D2.6 Report on ML-MFA of existing metallurgical plants

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HYINHEAT

Credits

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List of abbreviations

Abbreviations	Explanation
BF	Blast furnace
BFG	Blast furnace gas
BOF	Basic oxygen furnace
COG	Coke oven gas
CO_2	Carbon dioxide
DRI	Direct reduced iron
EAF	Electric arc furnace
MFA	Material Flow Analysis
NG	Natural gas
SPE	Speira GMBH
SSAB	SSAB EMEA AB
TME	Toyota Motor Engineering
WP	Work package

Executive Summary

This report covers the material and energy flows and emissions of selected metallurgical plants by using material flow analysis. The steel plate mill of SSAB in Oxelösund, Sweden, the aluminium rolling mill of Speira (SPE) in Hamburg, Germany, and the engine plant of Toyota Motor Engineering (TME) were selected as case studies. In a first step, the systems were defined and are presented. In a second step, these systems are quantified using the data from the industrial partners together with literature data and assumptions. The SSAB plate mill is presented in an aggregated version with only publicly available numbers to ensure confidentiality. The rolling mill of Speira is quantified in a generalized way due to conflicting data and in order to transfer the findings of this study to other existing plants. For TME, the quantification is focused on the natural gas demand of the heat treatment furnace and the corresponding emissions.

1. Introduction

In this report, the material and energy flows as well as the emissions of selected metallurgical plants are mapped and analysed. Material flow analysis (MFA) is used as a methodology as described in deliverable D1.2. The results of the baseline definition will be compared in WP7 with the hydrogen solutions developed in WP5 and WP6 in order to evaluate the alternative heating solutions in terms of energy demand and emissions and to analyse potential systemic effects.

The three case studies cover both the aluminium (SPE and TME) and steel (SSAB) sectors. In the following, the systems are defined and quantified. This was done in collaboration with the experts from the companies and additional data from literature.

2. Methodology

2.1 System definitions

2.1.1 SSAB system definition

The plate rolling mill of SSAB in Oxelösund, Sweden, produces heavy steel plates with applications e.g. for transport, lifting, carrying or security applications. A detailed version of the current system definition is shown in Figure 1. The baseline year is 2023. The focus of the HyInHeat project is the rolling mill and its reheating furnaces. By 2027 the blast furnace steelmaking will be replaced by an electric arc furnace (EAF). Thus, we consider the steelmaking system as well to account for the interconnections and systemic effects of both subsystems.

Steel making and casting

Currently, the plant works as an integrated steel plant, using the blast furnace (BF) and basic oxygen furnace (BOF) processes. By the end of 2026, the blast furnace and the connected coking plant and BOF will be closed and replaced by an electric arc furnace (SSAB, 2023b).

In the coke oven plant, coke is produced from coal in the coke oven. Coke oven gas (COG) is generated as a byproduct or process gas. The COG is then reused as a fuel in the coke oven and in other processes within the plant. Other energy inputs of the coke oven are blast furnace gas (BFG) and smaller amounts of electricity.

Iron ore, e.g. in the form of pellets, is used in the blast furnace together with the coke and other material and energy inputs to produce liquid iron or hot metal. CO_2 (and other) emissions, slag and blast furnace gas are other outputs of the blast furnace process.

In the BOF, the carbon content of the hot metal is reduced to produce crude or liquid steel. The BOF process uses scrap and other iron containing inputs, oxygen and energy sources such as COG and electricity. Slag, CO_2 and other emissions and residues like dust can be named as other outflows.

In the EAF (starting from 2027) steel scrap and sponge iron (DRI) are melted to liquid steel using mainly electricity. Natural gas is used in the beginning of each batch to preheat the input material. The EAF off-gas contains mainly of CO, some CO_2 and smaller amounts of H_2 (Meier *et al.*, 2017) and the heat can be recovered within the furnace and also used for steam production (Bonacina *et al.*, 2024). However, it could not be used as the COG as a fuel for heating processes in the rolling mill.

The liquid steel is casted into slabs in a continuous casting line and further processed in the rolling mill. Some of the slabs produced are exported to other SSAB facilities in Sweden. Before entering the rolling mill, the casted slabs are grinded and scarfed where some scrap occurs.

Rolling mill

In the rolling mill, the slabs, of which some are annealed in electric furnaces, are cut into shorter lengths either by sawing or by torch cutting using propane. Afterwards they are reheated in two pusher type furnaces to typical rolling temperatures between 1050 °C and 1300 °C (Aries *et al.*, 2022). The furnaces are heated by the combustion of natural gas, coke oven gas, heavy fuel oil and propane. The combustion of these fuels leads to the release of CO_2 emissions as well as NO_x emissions.

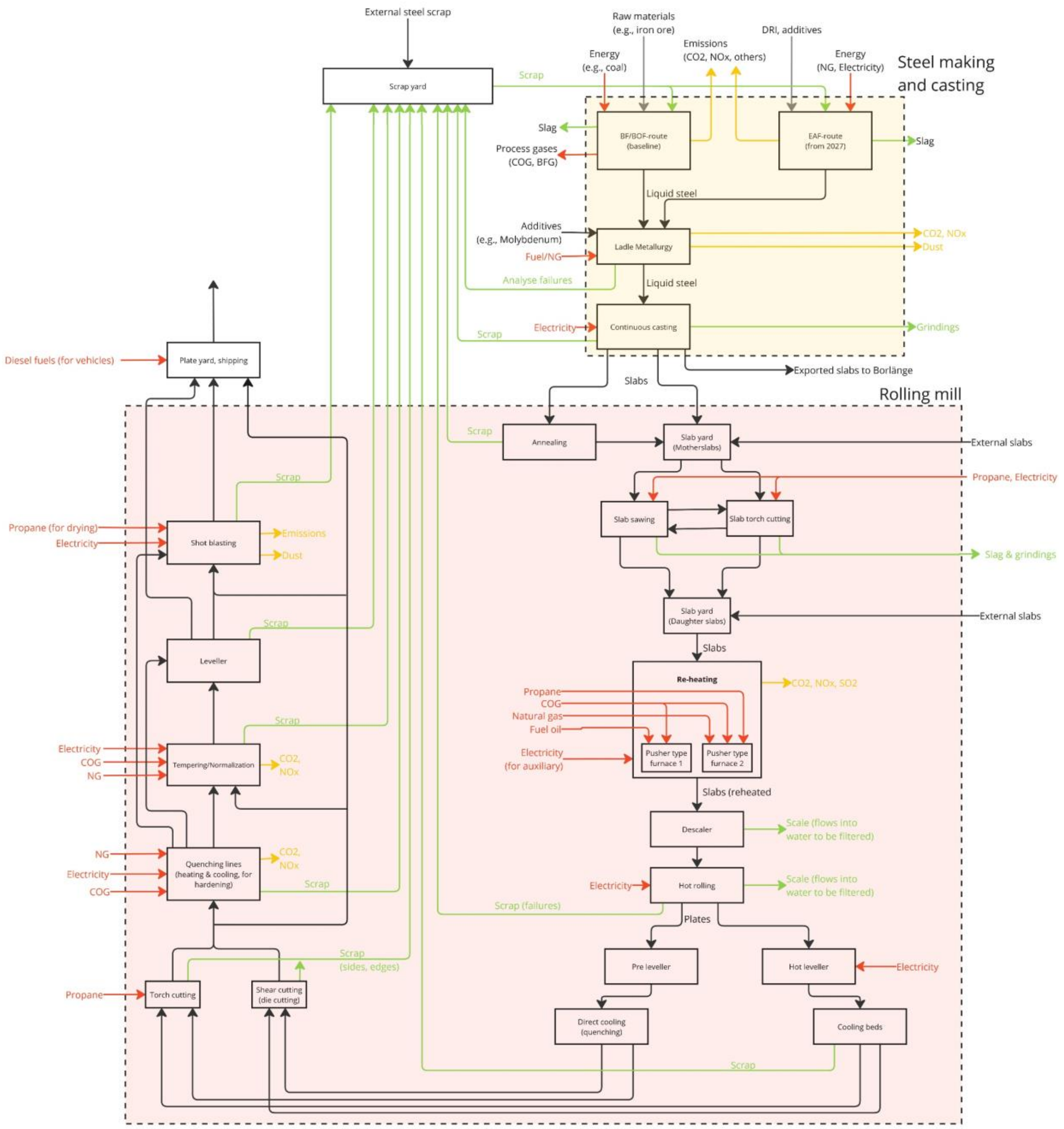

Figure 1: SSAB system definition (detailed)

The reheated slabs are further descaled and rolled to plates between 4 mm and 150 mm thickness and up to 40 m length. The plates are cooled down via direct cooling or on air. It follows a cutting process where the plates are cut into smaller sizes and where also sides and ends can be cut off, leading to some scrap.

In addition, quenching and tempering can be performed as a post-heat treatment at temperatures from 200 °C to up to 900 °C. During quenching the plates are heated and rapidly cooled down using water. The quenching and tempering furnaces use either coke oven gas, natural gas or electricity as energy sources. Levelling and shot blasting are additional processes that are performed within the rolling mill.

During all these processes, material losses occur in the form of failures, cuttings, or scale. Some processes also consume cooling water, which is not considered in the material flows here. Since the focus of this task is on the heating, only energy demand for the heating (annealing, reheating, quenching and tempering) is considered.

2.1.2 SPE system definition

The aluminium rolling mill of Speira (SPE) in Hamburg, Germany, produces aluminium sheets for building, transport and industrial applications. A detailed system definition is shown in Figure 2. The focus of the HyInHeat project is the rolling mill and the reheating furnace. However, the casthouse is included as an additional subsystem to put the energy demand and emissions of the rolling mill into perspective.

Casthouse

In the casthouse, aluminium scrap, primary aluminium and other input material such as alloying elements are melted in several melting furnaces using mainly natural gas. Scrap input can be internal processing scrap as well as external scrap. Primary aluminium is supplied by Speira's neighbour company Trimet. The liquid aluminium is then casted into slabs.

Rolling mill

In the rolling mill, the ends of the slabs are cut off during sawing. The slabs can be milled in an additional step to assure a smooth surface. Another optional step is the homogenisation where the slabs are heated to 570-590°C (Valder, 2009) to homogenize the microstructure and reduce the segregation. For some slabs, different alloy layers are combined prior to rolling in the clad assembly.

Prior to rolling, the slabs are reheated to rolling temperature (500°C - 600°C) in pusher type furnaces using natural gas. Due to the combustion of the natural gas, CO_2 and NOx emissions are generated.

The reheated slabs are rolled in several rolling stitches to sheets between 5 and 10 mm. After that, sides and ends of the sheets are cut and the sheets are coiled. The coils are further cold rolled to thinner sheets (between less than 1 mm and 5 mm). The coils are heat treated in electric or gas fired chamber furnaces during, after, or in between of the cold rolling stitches.

Levelling and slitting steps can be performed after processing where additional scrap is generated. These steps vary between different products and customer demands.

The actual production steps that are involved in producing an aluminium coil depend highly on the product specifications and customer demands. Process steps such as scalping, homogenisation, clad assembly, the number of cold rolling stitches, heat treatment, and after processing can vary significantly.

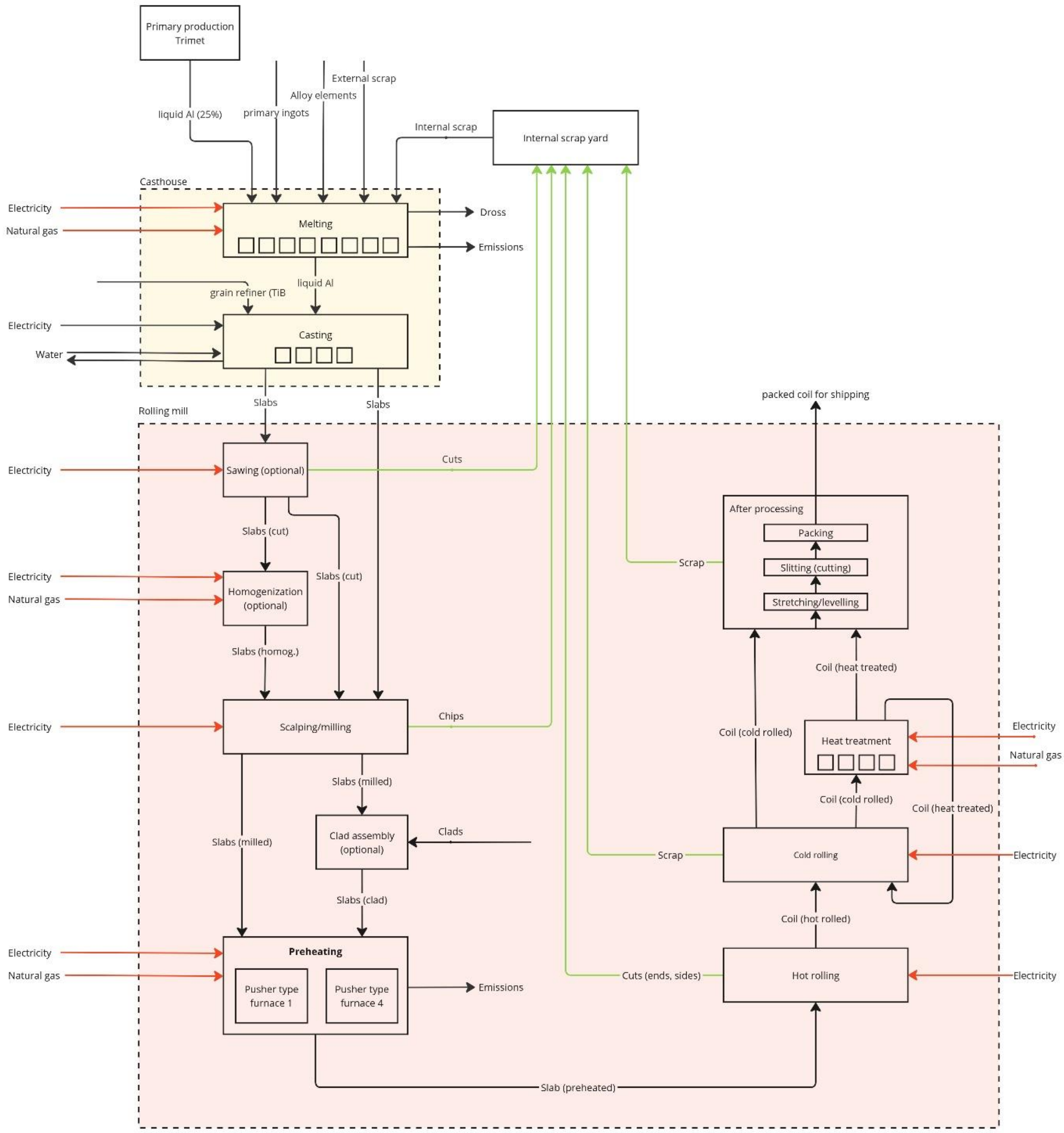

Figure 2: SPE system definition (detailed)

2.1.3 TME system definition

In the casting shop within the engine plant of Toyota Motor Engineering (TME) in Walbrzych, Poland, cylinder blocks for internal combustion engines are produced. The system definition of the casting shop and the connected processes is shown in Figure 3.

The casthouse receives liquid aluminium from an external recycling company next to the TME plant. The liquid aluminium is kept on casting temperature in an electric holding furnace. Smaller amounts of electricity are consumed during holding and some minor losses might be generated. In a next step, the aluminium is casted into cylinder blocks in a die casting machine consuming electricity. During the casting, some aluminium scrap is generated (e.g., feeders or overflows). In a first machining process, edges are smoothed out. Electricity is used for this, and some smaller amounts of scrap are generated.

The cylinder blocks are automatically moved from the machining into and out of the heat treatment furnace by robotic (un-)loading. The T5 heat treatment is performed in a rotary furnace where the cylinder blocks are heated to ~230°C. Currently, natural gas is used as a fuel which generates CO_2, NO_x and other emissions. Electricity is used for the rotating and automation of the furnace.

The removed parts are cooled by fans and under ambient conditions, further processed in a machining process, and assembled with other engine components. The machining generates additional scrap.

All scrap is collected and sent back for recycling to the supplier of the liquid aluminium. The electricity used within the plant is green electricity according to TME.

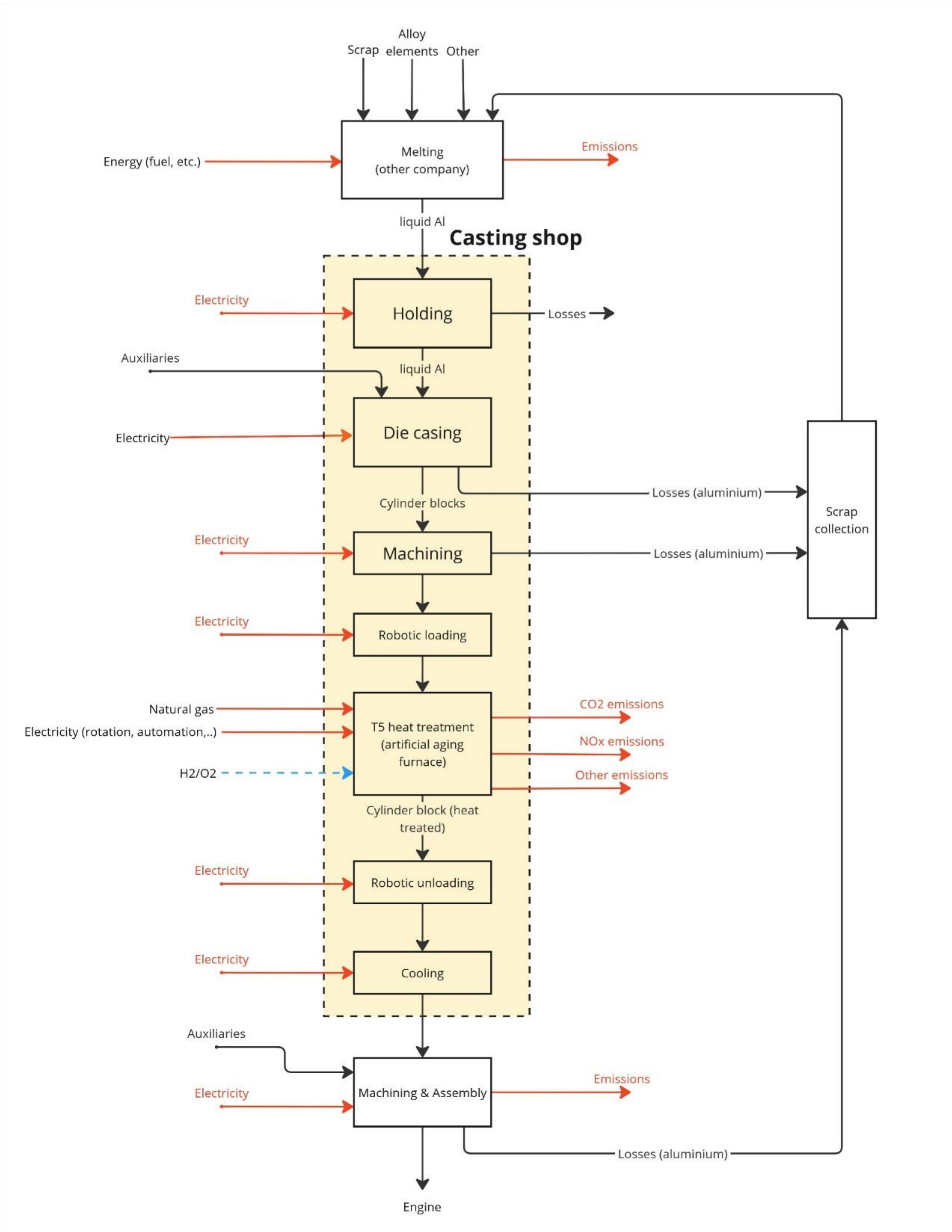

Figure 3: TME system definition

2.2 Quantification and model approaches

2.2.1 SSAB quantification

The quantification of the SSAB system (Figure 1) is based on proprietary SSAB data (public and internal), together with literature and additional assumptions when needed. Values for steel slabs casted (prior to export) and plates shipped are taken directly from SSAB's annual report (2023a). Based on these values, the parameters shown in Table 1, and mass balance, the rest of the material flows in the rolling mill are quantified. The additional losses from the "plate yard & shipping process" are used to ensure mass balance between the mass of plates produced from the hot-rolling and finishing and the total mass of plates produced.

Energy demands are calculated based on the material flows and data for specific energy demand (Table 1). Typical European reheating furnaces consume on average around 340 kWh/t (European Commission: Directorate-General for Research and Innovation *et al.*, 2011), which is supplied by different fuels in the case of the SSAB plant. Direct emissions are calculated based on emission factors for the combustion of these fuels. In addition, NO_x emissions from reheating are ~500 mg/Nm^3, but highly depend on the fuel composition and air preheating temperature (Aries *et al.*, 2022). The specific energy demand for quenching and tempering depends on the actual temperature and product. As an aggregated value, ~320 kWh/t of rolled plates can be estimated.

Table 1: Parameters for SSAB steel rolling mill

Parameter	Value	Unit	Source/comment
Steel slabs casted (in 2023)	968	kt/yr	SSAB (2023a)
Steel plates shipped (in 2023)	513	kt/yr	SSAB (2023a)
Yield continuous casting	96.5	%	Cullen et al. (2012)
Loss in scale during casting	0.45	%	13% of scrap from casting is lost as scale (Cullen et al. (2012))
Loss in casting failures	3.05	%	Rest of casting losses
Share of slabs exported	33	%	Approx. value
Share of slabs annealed	20	%	Estimated
Yield sawing	98	%	Assumption
Yield hot rolling	98.85	%	Cullen et al. (2012)
Yield cutting	92	%	Based on World Steel Association (2009)
Energy demand annealing	170	kWh/t	Assumption
Energy demand reheating	340	kWh/t	Typical energy demand of European reheating furnaces (European Commission: Directorate-General for Research and Innovation *et al.*, 2011)
Energy demand quenching & tempering	320	kWh/t	Aggregated value for both processes together; estimated based on SSAB data
Emission factor COG	0.160	$kg_{CO2\text{-}eq.}$/kWh	Based on IPCC (2006)
Emission factor natural gas	0.202	$kg_{CO2\text{-}eq.}$/kWh	Based on IPCC (2006)
Emission factor HFO	0.279	$kg_{CO2\text{-}eq.}$/kWh	Based on IPCC (2006)
Emission factor propane	0.227	$kg_{CO2\text{-}eq.}$/kWh	Based on IPCC (2006)

2.2.2 SPE quantification

For the quantification of the SPE system (Figure 2) simplifications had to be made. Due to missing or conflicting data on the plant's material flows, we used literature data to generalize the system. This also allows to transfer the findings to other aluminium plants. This generalized system (Figure 5) represents a generic aluminium hot-rolling mill producing aluminium flat products but does not account for the specific characteristics of Speira's production chain.

The starting point of the quantification is the annual production of the plant, about 150 kt of finished products (deviations might occur). Based on this, aluminium and scrap flows are calculated using the yields and parameters from Table 2 and mass balance. Energy demands are calculated based on the material flows and data for specific energy demand (Table 2). The reheating furnaces consume on average 234 kWh natural gas and 31 kWh electricity per ton of reheated slabs. Direct and indirect CO_2 emissions are calculated based on emission factors for natural gas combustion and the average German electricity mix in 2023. In addition, NOx emissions are approx. 190 mg/m^3.

Heat treatment can be done either with electric or gas fired furnaces, but we assumed that only electric furnaces were used, which could lead to an overestimation of the electricity demand for heat treatment processes. For some processes, such as castings, the energy demand could not be estimated due to a lack of data.

Table 2: Parameters for SPE aluminium hot rolling mill

Parameter	Value	Unit	Source/comment
Finished sheets	150	kt/yr	Assumption based on Speira's annual production
Yield melting	96	%	Based on Cullen and Allwood (2013)
Yield casting	98	%	Based on Cullen and Allwood (2013)
Yield Sawing	95	%	Based on Cullen and Allwood (2013)
Yield Scalping/milling	95	%	Based on Cullen and Allwood (2013)
Yield hot rolling	89	%	Based on Cullen and Allwood (2013)
Yield cold rolling	97.5	%	Calculated based on Speira data
Yield after processing	90	%	Calculated based on yields for scalping, hot rolling, cold rolling above and the yield for sheet production (0.74) from European Aluminium (2018)
Share of liquid aluminium	25	%	Assumption
Electricity demand sawing	3	kWh/t	Calculated based on Speira data
Electricity demand scalping/milling	17	kWh/t	Calculated based on Speira data
Electricity demand hot rolling	105	kWh/t	Basen on Neumeister (2007) and validated with Speira data
Electricity demand cold rolling	98	kWh/t	Basen on Neumeister (2007) and validated with Speira data
Electricity demand cutting/slitting	17	kWh/t	Calculated based on Speira data
Electricity demand stretching	3	kWh/t	Calculated based on Speira data
Electricity demand heat treatment	175	kWh/t	Based on assumption that only electric furnaces are used and that their energy demand is similar to gas fired heat treatment furnaces as in Menzler (2009)
Natural gas demand for reheating	234	kWh/t	Based on Speira data. Average data for both reheating furnaces.
Electricity demand reheating	31	kWh/t	Based on Speira data. Average data for both reheating furnaces.
Emission factor natural gas	0.202	$kg_{CO2\text{-}eq.}$/kWh	IPCC (2006)
Emission factor electricity	0.382	$kg_{CO2\text{-}eq.}$/kWh	Based on the average German electricity mix in 2023 from Ritchie and Rosado (2020) and emission factors from IPCC (Moomaw *et al.*, 2011)

2.2.3 TME quantification

Due to confidentiality, only the hourly energy demand without the corresponding material flows can be reported. Electricity demand for holding and casting is small (<1 kWh per production hour), and no indirect emissions are associated with this considering the green electricity.

The natural gas demand of the heat treatment process is ~42 kWh per production hour, leading to emissions of ~8.5 $kg_{CO2\text{-}eq.}$ considering an emission factor of 0.202 $kg_{CO2\text{-}eq.}$/kWh (IPCC, 2006). NO_2 emissions can be reported as 0.0168 kg/h. This is visualized in Figure 6.

The electricity demand for the heat treatment, robots, fans, and other machines from other lines can be summed up to ~120 kWh per production hour. Separate electricity consumption for the processes included in this study are not available.

The values for hourly energy consumption are average values and might also include times where the machines are not working, increasing the uncertainty of these values.

3. Results

3.1 SSAB

The quantified material, energy and emission flows in the SSAB plant in Oxelösund are shown in Figure 4. Due to confidentiality, only official numbers such as the plates shipped and casted slabs is shown here. Since the focus of the project is on the rolling mill and the reheating furnace, this figure only shows the liquid steel and process gases for the steelmaking. The numbers shown here only represent rough estimates and do not represent the actual numbers of the plant. Emissions are shown for direct emissions due to fuel combustion only. Indirect emissions due to electricity use would be small due to the low-carbon electricity mix of Sweden. Energy demands are only shown for heating processes and not for auxiliary energy such as rolling or cutting.

In 2023, 968kt steel slabs were casted using ~1003 kt of liquid steel. One third of the slabs is exported while the rest is further processed in the rolling mill. Around a quarter of the process gases that are generated during the steelmaking is used as a fuel in the rolling mill. It is estimated that ~20% of the slabs were annealed in electrically heated furnaces. The reheating of the slabs in two pusher type furnaces consumed ~250 GWh natural gas, coke oven gas, heavy fuel oil and propane. The combustion of these fuels generated emissions of ~50 $kt_{CO2\text{-}eq}$.

The other main consuming heating processes are the quenching and tempering. Some steel plates might only be quenched and not tempered while for others both processes are used. Overall, ~200 GWh coke oven gas, electricity and natural gas are consumed by both heat treatment processes. This generates another ~20 $kt_{CO2\text{-}eq}$. After finishing, 513 kt plates are shipped to customers. During the different processing steps ~180 kt of scrap are generated, which is based on bass balance.

An additional scrap flow is allocated to the plate yard & shipping process as the last process within the system. In reality, this scrap is generated along the production chain of the rolling mill. However, due to uncertainties about the exact origin of the scrap, it is allocated to the end of the production chain.

The direct emissions of the rolling mill (~77 $kt_{CO2\text{-}eq.}$ in total) only represent a small share of the total plant emissions when including the blast furnace steelmaking as well. Total direct emissions from SSAB Oxelösund were 1644 $kt_{CO2\text{-}eq.}$ in 2023 (SSAB, 2023a), leading to a share of ~5% for the rolling mill.

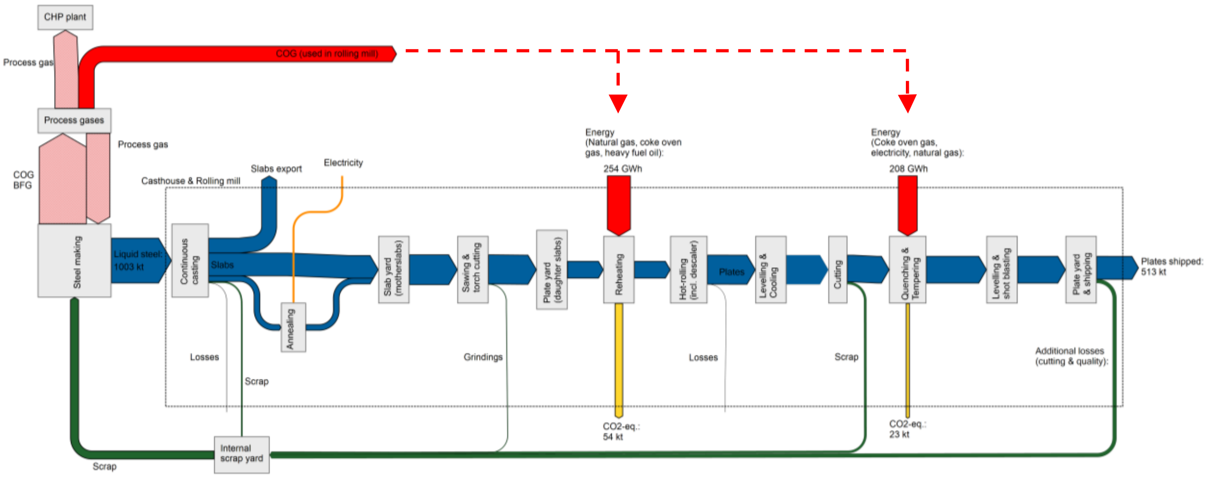

Figure 4: Quantified SSAB system, including material, energy, and emission flows. Due to confidentiality, only official or aggregated numbers are shown. The flows shown here only represent rough estimates mainly based on literature and do not represent the actual numbers of the plant.

3.2 SPE

An estimation of the quantified material, energy, and emission flows of the Speira plant in Hamburg is shown in Figure 5. These flows do not represent the actual situation at the rolling mill but are based on literature. However, they can be interpreted as a typical value chain for aluminium flat products.

To produce 150 kt of aluminium coils, ~213 kt slabs need to be casted and ~217 kt liquid aluminium must be melted. In total, 63 kt scrap is generated from sawing, scalping, hot and cold rolling, and finishing (after processing) and internally recycled. Approximately 13 kt of aluminium is lost in melting and casting dross. Melting and casting are the most relevant natural gas consumers with ~148 GWh/yr and ~45 GWh/yr, respectively. This generates ~30 $kt_{CO2\text{-}eq.}$ and 9 $kt_{CO2\text{-}eq.}$, respectively. Direct emissions from heat treatment would come in addition when using natural gas fired furnaces. Due to the relatively high carbon intensity of the German electricity mix, indirect emissions due to electricity consumption are also relevant. Heat treatment, hot and cold rolling are the largest source of indirect emissions with ~11 $kt_{CO2\text{-}eq.}$, ~7 $kt_{CO2\text{-}eq.}$, and 8 $kt_{CO2\text{-}eq.}$.

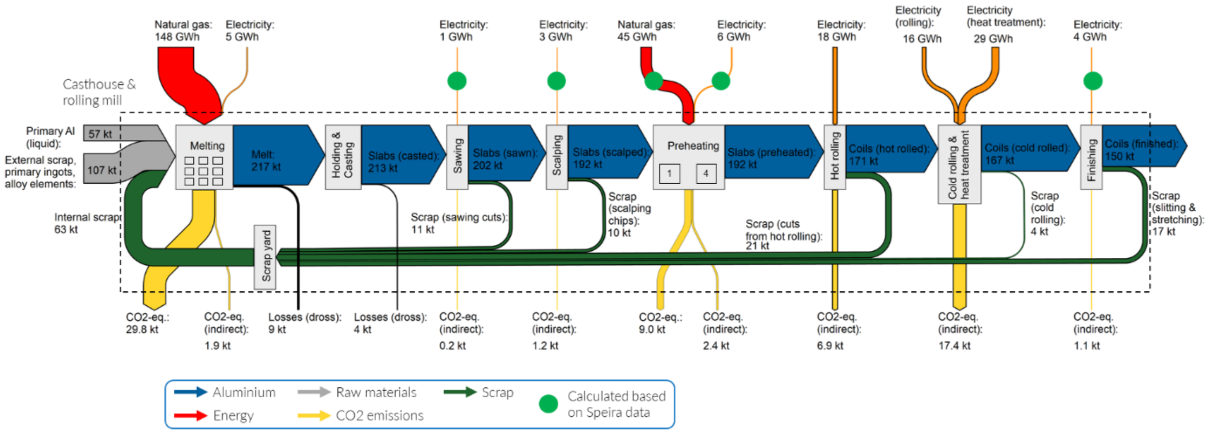

Figure 5: Generalized and quantified SPE system, including aluminium, energy and CO_2 emissions (based on literature values).

3.3 TME

The energy demand and emissions per production hour of the TME heat treatment process are visualized in Figure 6.

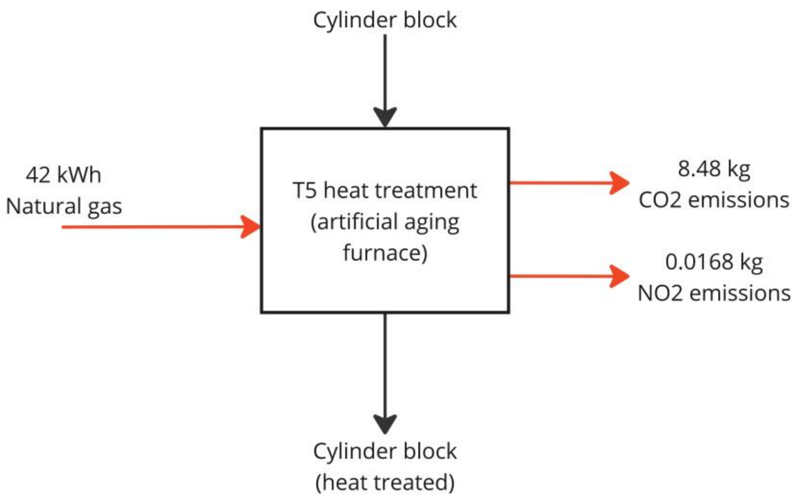

Figure 6: TME system quantified for natural gas demand and emissions of the heat treatment furnace per production hour

4. Next steps

The findings of this report lay the foundation for the further analysis in work package 7, where the baseline cases will be compared with the implementation of hydrogen combustion technologies, using life cycle assessment (task 7.2), MFA (task 7.3), and an economic analysis (task 7.4).

Scenarios for the implementation of hydrogen combustion technologies will be developed using results from the demonstrators (WP5 & WP6).

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