric
Boliden, Kokkola	Zinc (291 kt in 2019)	Both domestic and imported concentrates	Roaster and direct leaching Electrolysis
Boliden, Harjavalta	Copper (120 kt in 2019), nickel (26 kt), silver (62 000 kg) and gold (2 500 kg)	Both domestic and imported concentrates	Flash smelting
MMC Norilsk Nickel: Harjavalta Nickel	Nickel (capacity 65 kt per year)	Both domestic and imported concentrates	Hydrometallurgical from nickel matte
Terrafame, Sotkamo	Nickel (27 kt in 2019), zinc (55 kt), cobalt and copper	Terrafame mine	Heap leach

Sources: Heikkinen V. and Loukola-Ruskeeniemi K. (2015) and company websites

Given the small size of the country, Finland is a significant producer of metals both in the European scale but also globally (see table 2). Net exports exceed imports. Economic trends, however, have a strong impact on the export volumes and capacity utilization rates. The economic crisis in 2008, for example, reduced exports by a quarter and the ongoing covid-19 crisis strongly cuts exports.

Table 2 Finland's share of metals market

Metal	Market share information
Ferrochrome	Outokumpu is the only producer in Europe
Stainless steel	Outokumpu produces 30% of stainless-steel in Europe and 5% of global supply
Steel	36th largest steel producer globally and 16th largest in the EU-27 in 2019
Zinc	Boliden Kokkola is the second largest produce in Europe
Nickel	Boliden Harjavalta is the largest producer in Europe

Sources: Steel/World Steel Association, other data from companies

2.2 Processes

This chapter describes the basic processes in iron ore based steel making (hereafter frequently referred to as 'oxygen steel') and recycled/scrap steel based steel making (hereafter often 'electric steel'), production of stainless steel as well as copper and zinc production. The description includes remarks on the processes of SSAB, Ovako, Outokumpu and Boliden.

Out of the total 4.1 million tonnes of steel produced in Finland in 2018, 68% was produced by the oxygen process and 32% by the electric process.

Blast Furnace (BF) - Basic Oxygen Furnace Based Steelmaking (BOF) - SSAB

Blast Furnace (BF) - Basic Oxygen Furnace (BOF) process route is used to produce steel from enriched iron ore fines. As the first step, a sinter plant agglomerates iron ore fines with other fine materials at high temperature to create a product that can be used in a blast furnace. Alternatively, sintered iron ore pellets can be procured from the world market. SSAB stopped its own partial sintering process in the Raahe plant in 2011 when the sintering plant reached end-life. In 2012, a briquette plant was opened where dust, slurries and other fines containing iron recovered from the whole process chain can be agglomerated, to allow recycling back to the ironmaking process.

Metallurgical coke is produced in the coking plant by heating of coal blend in the absence of oxygen. Coke is used as fuel and to reduce iron ore in a blast furnace. Iron ore sinter or pellets, coke and flux (lime) are continuously charged to the blast furnace which reduces iron ore into metallic form and melts it as pig iron. SSAB produces its own metallurgical coke and procures the lime it needs.

Pig iron contains impurities and excess carbon and it is therefore decarbonized into crude steel. Today, practically all iron ore-based steel mills are iron and steel production integrates where pig iron from the blast furnace is directly input into a basic oxygen furnace or converter with or without recycled steel scrap. In the converter, oxygen is blown into the metal bath at high temperature to reduce carbon. The result of this sub-process is crude steel.

Crude steel is transferred to a secondary steel making process by tapping it out into a ladle were final adjustments of chemical composition are made. In the following step, continuous casting machines are used to produce semi-finished casting products, slabs.

The next steps are hot and cold rolling which is a metal forming process in which steel slab is passed through one or more pairs of rolls to reduce the thickness and to make the thickness uniform.

At the SSAB plant, there is an on-site power plant operated by energy company Raahen Voima Oy. It provides 200 GWh of excess heat each year to Raahe city; more could be sold should there be more heat load.

SSAB procures oxygen from another company producing it on-site.

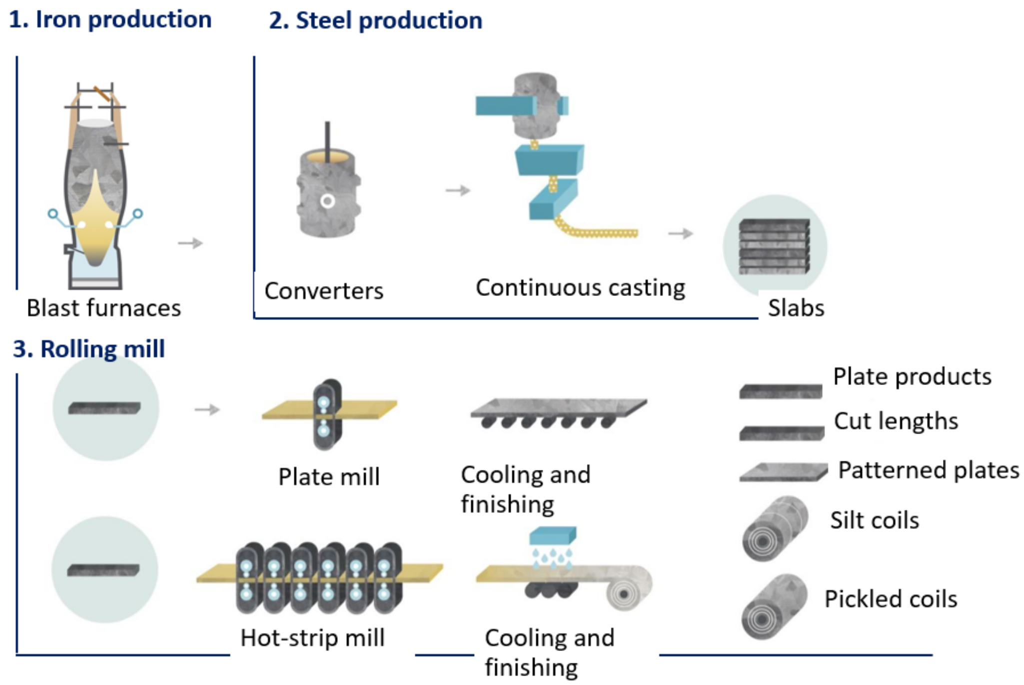

Figure 1. SSAB's BF-BOF steel process in Raahe, Finland. (Source: SSAB Finland)

Recycled Metal Based Steel Production – Ovako

Electric Arc Furnace (EAF) process is used to produce steel from recycled steel. A steel melting shop can be composed of different sub-processes but an electric arc furnace (EAF) is the core of the process which is energized by electric arcs between electrodes and charged steel scrap.

Other sub-processes are a ladle metallurgy facility (LMF, an intermediate steel processing unit that further refines the chemical composition and temperature of molten steel while it is still in the ladle). This may also include a vacuum degassing facility and continuous casting after which molten metal is solidified into a "semi-finished" billet or bloom (both being forms of crude steel) for subsequent rolling in the finishing mills. The process of Ovako in Imatra includes all three sub-processes. In many EAFs it is possible to also add energy with burners – in Imatra's case natural gas – to fasten the melting process. However, electricity is the main energy source.

Limestone or burned lime is needed to make a good slag facilitating the removal of sulphur and phosphorus, and for providing a safer platform to withstand high intensity arc plasma in the EAF. Oxygen is used for generating foaming slag during melting in the EAF; it helps to optimize the efficiency of the process and decreases heat losses.

Ovako runs two rolling mills, a heavy bar mill and medium bar mill. A third intermediate rolling mill could be part of the process. Ovako's further processing includes hardening and tempering furnaces using natural gas.

Ovako procures the needed lime and air gases. It also purchases all the electricity it needs.

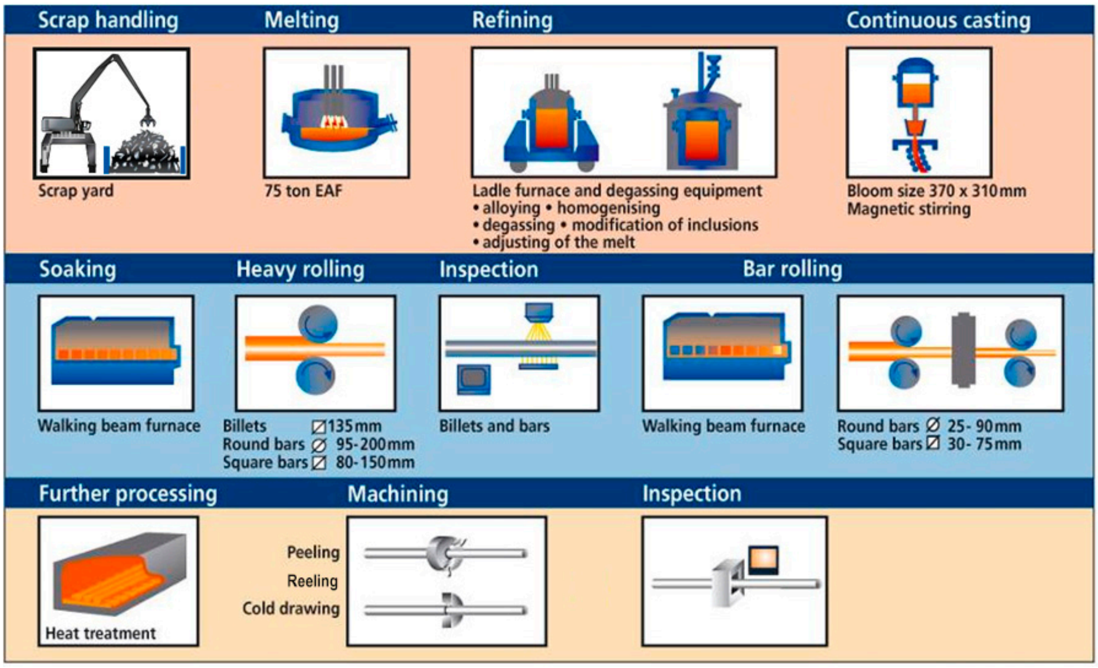

Figure 2. Ovako's electric steel process in Imatra, Finland. (Source: Ovako)

Stainless Steel and Ferrochrome Production - Outokumpu

Outokumpu stainless steel integrate in Tornio is the largest in the world. It also runs the only chrome mine (in Kemi) and ferrochrome plant (in Tornio) in Europe. The ferrochrome plant consumes half of all energy in the Tornio integrate.

Ferrochrome is the precursor of chrome which is the most important raw material in the production of stainless steel; stainless steel is steel that contains at least 10.5% of chrome. The ferrochrome plant is composed of pellet production, a sintering plant and three submerged arc furnace based smelters. Majority of 530 000 tonnes of ferrochrome produced per year is consumed internally by Outokumpu's own plants in Finland and other countries, and approximately 25% of the production is sold to other companies. Each year about 1 TWh of carbon monoxide is formed in ferrochrome production of which about one third is sold to an energy company Tornion Voima and a lime producer. Rest is used as an indigenous energy source in Outokumpu's processes.

The stainless steel melt shop is composed of drying of recycled steel (scrap), a ferrochrome converter, two electric arc furnaces, two AOD converters (argon oxygen decarburization), two ladle furnaces and two continuous casting machines. The globally unique feature of the plant is that molten ferrochrome is conveyed into the stainless steel melt shop, which significantly reduces energy consumption.

Rolling at Outokumpu is composed of both hot and cold rolling plants, including annealing and pickling processes, rolling and finishing lines. In addition, there is an integrated RAP line (rolling, annealing and pickling). Almost one third of black hot bands produced in hot rolling are exported.

Many commodities are produced at the Outokumpu site by Outokumpu or other companies, e.g., compressed air by Outokumpu itself and air gas and heat by other companies. The power plant is operated by Tornion Voima, an energy company.

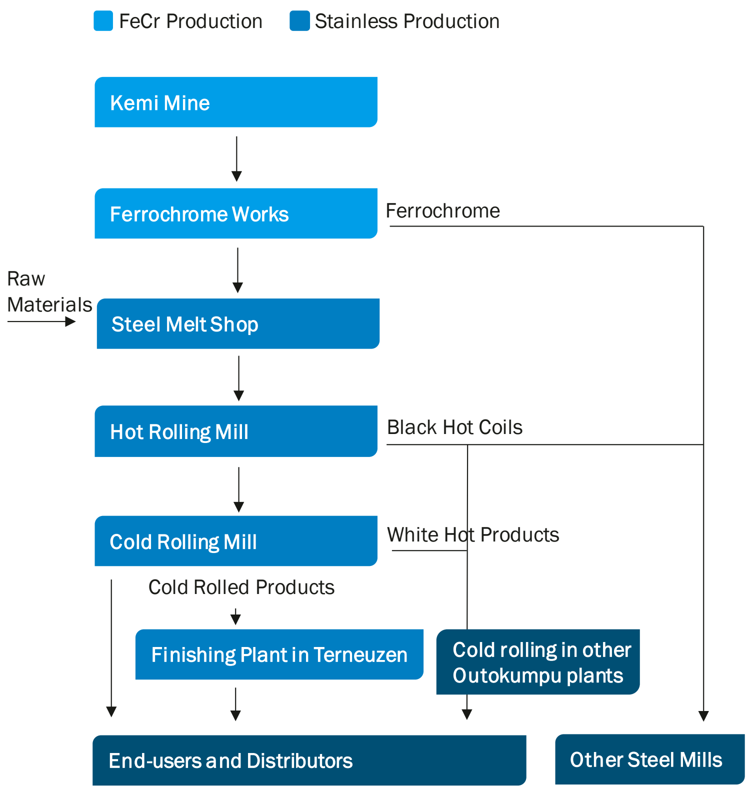

Figure 3. Outokumpu's ferrochrome and stainless steel processes in Kemi and Tornio, Finland. (Source: Outokumpu)

Copper – Boliden Harjavalta

Boliden's Harjavalta plant is a multi-metal plant the main products being copper, nickel, silver and gold. Here, a description of basic copper production process is given.

Copper ore contains only 0.3-3% of copper meaning that it needs to be enriched into copper concentrates before copper production. Copper concentrates need to be dried before smelting. The dominating smelting technology is flash smelting[1], which has been developed for sulphur-

[1] The alternative process for flash smelting is older and it consumers almost twice as much energy. It is based on roasting, smelting in reverberatory furnaces (or electric furnaces for more complex ores),

containing ores. Compared to other technologies, it is energy efficient as an exothermic process using energy from the ore or concentrate. Gangue and silica sand are fed into the furnace. In addition, oxygen enriched air is needed. The reactions in the flash smelting furnaces produce copper matte, iron oxides and sulphur dioxide.

Slag contains valuable metals and to recover those it needs to be cleaned. At Harjavalta, slag concentrate is recovered and circulated back to flash smelting. Technology options for slag cleaning are an electric arc furnace and a slag concentrator where slag is first cooled in large ladles and then processed through grinding and flotation. Harjavalta applies the latter more energy consuming slag concentration method.

A converter is used to reduce impurities from the copper matte to make blister copper. The process is exothermic. An anode furnace removes any remaining traces of sulphur and oxygen after which refined anode copper is cast directly from the anode furnace into moulds on the casting table. The last cleaning step is electrolysis to make 99.99% pure copper. At Boliden, this takes place in an electrolysis plant in Pori located 30 km from Harjavalta.

The sulphur dioxide produced by flash smelting is typically captured in a sulfuric acid plant. The process is exothermic. Other processes in the copper plant include e.g. production of compressed air, pumping and gas removal. Compressed air and oxygen are procured commodities.

Boliden's Harjavalta plant operates waste heat boilers and sells excess process steam (about 380 GWh/a) to STEP, which is an energy services company operating within the industrial park where Boliden's plant is located. Boliden also procures energy from the same energy service provider.

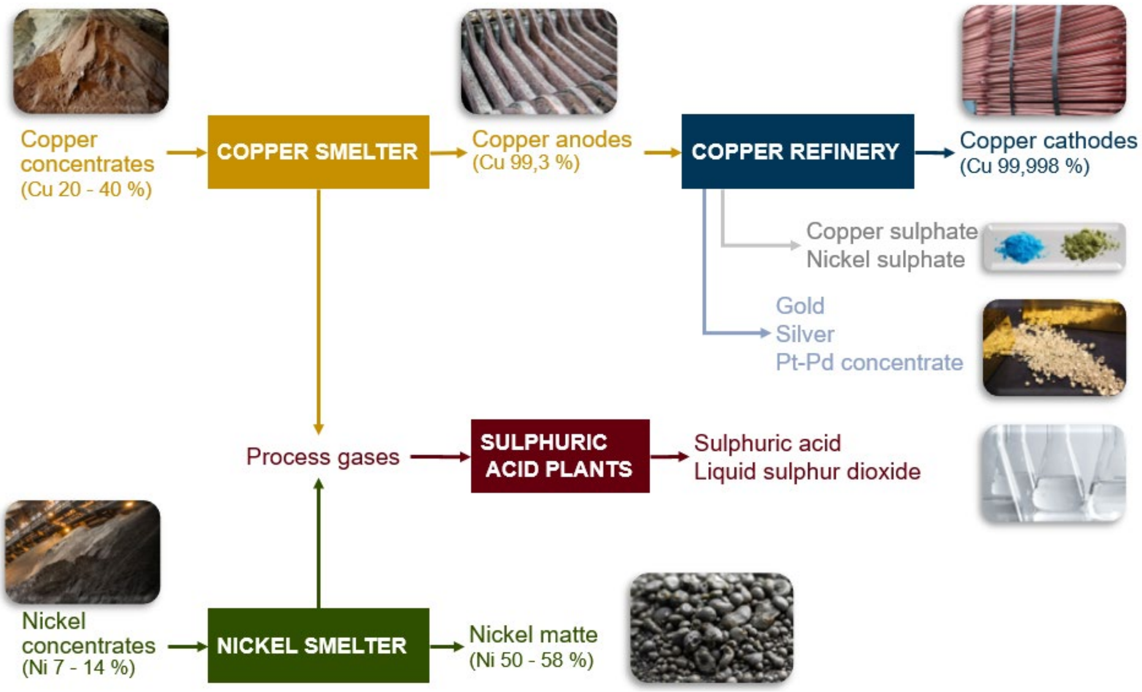

Figure 4. Boliden's copper process in Harjavalta, Finland. (Source: Boliden)

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producing matte (copper-iron sulphide), and converting for production of blister copper, which is further refined to cathode copper.

Zinc – Boliden Kokkola

Boliden's operates a zinc plant in Kokkola; silver is a by-product. The zinc plant is the second largest in Europe.

Zinc ore contains 3-10% of zinc and needs to be enriched at mines into zinc concentrates before it can be treated in a zinc smelter.

Zinc is typically produced by a Roaster-Leaching-Electrolysis (RLE) process. Some sites are also using different direct leaching technologies where the roaster is partially bypassed with a hydrometallurgical process.

The sulphur dioxide produced in the roasting process is captured in a sulfuric acid plant in an exothermic process.

In leaching zinc calcine is leached into sulfuric acid to produce leach solution. Next, leach solution is refined to produce zinc solution. Zinc solution is subject to electrolysis to make cathode zinc. Slab zinc is produced by melting and casting cathode zinc.

Boliden's Kokkola plant sells about 440 GWh steam and district heat per year to the energy local utility Kokkola Energia. Energy sales reduce Kokkola plant's net energy consumption by 25%.

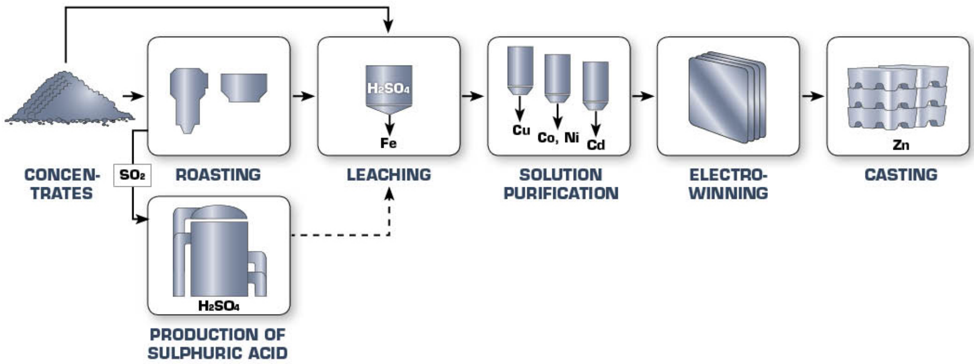

Figure 5. Boliden's zinc process in Kokkola, Finland. (Source: Boliden)

2.3 Energy Statistics and System Boundaries

This subchapter provides an overview of statistics on energy use in metals production industry. It briefly explains, among others, the statistical procedure for energy sales, non-energy use and recovered gases as well as the impact of industry structure on energy statistics. Conclusions drawn on the impact of these factors on energy indicators and country or company comparisons are given in Chapter 5.2.

Figure 6 shows the development of final energy consumption in steel industry and in production of non-ferrous metals from 2000 to 2018. While the consumption of non-ferrous metals has been rather stable, that of steel has fluctuated along with production volumes.

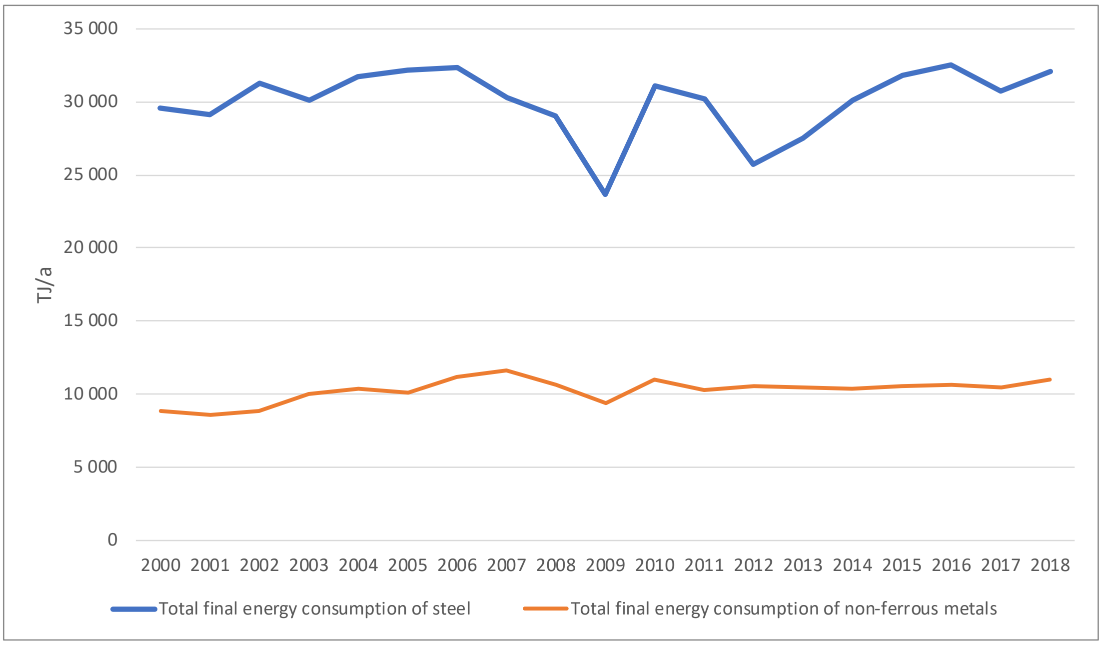

Figure 6. Total final consumption of production of steel and non-ferrous metals in Finland in 2000-2018. (Sources: Odyssee ref. Statistics Finland and Eurostat)

Impact of selling energy

In national and Eurostat energy statistics electricity sold by metal industry is taken into account in calculating final energy consumption. This has relatively little impact on Finnish metal industries because none of them generates electricity themselves; however, there is some purchasing and reselling to subcontractors. Also sold heat is subtracted from purchased heat. SSAB steel plant and Outokumpu stainless mill, Boliden's Harjavalta multi-metal plant and Boliden's Kokkola zinc plant all sell heat and steam.

The picture becomes complex when heat is not purchased but it is a by-product of the process and sold to other parties. Sometimes excess heat is generated in waste heat boilers or exothermic processes in industry. When this energy is sold to district heating or otherwise transferred to another company, this is not credited to the industrial plant which has generated it. Statistics Finland has recognized the issue but considers it difficult to change statistical procedures without interference to the basic logic of forming the energy statistics and energy balance. However, it fully supports the idea of trying to collect data on waste heat utilization by different means which, as the next step, could be made more visible also at the statistical level.

Carbon monoxide (CO) is formed as a side stream in ferrochrome production. Part of the CO produced is used by the Outokumpu integrate itself and included in the final energy consumption. CO used by the ferrochrome smelter (see 'Impact of recovered gases') or sold to other operators are not included in Outokumpu's final energy consumption.

Impact of ownership structure

In energy statistics, energy consumption by any plant is categorized according to the Nace[2] international industry classification of the owner of the plant. If, for example, a power plant operating within a steel integrate is owned by a steel producer, its energy consumption is allocated to metal industry but if the owner is an energy company, its' energy consumption is allocated to the energy sector. Similarly, energy use in the production of air gas, oxygen or lime could be part of consumption by the metal industry or, e.g., chemical industry, depending on the ownership structure.

Impact of non-energy use

Metals production involves the use of fuels to non-energy uses. Such non-energy uses are also part of total final energy consumption, but not in any manner coupled with the final energy consumption by industry either in the national energy statistics or by Eurostat.

Impact of recovered gases

Metallurgical coke used in blast furnaces is part of the energy transformation sector and therefore not included in final energy consumption. However, the output, blast furnace gas, is included in final energy consumption. Similarly coke oven gas is part of final energy consumption but not the input coal, which is reported to the transformation sector.

In ferrochrome production large amount, about 1 TWh/a, of carbon monoxide is formed (called 'other recovered gases'). Out of this 47% is allocated to the final energy consumption by Outokumpu integrate. 13% is recorded as part of the energy sector as it is used in the ferrochrome smelter where it is produced, 5% is used in flairs and 24% is sold to the Tornion Voima energy company (part of transformation sector) and remaining 10% is sold to production of non-metallic minerals.

The logic in all these cases is the same both in national energy statistics as well as in Eurostat.

Differences between energy statistics and emissions trading/emissions inventory

In emissions trading and national emission inventory system boundaries are different than in energy statistics. They are actually wider than in the energy statistics covering the whole production site regardless of the ownership of sub-processes. Therefore, outsourced facilities, such as power plants or oxygen production facilities, are included.

Emissions are calculated based on mass flows instead of energy flows. Therefore, they also cover, e.g., non-energy uses of energy carriers. It should be noted, however, that Tornion Voima is not part of Outokumpu's mass balance.

[2] Nace Rev. 2, Statistical classification of economic activities
in the European Community, https://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF

2.4 Policy Measures for Energy Efficiency Improvement

There are both European and national energy efficiency measures in place addressing energy intensive industries.

Metals producers participate in the EU Emissions Trading Scheme. Since 2017, energy intensive industry has received compensation for the impact of emissions trading on electricity price. In 2018, 11 facilities received a total compensation of 6.64 million euros.

A long-running national policy measure have been the voluntary energy efficiency agreements[3] first introduced in 1997. The current third generation of agreements is running from 2017 to 2025 and it is one of Finland's main measures to fulfil the obligations set in Energy Efficiency Directive's Article 7. All energy intensive industries participate into the agreement and monitoring results show significant energy savings. Monitoring results show that savings of 290 GWh/a savings were achieved through 144 individual measures implemented in 2017-2019 in the metal industry sub-sector. Corresponding investments in energy efficiency measures totaled 30 million euros.

The Energy Audit Programme started in 1992 and subsidised energy audits were implemented by trained professionals widely in the industry. The scheme is still in operation but has been by and large replaced by the mandatory energy audits required by the Energy Efficiency Directive. Investment subsidies are available for the implementation of energy efficiency measures.

The National Environmental Protection Act transposed the EU-wide Integrated Pollution Prevention and Control (IPPC) Directive into Finnish law. It determines the appropriate controls for industry to protect the environment through a permitting process and includes control levels of energy use and CO_2 emissions.

Energy taxation an important steering instruments in Finland, and at present, the revision of the energy tax scheme is underway.

[3] Energy Efficiency Agreements (in English): https://energiatehokkuussopimukset2017-2025.fi/en/agreements/

3 International Comparison

International comparison data is derived from two principal sources, the European Odyssee database (country level data for steel) and commercial sources (global plant level data for steel, copper and zinc). These are discussed in the next two chapters.

3.1 Odyssee Indicators for Steel Production

The Odyssee database[4], developed with EU funding over last decades, includes energy efficiency indicators for different sectors. While the Odyssee database has no "official" status in the EU, it is widely used in the European fora because of, e.g., the extensive data contents and its' European origins. The International Energy Agency (IEA) runs a parallel global energy indicator database with energy indicators for metals industry.

In the metals industry, only the specific consumption of steel production is given in the Odyssee database (Figure 7). Steel production in the database includes also other operations in steel plants in addition to production of crude steel[5]. These include very energy intensive rolling processes and other thermomechanical processing.

Only specific consumption of steel is given in the Odyssee database due to lack of energy consumption data for other metals. In many countries there are not enough producers for the statistical authorities to be able to disclose data for confidentiality reasons. The International Energy Agency also publishes the specific consumption of steel production but also does not do so for other metals.

All data in the Odyssee database is based on regular data collection from national project teams; in Finland the data is provided by Motiva Oy in co-operation with Statistics Finland.

The energy data reported to the database for steel is derived by Statistics Finland from Eurostat databases and includes the following Nace classes for steel:

- 24.1 Manufacture of basic iron and steel and of ferro-alloys
- 24.2 Manufacture of tubes, pipes, hollow profiles and related fittings, of steel
- 24.3 Manufacture of other products of first processing of steel
- 24.51 Casting of iron
- 24.52 Casting of steel

Crude steel production data reported to the Odyssee for Finland is taken from World Steel Association (World Steel Association 2020). According to the data, crude steel production in Finland has remained quite steady in the last decade. Total crude steel production grew from 4 030 kt in 2010 to 4 146 kt in 2018. Production of oxygen steel (BF-BOF) slightly increased from

[4] The Odyssee and Mure databases: https://www.odyssee-mure.eu/

[5] Crude steel is steel in the first solid state after melting, suitable for further processing or for sale. (World Steel Association)

2 765 kt in 2010 to 2 800 kt in 2018 while production of electric steel (EAF) increased from 1 265 kt to 1 350 kt over the same period.

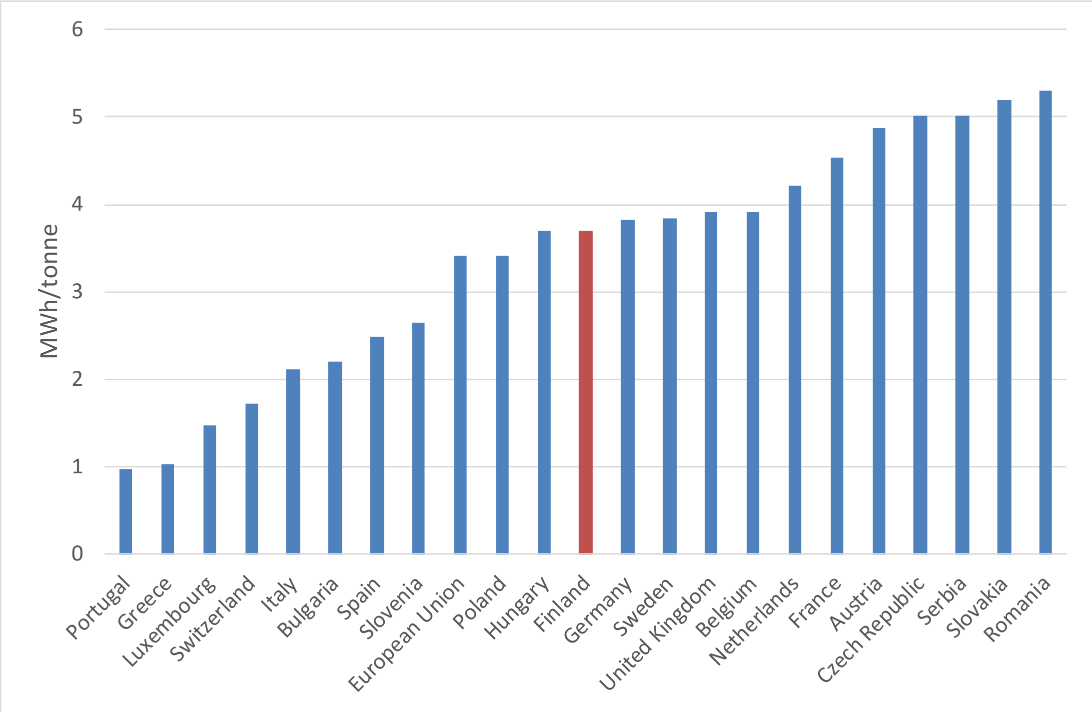

Figure 7. Specific consumption of steel production in Europe in 2018, MWh/tonne. Note! Energy consumption includes also thermomechanical processing such as rolling, and energy consumption of some metal foundry companies. (Source: Odyssee)

Finland appears to rank in the mid-range of countries in this comparison. The lowest specific consumptions can be found in Portugal and Greece and the highest in Romania and Slovakia.

There are multiple factors which imply that **this kind of simplified comparison of specific consumption can be horrendously misleading**. The problems include:

- Countries are using electric steel and oxygen steel making processes in varying degrees. The specific consumption of these two basic process routes are profoundly different muddling the simplified comparison. Best BF-BOF processes can consume 6-7 times more energy than best EAF processes (see Figure 8).
- While system boundaries in energy statistics are clearly defined as such, the ownership structure within one steel plant or integrate can lead to variations in the inclusion or exclusion of process units. For example, an oxygen plant, a lime incinerator or a power plant may be owned by another company operating, e.g., in the chemical or energy sector and their energy consumption is reported to the respective Nace classes. This automatically reduces the specific consumption.
- Energy consumption and volume of product are not a pair:

- Energy consumption of manufacturing of steel products (Nace 24.2 and 24.3) is included in the specific consumption where the divider is 'tonnes of crude steel'.
- Energy use covers all energy use of the metal company, but production only includes crude steel production.

- At the end of the process, there can be differences, e.g., in the inclusion or exclusion of rolling or other thermomechanical processing which are energy-intensive and can contribute up to 50% to the total final energy consumption of the integrate.
- Sintering of enriched iron ore fines may be done within the steel plant or the plant can use procured sintered iron ore pellets. The impact of sintering is around 10% of the energy consumption of a tonne of crude steel.
- In the ODYSSEE database, fuels used for the production of sold heat are not reduced from the energy use of the industrial sub-sector.
- Plant sizes, heat sizes, capacity utilization rates and product mix (quality of products and the number of different grades) all have a considerable impact on energy consumption.
- Intermediate products sold and exported, such as surplus ferrochrome, are not included in the denominator (tonnes) but they are part of the numerator (energy consumption).

Figure 8 shows the specific consumption of different European steel producing countries in respect to the process routes used. Taking into account the share of the two process routes hence alleviates one, but only one, of the concerns discussed above.

Among those producing about one third of their steel production with the EAF process route (blue column in the figure), Finland has the lowest specific energy consumption. Theoretical good levels of energy consumption in the BF-BOF and EAF process routes have been marked by red circles in the figure.

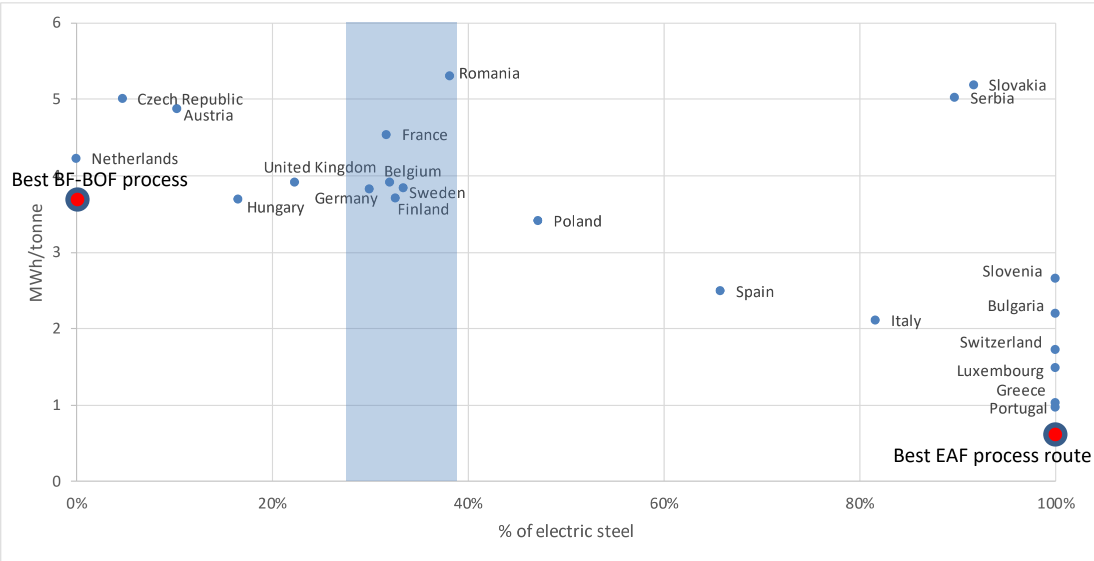

Figure 8. Specific consumption of steel production in Europe by the production process in 2018. Note: Energy consumption includes also thermomechanical processing such as rolling. (Source: Odyssee)

Figure 9 shows the development of energy intensity of metal industry (Nace 24) and unit consumption of crude steel production over the two last decades. While the two graphs are not exactly a pair because the first one includes also non-ferrous metal industry contributing about a quarter to the final energy consumption in Nace 24, they yet illustrate the setbacks of using energy intensity as a proxy of energy efficiency. Nevertheless, this is quite often done. While the IEA itself advices against the use of energy intensity as an energy efficiency indicator (IEA 2014), it still uses it[6]. The problems are also well known within the Odyssee Project, but intensity indicators are still published.

The graph shows that the specific energy consumption of crude steel has been quite steady over the last two decades with slight decline towards the end of the period. During and in the aftermath of the 2018 crisis the value added of steel plummeted causing a dramatic peak in the energy intensity of primary metals production. The two indicators have had quite different trends. ***Drawing any conclusions on the development of energy efficiency based on the evolution of energy intensity would have been fundamentally flawed.***

[6] See: https://www.iea.org/reports/energy-efficiency-indicators-2020

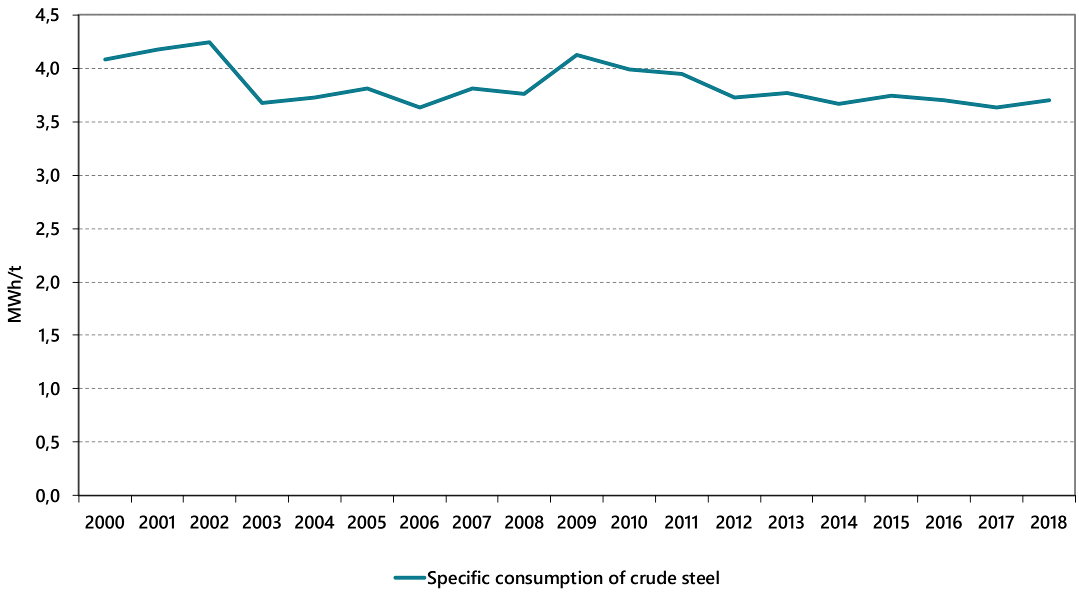

Figure 9. Energy intensity of primary metals production and specific consumption (unit consumption) of steel production in Finland in 2000-2018, kWh/euro and MWh/tonne (Source: Odyssee)

3.2 Wood MacKenzie's Plant-specific Data

The data consultant Wood MacKenzie collects its' plant data using multiple data sources: statistics, annual reports of the metal companies, industry surveys and interviews as well as general and industry-specific media.

Energy consumption data of a given metal integrate or plant includes all energy consumption within the site regardless of ownership of the sub-processes. This means that sub-processes run by contractors are included in the data. However, energy consumption is not included in situations where the operator does not operate all the typical unit operations and uses another plant in their group to perform that operation.

In steel production, a boundary is set at production of crude steel excluding downstream processes, such as rolling. In zinc production the boundary is set to include zinc slab and in copper production at copper cathode.

3.2.1 Data on Oxygen Crude Steel

Plant-specific data on energy consumption and crude steel production covered 158 BF-BOF route based plants globally. For some plants either energy consumption or production volume was missing or coal/coke consumption for BF-BOF plants was not available. These plants were removed from the data stock. To make Figure 10 graphs readable, two BF-BOF route based plants with incorrectly low specific consumption (0.37 and 2.12 MWh/tonne) and 15 plants with extremely high specific consumption (15-112 MWh/tonne), were left out of the figure. The final number of data points for BF-BOF was 129. Data provided by SSAB Finland was added among the data. Including SSAB Finland, 37 of the plants within the data are European.

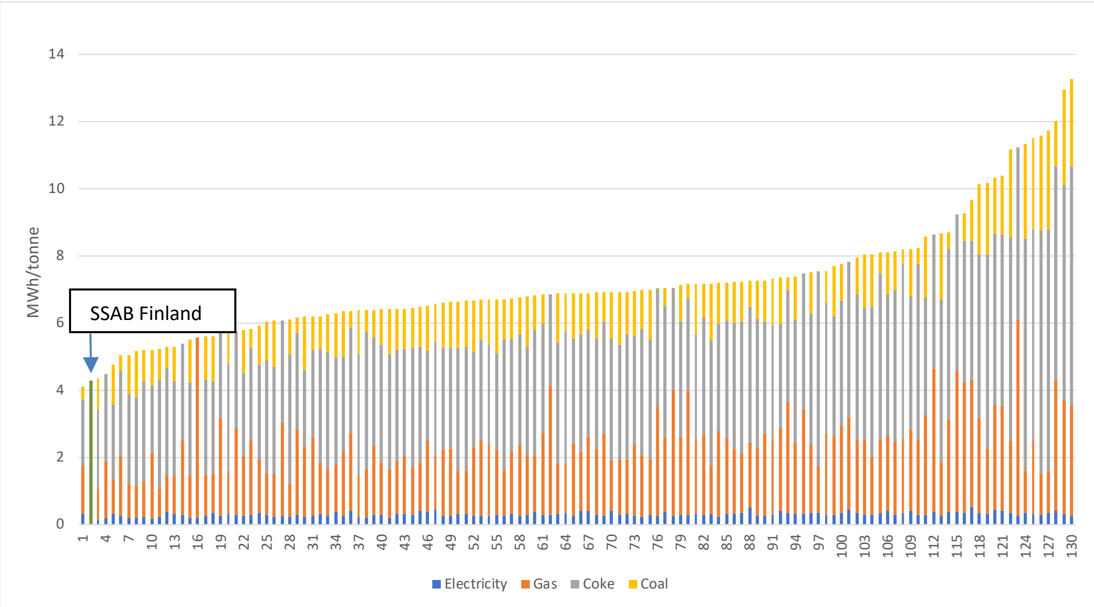

Figure 10. Specific energy consumption of 130 BF-BOF crude steel plants globally, MWh/tonne of crude steel. SSAB plant in Finland ranks second best. SSAB's consumption would be about 10% higher with own sintering. (Sources: Wood MacKenzie 2020a and SSAB)

SSAB Finland's specific consumption is second lowest in this global comparison. The specific consumption includes coking, briquetting, blast furnaces and the oxygen plant while heat sold is credited. The oxygen plant is not owned by SSAB, but it included in the data for better comparability. If SSAB would have its's own sintering plant, specific consumption could be about 10% higher.

3.2.2 Data on Electric Crude Steel

Wood MacKenzie's plant-specific data on energy consumption and crude steel production covered 116 EAF plants globally.

Figure 11 does not include data on 16 plants with specific consumptions in the range of 2-13 MWh/tonne of EAF steel[7]. Therefore, the final number of data points for EAF plants was 91. Data provided by Ovako was added among the data. 13 of the plants in the data are European.

Ovako's specific consumption was 0.86 MWh/tonne in 2018 consisting of 0.66 MWh/tonne of electricity and 0.20 MWh/tonne of natural gas when energy consumption up and including bloom[8] production is taken into account. This puts Ovako at 28th position, at the better end of the mid-range.

Although Outokumpu uses the EAF process, the integrate is globally unique and not comparable with EAF steel plants, principally due to stainless steel and ferrochrome production. Therefore, it is not included in the figure.

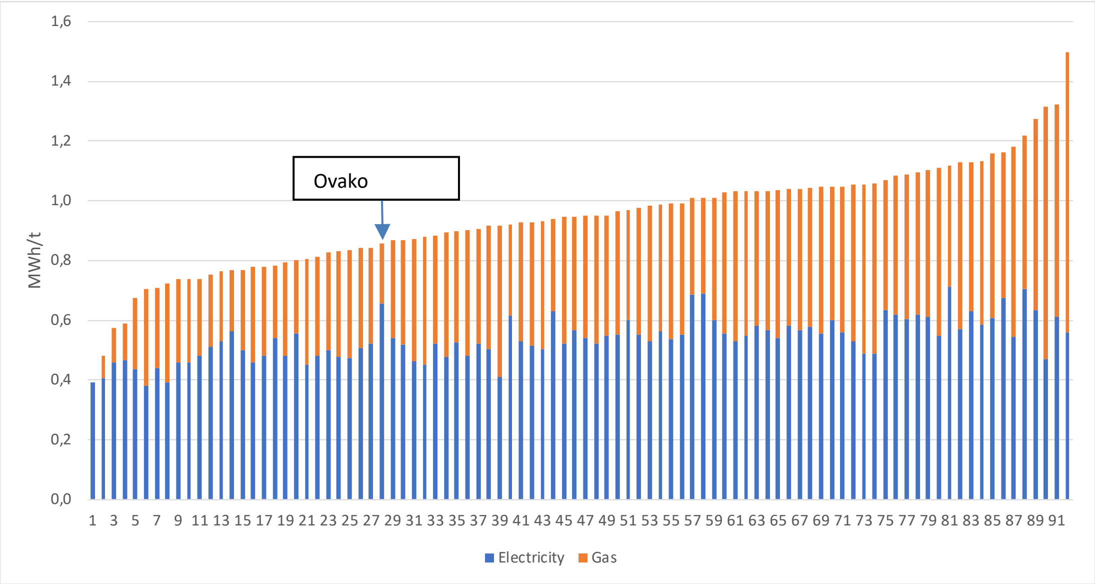

Figure 11. Specific energy consumption of 92 electric crude steel plants globally, MWh/tonne of crude steel. Ovako plant in Finland ranks 28th. (Sources: Wood MacKenzie 2020a and Ovako).

3.2.3 Copper Data

Data on copper plants includes data from 55 units globally. Nine of them are located in Europe. Boliden's Harjavalta unit ranks at 34nd, in the mid-range, in comparison of specific energy consumption per tonne of copper. Wood MacKenzie reports that the specific energy consumption is on net basis, i.e. sold heat is extracted from purchased energy. However, in reality Boliden's consumption (9 700 MJ/tonne copper cathode) is gross consumption which does not take heat

[7] The specific consumption of stainless steel is higher than that of other steel produced using EAF. Very high consumption figures suggest that some stainless steel production plants may have been included in the data.

[8] At Ovako, bloom is the first solid form of steel.

sales into account indicating an error in Wood MacKenzie's reporting. If heat sales would be taken into account, net consumption would be over 60% smaller. It is difficult to say what Boliden Harjavalta's ranking would be if all plants were reporting net consumption. However, it depends on actual possibilities for heat sales to other industries or to district heating, which is typical to countries with cold climates. Given this, it is highly likely that the ranking would be significantly better on net energy basis.

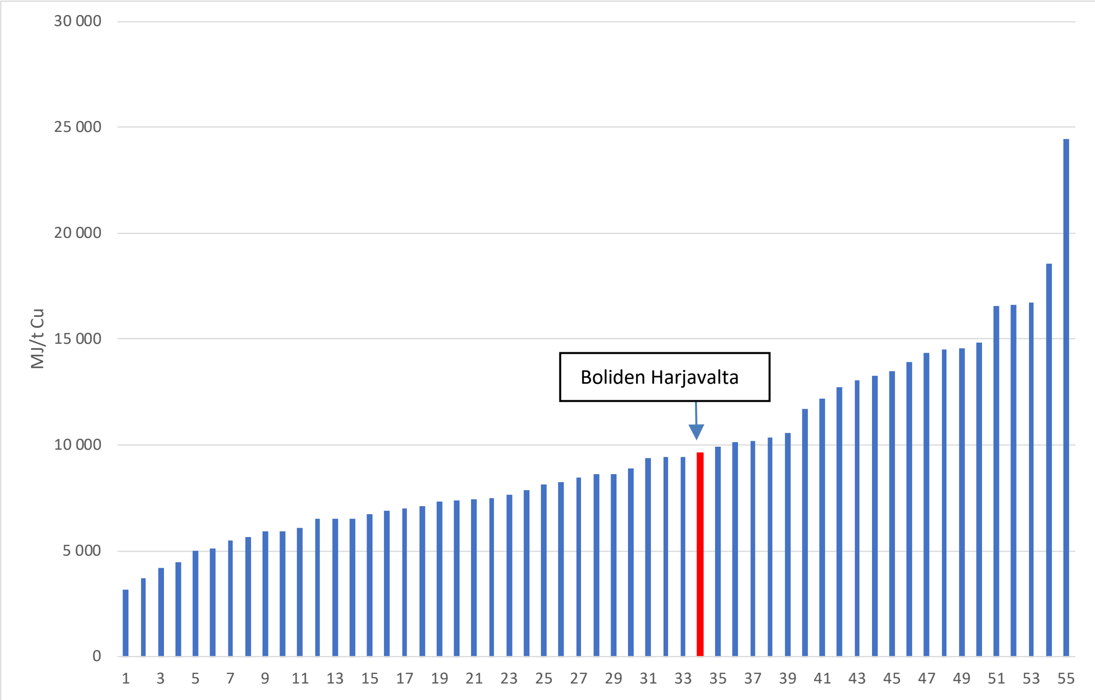

Figure 12. Specific energy consumption of 55 copper mills globally, MJ/tonne copper. Harjavalta copper plant in Finland is marked in red ranking 34th. (Source: Wood MacKenzie 2020b).

3.2.4 Zinc Data

Data on zinc plants includes data from 69 units globally. 13 of them are located in Europe. Boliden's Kokkola unit ranks second best in comparison of specific energy consumption per tonne of zinc. At Boliden Kokkola, the difference between gross and net energy consumption, which takes sold heat into account, is about 20%. It is not clear if Wood MacKenzie's data for zinc takes heat sales into account.

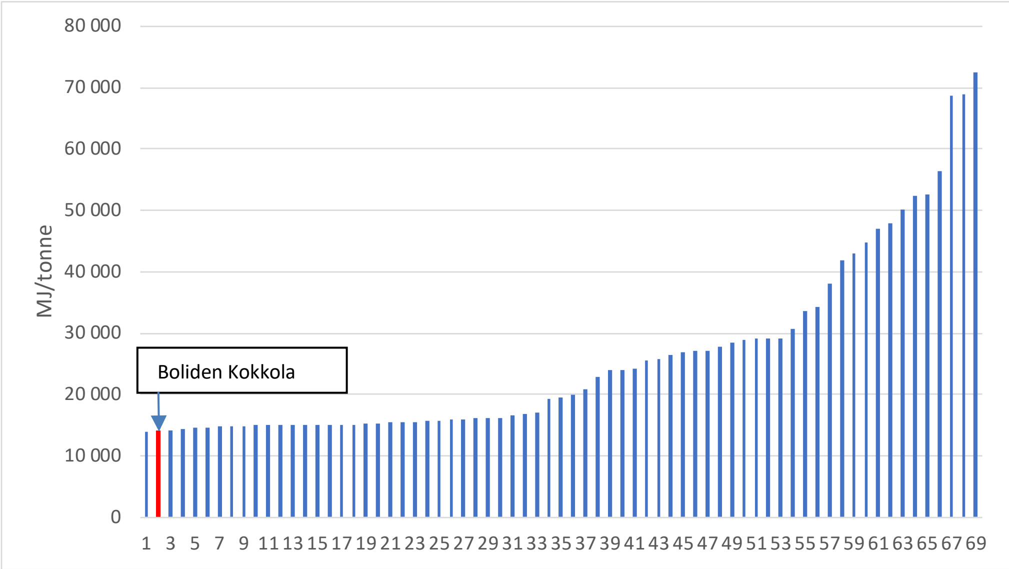

Figure 13. Specific energy consumption of 69 zinc mills globally, MJ/tonne slab zinc. Kokkola zinc plant in Finland is marked in red ranking 2nd. (Source: Wood MacKenzie 2020b).

4 Industry Interviews

4.1 Interviews

The objective of the interviews was to get insights to the real-life factors affecting energy consumption of each metal. Interviews were conducted among the Finnish metals producers Boliden (copper and zinc), Outokumpu (stainless steel and ferrochrome), Ovako (EAF steel) and SSAB (BF-BOF steel). In addition, interviews were made with Metso Outotec (metal technology company), University of Oulu (steel) and Aalto University (non-ferrous metals). Yet another interview was organised with Statistics Finland to clarify system boundaries in statistics.

The questions asked in the interviews were:

1. Which sub-processes are most significant in terms of energy consumption and what is their contribution to the overall consumption?
2. Which factors have the most significant contribution to energy efficiency of the production of this metal in different parts of the process? Options given were:
    - system boundaries
    - focus on total vs. net energy consumption
    - differences in production processes and equipment
    - differences in raw materials
    - concentrations of raw materials and enrichments
    - utilization of side-streams
    - level of heat recovery
    - sales of generated or recovered heat
    - single or multi-metal production
    - plant age
    - plant size
    - capacity utilization rate
    - climate
    - geographical location
    - fuel quality
    - differences in products, product distribution
    - product quality
    - HSEQ requirements
    - other factors
3. What is the overall energy efficiency level of your company compared to competitors?
4. What are the country specific or company specific features regarding energy use or energy efficiency compared to other countries or competitors?
5. Which factors can make comparison of countries or companies difficult regarding this metal?
6. What is the impact of above factors (question 5) on energy use and energy efficiency?
7. What are the process boundaries when monitoring energy consumption per utility? (This question had to be omitted due to time constraints in the interviews).
8. Which energy consumption is not visible in your own energy consumption or reporting (e.g. due to system boundaries)?

The questions posed to the universities were principally the same as questions 1-6 for metal companies. However, questions were modified to emphasize differences between countries more than differences between individual companies. Metso Outotec received the same set of questions as companies but was asked to an open question to provide comments on anything relevant to them as technology supplier.

Detailed information was received in the interviews on the energy consumption of various sub-processes of the plants as well as their current state of energy efficiency. Naturally, information on the situation of the metal industry in Europe and globally was more sporadic.

4.2 SSAB: BF-BOF Steel Production Route

Energy consumption of the SSAB steel mill in Raahe is 12-13 TWh/a if also energy carrying raw materials are included. Each year 200 GWh of district heat and steam is sold.

SSAB closed sintering process when the plant reached end-life in 2011, but if it would sinter all raw material itself, this would add energy consumption by 10%. Today, all iron bearing raw material is in the form of imported iron ore pellets. The amount of recycled steel used is small compared to competitors.

Two thirds of energy consumed is used in the two blast furnaces. SSAB reports that in some European comparisons these units have been among the five most efficient ones in Europe. An important factor in the energy consumption of blast furnaces is the quality of raw materials. Another one is the blast furnaces size. The charge size is only about 125 tonnes while in largest blast furnaces the charge size can reach 300 tonnes. While larger charge size enhances economies of scale, smaller load size allows more flexibility in production.

Other energy consuming processes are the coking plant, BOF-converters, and secondary metallurgical units including continuous casting as well as rolling. About 10% of all energy is consumed in rolling, which is already a secondary transformation process, not associated with the production of crude steel.

Some energy efficiency improvement measures have been identified in certain sub-processes, but their implementation has not been feasible according to technical and economic analysis.

An energy saving sub-process is direct quenching which is a Finnish invention allowing the production of ultra-high strength steel products with high elongation directly from hot rolling without cooling between process steps.

Lime and oxygen are procured, i.e., they are not part of SSAB's energy consumption in the energy statistics.

The product mix with a large number of specific steel grade and measure combinations adds energy consumption.

The SSAB plant in Finland, like most European steel plants, is relatively old but continuous investments have been made to modernization. For example, the power plant is new and blast furnaces have been subject to major overhauls. SSAB has been a forerunner in the use of process automation but other companies have been catching up.

SSAB will replace use of coke in steel production by carbon-neutral electricity and hydrogen based HYBRIT process in the Raahe plant by 2029.

4.3 Ovako: EAF Steel Production Route

In 2018, total final energy consumption in the Imatra steel mill was 442 GWh, of which about half was electricity and half natural gas.

Quality of the raw material, recycled steel, is a significant factor in energy consumption.

The electric arc furnace uses 70% of all electricity consumed at the plant. At the moment of the interview, natural gas burners were not in use. Ovako considers that the energy efficiency of its EAF is in the mid-range compared to competitors. The charge size of 75 tonnes in the EAF is relatively small; most efficient units have charge sizes of over 200 tonnes.

Recent increases in the pouring temperatures reduce the energy efficiency of melting but simultaneously reduce the energy consumption of the ladle furnace.

Rolling is not part of energy consumption of crude steel but secondary transformation. Energy efficiency of the heavy bar mill (products in the size range of Ø95-200mm) is extremely good because of direct charging at hot temperature. This is not yet very common as only a few Japanese competitors are using the method. The method is described in the BAT reference document (BREF) of the Ferrous Metal Processing Industry as a BAT example (European Commission 2001).

Energy efficiency of the medium bar mill is considered to be at appropriate level but not nearly as high as in the heavy bar mill. All and all, double rolling is an energy consuming process. The rolling mill operates five days a week. Therefore, the soaking and heating furnaces that heats the blooms and billets to the rolling temperature are at stand-by temperatures of 600 ◦C over the weekend.

Hardening and tempering furnaces are partly old technology with mediocre insulations. New ones have good energy efficiency levels.

Ovako procures the needed burned lime and air gases, meaning that energy used in their production is not part of Ovako’s energy balance. It also procures all the electricity it needs.

All and all, the combinations of different sub-processes in melting and secondary metallurgical processing among EAF producers vary quite a lot making comparisons of different steel plants quite challenging. In addition, the product mix is a major factor. At Ovako, the number of different products is high composing of about 500 possible end-products with about 200 being made more regularly. Batch size is quite small as Ovako is not a bulk producer but typically produces highly specialized steel products for very demanding end-uses.

4.4 Outokumpu: Stainless Steel and Ferrochrome

In 2019, the energy consumption of the Tornio integrate was about 4.9 TWh and it is the single largest user of electricity in the whole country; consumption of electricity was 2.9 TWh. Natural gas consumption was 0.9 TWh, CO-gas 0.6 TWh and heat consumption 0.4 GWh in 2019. Procured coke is not an energy input but raw material, meaning that it is not reported into the energy statistics, but it is included in emission inventories.

Each year about 1 TWh of carbon monoxide is formed in ferrochrome production. Outokumpu feeds part of the carbon monoxide back to ferrochrome and stainless steel processes and about 360 GWh is sold to local power plant and lime plant. About 100 GWh/a of heat is recovered from the hot rolling mill and fed into the district heat network at the integrate site. Furthermore, 25 GWh/a of heat is sold to local service producers.

The largest energy consumer on the Tornio site is the ferrochrome plant. It consumes 1.75 TWh electricity and 0.320 TWh of the carbon monoxide produced within the ferrochrome process itself. Energy consumption in ferrochrome production in is very close to the theoretical minimum and only two thirds of the level in traditional processes.

As about a quarter of ferrochrome produced is processed outside Tornio, all energy used for the production remains in Outokumpu's energy balance whereas the semi-products and product tonnes exported are not included in the specific consumption of Outokumpu's stainless steel production.

A unique feature of the integrate is that molten ferrochrome is fed to the steel melt shops which significantly reduces energy consumption. There are no other similar examples globally. The stainless steel melting shop used 649 GWh electricity and 97 GWh natural gas in 2019.

Outokumpu produces all compressed air needed, which is a large energy consuming sub-process.

At the moment, Outokumpu is implementing digitalization projects which, among other benefits, help to optimize energy consumption and hence improve the specific energy consumption. Overall energy efficiency of the ferrochrome plant is already excellent. The level of heat recovery in the integrate is already very good. Some further potential could be found in the utilization of side-streams but the use of the largest one, carbon monoxide, is already at excellent level. The RAP line (rolling, annealing and pickling) is state of the art enabling a more integrated rolling process and larger production series.

Outokumpu operates its' own chrome mine and enrichment facility in Kemi near Tornio but the energy consumption of the mine is allocated to the mining sector, not metal sector in energy statistics.

One of Outokumpu's operating principles is to use best available techniques (BAT) to reduce emissions and minimize harmful environmental impacts that could result from the Group's operations. In this context, BAT means the best available pollution prevention technology from both technical and economic perspectives. Outokumpu is also an active participant in the process of updating the reference documents (BREFs), which specify related technologies, helping to set the high standards applicable within the European Union.

4.5 Boliden: Zinc

In 2019, the energy consumption of Boliden zinc mill in Kokkola was 1.4 TWh of which 1.2 TWh was electricity. Sales of steam and district heat are about 380 GWh per year.

Electrolysis is the main energy consuming sub-process contributing 70% to the total. Leaching and leach purification account for 20% of the total. main consumers of the remaining 10% are the foundry, roaster and acid plant.

The company reports that globally the zinc processes are quite similar to each other. Therefore, particularly European plants can be relatively well compared with each other, which is not the situation with most other metals. Plants with unusual process solutions may be found, e.g., when a plant is integrated with another one.

In electrolysis, energy efficiency depends on the size of electrodes which reduces the electric current density (A/m^2) and consequently energy consumption. New plants tend to have larger electrodes which is, naturally, also a matter of cost. Kokkola plant uses relatively high current density to maximize the production volumes with current cell house structure.

The particular strength of the Kokkola plant is heat recovery and sales of steam and district heat. If there was more demand for district heat, even more could be supplied. New investments would be necessary to produce steam at higher temperature levels.

Factors like quality of raw materials or product mix do not appear to be as profound factors in the energy efficiency in zinc production as is the case with some other metals. Using of recycled zinc does not necessarily reduce energy consumption because it is oxidized requiring reduction where coal is needed.

Technically it is possible to reduce the amount of waste, mainly iron residue, in zinc production by using pyrometallurgic waste treatment processes which significantly increase energy consumption. This could partially explain the differences in energy consumption between sites. These processes are mainly used in Asia, China and South Korea being the forerunners.

4.6 Boliden: Copper and Nickel

In 2019, the energy purchase of Boliden copper and nickel mill in Harjavalta and Pori electrolysis unit was altogether 562 GWh while energy sales were 326 GWh putting the net energy consumption at 236 GWh.

Enriched copper contains significant amount of all energy needed in the whole production process. Therefore, quality is an important factor both in terms of yield as well as possibilities for heat recovery in the waste heat boiler. Fortunately, the quality variations in enriched copper are moderate. They are more present in enriched nickel.

The exothermic flash smelting process releases more energy than it consumes oil.

The converters produce heat and need to be cooled down using recycled copper. The slag concentrator uses significant amount of energy mainly in grinding.

Although the plant is relatively old, sub-processes have been subject to continuous renovations. As an example, the electrolysis started using acid-proof steel sheets (permanent cathode) instead of starting sheets made of copper in 2007, which alone reduced electricity consumption by 20%.

Calculation of specific consumption of different metals is very complicated in a multi-metal factory. The problems to solve include allocation of energy inputs to different end-products as well as handling of sold semi-finished products. Nickel is sold to clients as nickel mattes containing 50% of nickel. Some copper producers report their copper production using production of anode copper, a phase preceding electrolysis, thus eliminating this energy intensive process step from the specific consumption. It is also not clear how competitors report coke, as energy use or as raw material used as reducing agent.

The plant procures the oxygen and compressed air it needs meaning that these commodities are not included in its’ energy consumption. Significant amount of process steam is sold to the near-by industrial park and part of heat is sold to a local municipality as district heat.

4.7 University of Oulu (Steel)

The university carries out plenty of research on coke-making and blast furnace processes, the latter being the largest energy consuming sub-process in iron ore based steel making. Although research in energy efficiency is increasing, energy efficiency itself is not necessarily the primary objective and the main one is efficient use of materials. Therefore, material efficiency has been the major focus in research for the last ten years. Another major driver are emission reductions; a huge undertaking (hydrogen based HYBRIT-project) at SSAB is underway which will dramatically reduce emissions but just as drastically increase use of renewable electricity.

Coke-making plants are large energy users and producers of CO_2 emissions. Temperatures may never decrease under 500 ◦C and once in operation, coking plants operate decades non-stop. European coking plants are relative old, and they are subject to life extensions – not always in very sound and robust ways. The quality of coal, such as humidity, have an impact of energy consumption in coking plants.

Quality of iron ore pellets used in blast furnaces, have an impact on slag formation. At SSAB, slag formation is small compared to the volume of pig iron produced. However, slag too is a by-product. In recycled steel, there is also a lot of variation in the quality of raw material, but all produces use same sources in the world markets.

The energy efficiency levels of blast furnaces are already quite close to optimal levels with thermodynamic laws or physics limiting improvement possibilities. Use of hydrogen, however, could reduce CO_2 emissions.

In electric arc furnaces up to 10% savings could be achieved by developing on-line monitoring of the progression of melting instead or running the process based on mass calculations; this is a subject of ongoing research. Electric steel producers inject coal dust to the electric arc furnace replacing some of the electricity needed; this is not done in production of stainless steel. In the future, coal could be replaced by biochar, possibly produced using low energy flows from the process. The bonus of biochar is that it does not contain sulphur.

Making better use of side-streams has been a growing trend for ten years. This has not always been preferred because secondary flows may reduce the yield of the (high-value) primary metal. Cost structures as well as pressure on sustainability have been changing the situation and efficient use of materials is really high on the agenda.

Rolling is an energy-intensive process. The best practice is direct hot charging which saves a lot of energy. This, however, is easiest when there is no large variety in the product mix. The number of different product grades and their level of specialization is high in all Finnish plants.

Energy consumption in lime production is defined by physical laws meaning that there are virtually no possibilities to make the processes significantly more efficient. A more important factor is the quality of lime.

A specific feature to the Finnish metal plants is that they are strongly integrated which reduces specific energy consumption but may reduce flexibility of the process. Electric steel process is more flexible to respond to demand changes than oxygen steel process. However, also the running of blast furnaces is changing because of the volatility of demand which, in turn, hinders the possibilities to reduce specific energy consumption.

4.8 Aalto University (Non-Ferrous Metals)

The level of metallurgy in non-ferrous metals in generally better in Europe than, e.g., in China. Although yield and production levels are high in the agenda – over matters such as energy efficiency – there is also a strong emphasis on quality. Strong environmental regulation, as well as sometimes close location of plants to the urban areas, necessitate focus on environmental considerations.

In Europe, metal plants and some core processes tend to be already somewhat old although many auxiliary equipment are state-of-the-art.

Raw material markets are global meaning that all producers use quite similar raw materials. Generally, the contents of valuable minerals in ores have declined and minerals processing is used to even out the differences. In copper, processing of gangue consumes energy and reduces the calorific value of the raw material. Differences in raw materials can, however, be somewhat compensated with good process control.

European producers, e.g., in Finland, Germany, Spain and Bulgaria use energy efficient flash smelting which can be used in copper and nickel production. In China, use of molten bath and top blown methods have become increasingly common despite of poorer energy performance. The benefit of flash smelting is that it uses the energy within the concentrate feed mixture and additional energy is needed only to compensate for the heat losses.

Declining mineral contents in ores has increased the use of hydrometallurgical processes. In the production of copper and nickel, the use of flash smelting as well as molten bath processes require grinding the ore into smaller particle size, the energy consumption of which depends on the particle size; the smaller the size, the more energy is used.

In the cleaning of copper slag, the technology options are more energy efficient electric arc furnace and slag concentrator with grinding-flotation method. Harjavalta is using the latter technology.

4.9 Metso Outotec (Technology Supplier)

Metso Outotec Corporation, created through a merger in 2020, sells globally technology, process equipment and life cycle services for the production of metals and minerals. It has developed environmentally sustainable technologies for the production of metals. The internal goal of the company is that emissions from the production of its own technology would always be 10% than that of competitors.

The company emphasized the need to monitor emissions rather than simply energy efficiency and covering the whole value chain from the mines to production and to recycling. In this respect, increased use of electricity is a way to cut emissions when national energy production is strongly relying on renewable energy, like in Finland[9]. Stronger reliance on electricity, however, does not necessarily lead to energy savings.

In the metal industry, all steps in the value chain and sub-processes and so large users of energy that even small savings percentage leads to large absolute savings. All equipment suppliers aim at lowering the energy consumption and improving other environmental features in their product mix. Outotec has been calculating the emission handprint of its technology; in 2019 this was 5-6 Mt/CO_2. From this year, Metso's operations will add to the handprint.

Metso Outotec sees Europe as rather uniform from the technological point of view. Age of main processes in the plants is rather high whereas somewhat newer plants can be found in China and North America. As the plant lifetimes are extremely long, changes are slow too and long-term planning can be difficult both from the company perspective and in industrial policy.

[9] In 2019, the share of renewable energy in Finland's total primary energy consumption was 37%. In domestic electricity production, the share of renewables was 46% in 2018.

In the interview, three main technological development streams were mentioned as the focus in metals production. The development of flash smelting has been one key innovation. Another focus area is new process equipment and third one zero-emission (coke/coal free) iron production. New efficient solutions are being developed also for other process steps than smelting (hydrometallurgy and chemical processes). There are, e.g., solutions for the reduction from oxides to metal. Other areas subject to improvements are grinding, crushing, extraction, filtering and pumping. In recycling, technologies for compacting used metal products, crushing and re-use allows taking used materials into use in a more efficient way.

Foundries are not as energy intensive as metal plants but there is energy efficiency potential there as well.

The interviewee considered the geographic location far away from raw materials and clients to be a small handicap for Finland together with the climate. High maintenance costs are a negative factor for energy efficiency as well. However, there are more positive factors for the use of modern technologies including the general high level of know-how and high level of education as well as open sharing of information and availability of peer support because the Finnish metal industries are not competing with each other.

5 Summary and Conclusions

Here, we first conclude what international comparison results seem to suggest on the energy efficiency of Finnish energy-intensive metals production industry based on specific consumption indicators and then summarize which are the underlying factors for these results.

While comparisons are hard to make and interpret, they suggest that the overall energy performance is good as the result of early attention to consistent energy management, constant technological development and innovation as well as energy efficiency policy supporting the processes.

5.1 International Comparisons

Comparison Results Based on The Odyssee Database

Finland is in the mid-range in the Odyssee specific consumption of steel production. In Chapter 3.1. multiple reasons were given why ***the information value of this simplified indicator is zero and we cannot conclude whether the result is correct***:

- Countries are using electric steel (EAF) and oxygen steel making (BOF) process routes in varying degrees. The specific consumption of these two basic processes are profoundly different muddling the simplified comparison. Best BF-BOF process routes can consume 6-7 times more energy than best EAF process routes.
- While system boundaries in energy statistics are clearly defined as such, the ownership structure within one steel plant or integrate can lead to variations in the inclusion or exclusion of process units. For example, an oxygen plant, a lime incinerator or a power plant may be owned by another company operating, e.g., in the chemical or energy sector and their energy consumption is reported to the respective Nace classes. This automatically reduces the specific consumption.
- Energy consumption and volume of product are not a pair:
    - Energy consumption of manufacturing of steel products (Nace 24.2 and 24.3) is included in the specific consumption where the divider is 'tonnes of crude steel'.
    - Energy use covers all energy use of the metal company, but production only includes crude steel production.
- At the end of the process, there can be differences, e.g., in the inclusion or exclusion of rolling or other thermomechanical processing which are energy-intensive and can contribute up to 50% to the total final energy consumption of the integrate.
- Sintering of enriched iron ore fines may be done within the steel plant or the plant can use procured sintered iron ore pellets. The impact of sintering is around 10% of the energy consumption of a tonne of crude steel.
- In the ODYSSEE database, fuels used for the production of sold heat are not reduced from the energy use of the industrial sub-sector.

- Plant sizes, heat sizes, capacity utilization rates and product mix (quality of products and the number of different grades) all have a considerable impact on energy consumption.
- Intermediate stainless steel products and surplus ferrochrome exported from Tornio are not included in the de-nominator (tonnes) but they are part of the numerator (energy consumption).

Comparison Results Based on Wood MacKenzie's Plant-specific Data

Plant-level comparisons are a degree more reliable than national comparisons removing some of the problems caused high degree of aggregation. At the plant level, factors like profound differences at production processes can be better recognized. This does not help, however, when a plant is so unique in its' specifications that there are no international peers to compare to, such as Outokumpu's stainless steel integrate.

While considerable effort has been made by Wood MacKenzie to harmonize data definitions and to collect good quality plant-specific energy data, there were still some outliers and other oddities in the data. Yet, the amount of data is large and, therefore, gives some indication on the energy performance of individual plants companies compared to others. The Finnish metals producers themselves consider that they rank rather correctly as compared to the others.

SSAB Finland is the second best among other BF-BOF route based steel plants in Wood MacKenzie's global data. Ovako ranks in the better end of the mid-range in Wood MacKenzie's global data on electric steel production. Boliden's zinc production in Kokkola is the second best globally and copper production in Harjavalta is in the mid-range in energy performance. In the comparisons, heat and steam sold is not credited to the plants. Taking this into account could dramatically improve, e.g., the ranking of copper production in Harjavalta.

Wood MacKenzie's data does not cover the production of ferrochrome and stainless steel and no other international benchmarks have been identified for Outokumpu in Tornio.

5.2 Factors Affecting Energy Efficiency Comparisons

Impact of Statistical Procedures

Statistical procedures are of profound importance in any comparisons. Some ambivalence is caused by the definitions and procedures adopted by Eurostat which are slightly different compared to various national statistical authorities, the competence of different national statistical authorities to deal with complicated industrial processes, and finally interpretations made by the rapporteurs in industry. While considerable effort has been made to harmonize definitions and reporting, guidelines and instructions do not automatically guarantee full harmonization.

Methodologically, a key issue is system boundaries. The basic definition is very clear: energy consumption of any plant is categorized according to the Nace international industry classification of the plant owner. The implications, however, lead to different end-results depending on the ownership structure within one metal integrate as well as the combination of upstream and downstream processes it is running. The more it has outsourced both, the lower the final energy consumption. In the Finnish metals production industry, quite many commodities and services are procured including burned lime, oxygen, air gases and sometimes compressed air. In contrast, there is a multitude of downstream processes with the possibility to produce a large mix of final products of high quality.

In national and Eurostat energy statistics electricity sold by metal industry is taken into account in calculating final energy consumption. This has relatively little impact on Finnish metal industries because none of them generates electricity themselves; however, there is some procuring and reselling to subcontractors. Also sold heat is subtracted from purchased heat. SSAB and Outokumpu steel plants, Boliden's Harjavalta multi-metal plant and Boliden's Kokkola zinc plant all sell heat and steam.

Sometimes excess heat is generated in waste heat boiler or exothermic processes in industry. When this heat is sold to district heating or otherwise transferred to another company, this is not credited to the industrial plant which has generated it. Statistics Finland has recognized the issue but considers it difficult to change statistical procedures without interference to the basic logic of forming the energy statistics and energy balance. However, it fully supports the idea of trying to collect data on waste heat utilization by different means which, as the next step, could be made more visible also at the statistical level.

Selling heat is an issue in countries where metal industry produces and sells large amounts of excess heat and there is a market for it, which is the case in Finland where climate is cold and district heating is used extensively. All and all, the matter of heat recovery and sales is becoming increasingly important as it is a measure included in the national energy efficiency policy.

Outokumpu sells carbon monoxide from its' ferrochrome production to other operators. These sales do not have any impact on the net energy consumption of the plants.

Impact of Process Technology

Process choices are an important factor in energy consumption, but these cannot always be changed once decisions on the basic process have been made decades ago. In steel making EAF, which uses recirculated steel, has lower specific consumption than BF-BOF but also steel made from ore is needed. In zinc manufacturing the profound choice is between the pyro-metallurgical process and the electrolysis process, which is more energy efficient; although in Kokkola a combination is used.

There are economies of scale to be achieved in metals production. Larger blast furnaces as well as electric arc furnaces are more energy efficient and the charge sizes at SSAB's plant in Raahe as well as Ovako's plant in Imatra are relatively small. At Boliden's Kokkola zinc plant the electrodes (anodes and cathodes) used in electrolysis are not as large as in newer facilities causing an upward pressure on electric current density, and consequently energy consumption.

Plenty of technological innovations have been made in the Finnish metal industry. Flash smelting used in non-ferrous metals was developed in Finland and has been the best practice globally for decades. In steel production, direct quenching saves energy and reduces the mass of final products as they are especially durable. Finnish metal plants have been forerunners in the use of process automation – a major focus in technological development in Finland - although others have been catching up. This early usage of many efficient technologies has been facilitated by the close co-operation between the metals producers and technology companies, such as Metso Outotec (Outotec until 2020).

Impact of Raw Materials, Product Mix, Semi-Finished Products and By-Products

In steel production, use of recycled steel reduces specific energy consumption. Also BF-BOF producers use some, although SSAB reports that they use it less than the competitors. In contrast to other metals, in zinc production use of recycled raw-material does not reduce energy consumption because it is oxidized requiring reduction where coal is needed. There are variations in the quality of enriched ores, but metals producers buy these from the world market meaning that in the bigger picture all use the same raw materials.

The product mix is a very important factor in the comparison of energy efficiency of metal integrates. When comparisons are limited to the early stage products, such as crude steel, this is not as profoundly important although process choices have been made with an eye on a certain product mix. However, when also thermomechanical processes are taken into account, the volume of different end-products as well as their quality become increasingly important.

Metal industries are large multinational companies and the metal companies studied and interviewed in this study are not an exception. It is not unusual that semi-finished products are processed in group's unit in another country, e.g., a large share of black bands produced by Outokumpu. This means that the energy input remains in the Finnish energy balance while the value added is created elsewhere.

Raw materials and semi-finished products can also be sold outside the company. For example, Outokumpu sells about a quarter of the ferrochrome it produces to other companies and exports some of it to its' own plants in Europe meaning that this does not contribute to the stainless steel tonnage at Tornio but the energy consumption of this energy-intensive process stays within Outokumpu's energy balance in Tornio.

Both Boliden zinc plant in Kokkola and copper and nickel plant in Harjavalta produce sulphur acid in their processes as by-product and sell it out.

Impact of Multiple Sustainability Objectives

Today, industrial companies face a multitude of challenges related to corporate responsibility meaning that multiple sustainability goals, such as carbon emission reduction, energy efficiency and circular economy, are pursued at the same time. Reduction of carbon emissions and energy efficiency can usually be achieved at the same time. However, there may be trade-offs between energy consumption and circular economy. For example, optimization of the use of raw materials and yield or reduction of waste can lead to increased use of energy, but yet these are both environmentally desirable objectives.

In industry, electricity is replacing other energy carriers. It can reduce final energy consumption but may also reduce emissions depending on the electricity production mix as well as emission factor used, that of average domestic generation (significantly lower than for coal, gas or oil) or the marginal emission factor (higher than for fuels). SSAB will replace use of coke in steel production by carbon-neutral electricity and hydrogen based HYBRIT process in the Raahe plant by 2029. This measure alone will reduce Finland's overall CO_2 emissions by 7%, but it will increase electricity consumption of the plant 6-7-fold. Statistically the final energy consumption of the plant may grow even more because use of coke is part of the transformation sector, but increased use of electricity adds to the final energy consumption.

Impact of Economic Factors

Economic situation has an impact on the possibilities of industry to run their facilities at optimal load. When demand for products declines in sluggish economic situation, industrial processes cannot always be adjusted accordingly. This is particularly the case in highly integrated process industries.

Companies also need to optimize their costs related to all process inputs including materials and energy. For example, running of a coke plant can be optimized from the point of view of energy consumption or cost.

5.3 Recommendations

The following recommendations are made based on the findings in the study:

- When any comparisons at the national or plant level are being made, the analysis should be extremely transparent in regard to the underlying uncertainties.
- Country level data is best when used for monitoring progress within one country, not in country comparisons.
- Energy efficiency of energy intensive industry should never be measured using energy intensity indicators because value added is strongly affected by prevailing economic conditions.
- Any analysis on the specific consumption of steel production at the national level should always include information on the share of oxygen and electric steel in crude steel production.
- Production of stainless steel and ferrochrome should not be calculated together with other steel production.
- Given the varying end products requiring sometimes energy intensive thermomechanical processing, comparisons should try to distinguish energy consumption of crude steel production processes from other consumption in the steel integrates. The same applies to thermomechanical processing of non-ferrous metals. This requires also good data management from producers themselves.
- Heat produced in exothermic reactions in non-ferrous metals production and sold outside the plant should be made visible in any comparisons and also in statistics. This is underpinned by the increasing importance of industrial waste heat in energy policy.
- Reduction of carbon emissions is a more high-level objective than energy saving as such despite multiple benefits resulting from energy efficiency. At the same time technological development leads to the use of new technologies which may use more energy, but which is outweighed by the emission reductions. Therefore, focus should be shifted from mere energy efficiency comparison to more comprehensive analysis of emission implications.

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