CHALMERS

Energy analysis of an integrated steel mill: Outokumpu Stainless – Avesta Works

Product related variations

Master's Thesis within the Sustainable Energy Systems & Innovative and Sustainable Chemical Engineering Masters programmes

VIKTOR KAMB & MARTIN LUNDSTRÖM

Department of Energy and Environment
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Cover:
The annealing and pickling line of Avesta Works.

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ABSTRACT

Knowledge about variations in energy use for energy intensive industries is becoming more important due to rising fuel prices and international competition. Many industries will need to produce a higher share of more refined products to survive. The knowledge about energy usage variations can be used for identification of potential energy and emission savings and for price setting of products.

In this master thesis the variations of the energy use of an integrated steel mill have been analyzed. The project was carried out at Outokumpu Stainless – Avesta Works in Avesta, Sweden. The aim was to identify production and product related parameters, which affect the energy use of the steel mill. Furthermore a calculation tool was built to predict the annual energy use with the annual production mix as input.

Existing energy log data was allocated to the process log data for 2010 to retrieve the energy usage indicators for each product group. This data was used to analyse the energy usage variations and was the foundation for the calculation tool. Two cases where the share of 'special' steel products was increased compared to the production mix of 2010 were implemented with the tool.

The results show that production of 'special' steel is more energy intensive than 'standard' steel. An increase of 'special' steel in the production mix could therefore increase the energy consumption, the CO_2 emissions and the production costs of the plant. Including energy related parameters in the price setting process could therefore improve it by charging the customer for the real energy costs.

Key words: Integrated steel mill, energy analysis, allocation methodology, production related variations.

Energianalys av ett integrerat stålverk: Outokumpu Stainless – Avesta Works
Produktrelaterade variationer
Examensarbete inom masterprogrammen *Sustainable Energy Systems & Innovative and Sustainable Chemical Engineering Masters*
VIKTOR KAMB & MARTIN LUNDSTRÖM
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SAMMANFATTNING

Kunskap om variationer i energiförbrukningen för energiintensiva industrier blir allt viktigare på grund av stigande bränslepriser och internationell konkurrens. Flera industrier kommer att behöva producera en större andel mer förädlade produkter. Kunskap om variationer i energiförbrukningen kan användas både till identifiering av energibesparingar, minskningar av utsläpp och vid prissättning av produkter.

I detta examensarbete har variationerna av energiförbrukningen vid ett integrerat stålverk analyserats. Projektet utfördes vid Outokumpu Stainless – Avesta Jernverk i Avesta. Målet var att identifiera produkt och produktionsrelaterade parametrar som påverkar energianvändningen. Dessutom konstruerades ett beräkningsverktyg för att förutspå den årliga energiförbrukningen baserat på produktionsmixen.

Data från energiloggar allokerades till processloggar från 2010 så att nyckeltal för energiförbrukningen för olika produkter kunde beräknas fram. Denna data användes för att analysera variationerna i energiförbrukningen och var grunden till beräkningsverktyget. Två scenarion konstruerades där andelen specialstål ökades jämfört med produktionsmixen för 2010.

Resultaten visade att det krävs mer energi för att producera specialstål än standardstål. En ökning av andelen specialstål i produktionsmixen skulle därför öka energiförbrukningen, koldioxidutsläppen och produktionskostnaderna vid anläggningen. Inkludering av energirelaterade parametrar i prissättningen av företagets produkter skulle förbättra denna process genom att kunde skulle få betala för de reella energikostnaderna.

Nyckelord: Integrerat stålverk, energianalys, allokeringsmetodik, produktions-relaterade variationer.

Contents

Preface

This report presents a master thesis project carried out for Outokumpu Stainless AB, Avesta Works. The project was done from January 2011 to May 2011 at the Department of Energy and Environment, Heat and Power Technology at Chalmers University of Technology, Göteborg, Sweden.

The project was done as a part of Avesta Works' participation in PFE (Programme for Improving Energy Efficiency in Energy Intensive Industries) run by the Swedish Energy Agency. The aim was to map and analyse the energy consumption of the steel mill. Focus was put on identifying the variations in the energy consumption in connection to different products and their production processes.

This report is written in English since it is requirement for the master programmes at Chalmers. Within the steel industry there are many technical terms in Swedish that have been translated into English in this report. These are available in a dictionary on pp. IX.

We would like to show our gratitude to our examiner professor Simon Harvey and our supervisor Nicklas Tarantino, for their commitment. We would also like to thank Torbjörn Gustavsson, Christina Wretstam, Elin Stål and the other employees at Avesta Works for their time and patience.

Göteborg May 2011

Viktor Kamb and Martin Lundström

Notations & Dictionary

Roman upper case letters

A	Area of heat transfer surface
C_i	Energy weight factor for hour i
$C_{p_{cw}}$	Specific enthalpy of cooling water
$E_{i,LPG}$	LPG consumption during hour i
$E_{x,i}$	LPG consumption for slab x during full hour i
$E_{x,in}$	LPG consumption for slab x during its inserting hour
$E_{x,out}$	LPG consumption for slab x during its exiting hour
$E_{x,tot}$	Total LPG consumption for slab x
G_i	Total weight factor for all slabs during hour i
$G_{x,i}$	Weight factor for slab x during full hour i
$G_{x,in}$	Weight factor for slab x during its inserting hour
$G_{x,out}$	Weight factor for slab x during its exiting hour
$H_{g,T}$	Enthalpy of flue gases at temperature T
$H_{y,g}$	Enthalpy of substance y in flue gas
H_{LPG}	Combustion enthalpy of LPG
$H_{l,T}$	Enthalpy of air at temperature T
$H_{steel,T}$	Enthalpy of slab at temperature T
L	Length scale for convective heat transfer
M_y	Molar mass of substance y
Nu_L	Nusselt number
P_{pump}	Pump power
$\Pr$	Prandtl number
ΔQ_{slab}	Heat absorbed by slab
Q_l	Energy in combustion air
Q_{cw}	Energy loss in cooling water
Ra_L	Rayleigh number
T_{cw}	Temperature of cooling water
T_{out}	Temperature of exiting slab/band
T_{in}	Temperature of ingoing slab/band
T_{out}	Temperature of exiting slab/band
T_s	Temperature of surface
T_∞	Temperature of surroundings
$S_{x,i}$	Share of total residence time during hour i for band/slab x
$V_{g,v}$	Real flow rate of flue gas

$V_{l,0}$	Theoretical flow rate of combustion air
$V_{l,v}$	Real flow rate of combustion air
V_y	Flow rate of substance y
$V_{y,0}$	Theoretical flow rate of species y in combustion air
W_x	Total electricity consumption for band/slab x
W_i	Electricity consumption during 'whole hour' i
$W_{i,ins}$	Electricity consumption during inserting hour i
$W_{i,exit}$	Electricity consumption during exiting hour i

Roman lower case letters

g	Gravitational constant
g_0	Theoretical specific flue gas flow
g_v	Real specific flue gas flow
h	'Lifting height' (lyfthöjd)
h_{conv}	Convective heat transfer coefficient
k	Thermal conductivity of air
l_0	Theoretical specific air demand
l_v	Real specific air demand
m_{cw}	The mass flow of cooling water
m_{slab}	The mass of a slab
m_x	The mass of slab x
$n_{y,g}$	Amount of substance y in flue gas
Δp	Differential pressure in furnace
q	Volumetric flow rate of cooling water
$t_{x,in}$	Time period slab/band x is inserted into the furnace
$t_{x,out}$	Time period slab/band x is exiting the furnace
$t_{x,ins}$	The 'whole hour' slab/band x is inserted into the furnace
$t_{x,exit}$	The 'whole hour' slab/band x is exiting the furnace
v_g	Flow rate of combustion air out of windows

Greek lower case letters

$\varepsilon_{furnace}$	Emissivity of furnace surface
ε_{tot}	Total emissivity of flue gases
ε_y	Gas emissivity of substance y in flue gas
$\Delta\varepsilon$	Correction factor for flue gas emissivity
λ	Air excess ratio
ρ_g	Density of flue gases
ρ_l	Density of combustion air

ρ_y	Density of substance y
σ	Stefan Boltzmann's constant
τ_i	The total residence time of all slabs during 'whole hour' i
$\tau_{x,i}$	The residence time for slab/band x during 'whole hour' i
$\tau_{x,in}$	The residence time for slab/band x during the 'inserting hour'
$\tau_{x,out}$	The residence time for slab/band x during the 'exiting hour'

Dictionary

Annealing	Glödgning
Annealing and pickling line (APL)	KBR - kallt, brett, rostfritt
Blasting	Blästring (slungabehandling)
CGS	Slabs ID-nummer på varmbandsverket
Casting box	Gjutlåda
Charge	Stålsmälta/smältomgång i stålverket
Chill	Kokill
Coiler furnace	Haspelugn
Cold grinding (CG)	Kallslipanläggning
Continuous casting	Stränggjutning
Electric arc furnace (EAF)	Ljusbågsugn
Hot grinding (HG)	Varmslipanläggning
Hot rolling mill (HRM)	Varmbandverk
Hydroflouric acid	Flourvätesyra, vattenlösning av HF
L76	Linje 76 - glödgnings och betningslinje
Ladle furnace	Skänkugn
Pass	Stick
Pickling	Betning (syrabehandling)
Recuperator	Rekuperator/luftförvärmare
Roughing mill	Förpar
Run	Körning
Run program	Produktionsväg
Steckel/steckel mill	Steckelvalsverk
Steel mill (SM)	Stålverk
Strand	Sträng
Switchgear	Ställverk
Walking beam furnace (WBF)	Stegbalksugn

WRD oil	Eldningsolja liknande EO1
Z-high	Kallvalsverk

1 Introduction

1.1 Background

The steel industry is the second largest energy consumer in Swedish industry (Swedish Statistics, 2009). Although many improvements regarding the energy use have been made, the potential for further savings within the industry is still significant (Dahl et. al, 2008). Outokumpu Stainless AB, Avesta Works produces a wide range of stainless steel types, specializing in stainless ‘special steel’, which means high temperature resistant, high alloy and duplex steel. Some statistics about the production mix of the mill are presented in Table 1.1.

1.1.1 Production at Avesta Works

The plant constitutes of three main departments: Steel mill (SM); where metal scrap is melted and then cast to slabs, Hot rolling mill (HRM); where the slabs are rolled in a heated state and Annealing and pickling line (APL) where the steel is surface treated and cold rolled. Since the steel mill is of electric arc furnace type (EAF) the electricity consumption is significant. Apart from electricity, the energy consumption of the plant consists of liquefied petroleum gas (LPG) and WRD oil – EO3A (Svenska Shell, 2010). The energy consumption has, as well as being directly connected to CO_2 emissions, an appreciable influence on the production cost. The use of energy and other resources at the plant can be seen in Table 1.2. Note that the CO_2 emissions only include the emissions on site and does not include emissions from electricity usage.

The end product of the plant is a thin steel plate (1-13mm thick) which is called a ‘band’. These are usually 100 to 500 meters long and are transported and sold as rolls. The plant produces the steel on order, the process is of batch type and the type of product that is processed at each department can change quickly (every hour). For example at APL, about three bands per hour are processed, and the type of steel and thickness of the band processed changes very often. The time from melting of the scrap at SM until the band is finished at APL is approximately three weeks. All of this time is not effective production time though as the slabs usually lie outside waiting for processing at HRM. The effective production time depends on steel type, production logistics and if any reprocessing has to be done. Furthermore, bands might have to be reprocessed or scrapped at different parts of the plant. All of this implies that the energy consumption can vary rapidly in time and between different products.

Table 1.1 Annual production mix for 2010 at Avesta Works. (Löfgren. A, 2011)

Steel type	**Ton delivered**	**Percent**
1	133 155	71,1%
2	25 284	13,5%
3	13 058	7,0%
4	11 704	6,2%
5	3 345	1,8%
6	824	0,4%
Total	**187 370**	

Table 1.2 Energy and resource usage at Avesta Works (Tarantino. N, 2010 & Mogard. S, 2008).

Energy use (2010)	**[MWh/year]**
Electricity	358 621
LPG	239 418
WRD oil	103 185
Production (2010)	**[Ton/year]**
Production Steel mill	352 126
Production Hot rolling mill	322 699
Production Annealing and pickling line	194 139
Resource usage (2008)	**[Ton/year]**
Metal scrap	364 271
Alloy substances	102 730
Dehydrated lime	53 102
Fluorspar	6 464
Dolomite	10 355
Pulverized coal	1 886
CO_2 emissions (on site)	125 218

1.1.2 PFE

Avesta Works is since year 2004 part of the "Programme for Improving Energy Efficiency in Energy Intensive Industries" which is run by the Swedish Energy Agency. The industries that join and complete the programme get an energy tax cut. The first two years of the programme involves an obligation of mapping and analyzing the energy consumption and its variations as well as introducing a certified energy management system. During the three remaining years there is an obligation of working with improving the energy efficiency of the facility. Both after the first and the second period the work has to be presented to the agency and approved by them (Swedish Energy Agency, 2010). Avesta Works has completed the first five-year period and is now in a second five-year period, which will run until 2014. This means that during 2011 the mapping and analysis of the energy consumption has to be presented.

In connection to PFE the energy consumption of the plant has been surveyed and several investigations regarding possible process improvements have been done. One example is improved preheating of the metal scrap. Investments were done in new scrap metal baskets so that a larger share of the metal scrap can be preheated to the target temperature 300°C before being melted in the electric arc furnace. However, no overall investigation of how the production mix affects the energy consumption has been done.

Avesta Works wants to increase their share of 'special' steel in their production mix, which could results in a higher specific energy consumption. This would have to be motivated for PFE since the programme only looks at the energy consumption per produced amount and not at the type of steel produced. Quantifying this potential change in energy consumption is therefore of great importance for the future.

1.1.3 CO_2 emissions

As stated earlier the energy consumption has a strong connection to CO_2 emissions. Starting in year 2013 the trading system for emission permits will have tougher rules. During the two previous trading periods the allocation of permits was done nationally, based on 'grandfathering'. This means that the permits were acquired for free based on historical emissions. For the new period (2013-2020) the allocation will be done partly by 'benchmarking'. This means that emissions will be compared with the average of the 'EU-best-practice-10-percentile'. Industries that are not subject to international competition will be given permits for 79% of 'best practice' and pay for the rest. Industries that are subject to international competition (like Avesta Works) will pay for their emissions exceeding 'best practice'. All of the emissions will be sold by auctioning and the amount of free permits will decrease gradually in the future (Swedish Environmental Protection Agency, 2010).

The tougher rules are expected to increase the price for electricity in the European Union and this increase will probably have a larger impact than the cost for emission rights for electricity intensive industries (Swedish Environmental Agency, 2006). So due to these new rules the CO_2 emissions are of interest to Avesta Works both due to environmental and economic reasons, especially in connection with the potential change of production mix.

1.1.4 Price setting

A more detailed knowledge about the specific consumption for different products could also be helpful in the price setting process of products. Today the energy cost is allocated to the products with the energy consumption included partially. The price setting of the produced steel at Avesta Works is dependent on different so called "drivers". Some examples of drivers are raw material costs, processed weights and residence times in different units. The electricity consumption of two process parts (electric arc furnace and the ladle furnace) are included as energy related drivers. Fossil fuel is not used as a driver. If the energy consumption for different steel types was known in detail this could be included as drivers in the price setting. Thereby the customer could be charged for the actual energy and emission costs for the steel type requested.

1.1.5 Summary

Partial studies of the influence of different production parameters on the energy use have been done for some sub process parts. But no investigation of the whole plant has been done. A survey of how the energy use is affected by which type of steel that is produced and under which circumstances would as stated above be of great use in many issues. These are: communication with authorities and in especially in connection with PFE, to identify where further production and process improvements could be done and for prediction of production costs and CO_2 emissions.

1.2 Objective

The main objective of this thesis is to map the difference in energy consumption (for the whole plant) between the production methods of different steel qualities. Furthermore, an identification of the most important product and production parameters that affect the energy consumption is to be done. This together with an analysis of possible improvements regarding equipment and production patterns. The main end product of the work is a 'calculation tool' for estimating the energy consumption and emissions for the whole plant for a production year, with the produced steel qualities as input.

1.3 Problem Analysis

The gathering of data for the survey is a time consuming activity. Thereafter the unimportant data has to be filtered, which demands a good insight into how the process works. The data is generally logged in three different systems for each of the three departments. One process log, where product ID-number, steel type, dimensions, temperatures etc. can be found. The other two logs are for electricity and fossil fuel. The time steps used for the logging systems are not of the same size and vary for the process logs. This together with the complexity of the production pattern at the plant makes the process of sorting and aggregating data rather complicated. Because of the differences in time steps between data logs, methods for inserting and allocating the energy data into the process log must be developed. Furthermore, the linking of the results from the three departments must be planned initially.

1.4 Methodology

A flowchart of the work procedure can be seen in Figure 1.1. The end results of the project are marked with red borders. The project started with a literature study to gain insight in how the steel making process works and to understand the most important energy aspects of it. Since some mapping work already was done for parts of the plant the project carried on with a study of this work. Learnings from this study was methodology regarding data gathering and structuring, and other conclusions made.

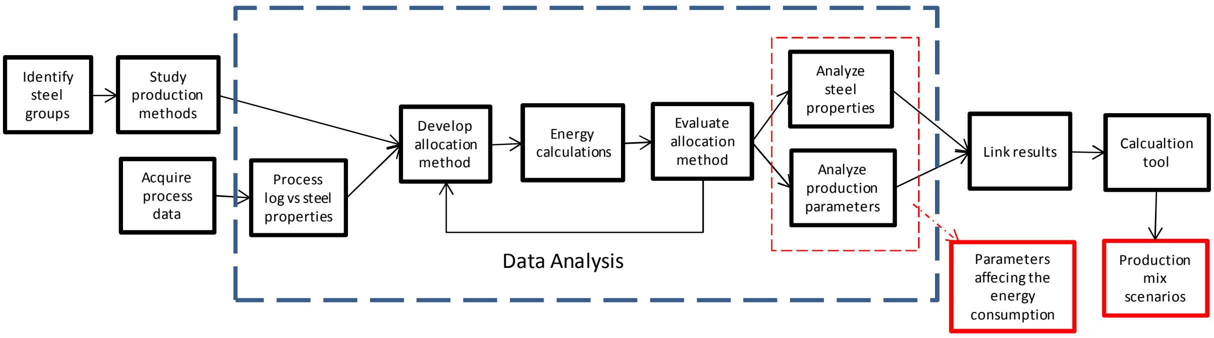

Figure 1.1　　Flowchart of analysis procedure.

A study of the different steel qualities produced was done and these were divided into different groups depending on steel type, surface, thickness etc. Thereafter the production methods for each group were studied beginning from the back end of the process, i.e. APL. This because it is here that the largest differences between the products are created. A summary of the possible relations between product and production parameters and the energy consumption is found in Chapter 3. Process log, electricity and fossil energy consumption data was acquired and imported to MS-Excel. The data was taken for the whole production year 2010. This because the process at the plant has evolved both physically and operationally in recent years, so using older data would not have been accurate.

Then the process log was studied to find out how production parameters relate to steel properties. Based on this study a method for linking energy and process log data was evolved. This method was used to insert and allocate the energy data to the process log and then do the energy calculations. The ‘allocation method’ was evaluated by comparing the real energy consumption with the estimated energy consumption in the process log. Furthermore, tools such as energy balances, analysis of ongoing process reactions as well as molecular species balances were used where applicable (e.g. furnaces) for evaluation. The allocation methods are described in Chapter 4 and more information about the choice of the analyzed data can be found in Chapter 5.

When this had been done the effect of steel properties and production parameters on the energy consumption was analyzed. During this analysis possible process or production improvements were identified. The results from this work can be found in Chapter 6, and a summary of the identified parameters in Section 6.8. Due to the large amount of data pivot tables were used in MS Excel. This procedure was repeated for each of the three main parts of the plant. The results from the three production plant units were then linked together and provided the basis for the ‘calculation tool’ which was constructed in MS Excel. The calculation tool was then used to predict how a change in production mix affects the energy use, which is described in Chapter 8.

1.5 Limitations

The study focused on fossil fuel and electricity usage so other media and chemicals were excluded since this would rather be mapped in an LCA-analysis. However, two exceptions were made to this. Firstly, significant amounts of oxygen are used in some process parts and air separation is a rather energy intensive process, therefore it was included. Secondly, some chemicals are added which fuel exothermic reactions in the steel mill, so these were included. Energy consuming units that are not affected by the product produced were not analyzed in detail. However, data for all processes are presented and used in the calculation tool to stress how large the variable part of the energy consumption is. For example, lighting, cooling systems are running at constant speed and belongs to this category. The process of completion of the bands which is found after the annealing and pickling line was excluded since it is not that interesting from an energy variation view point.

2 The steel making process at Avesta works

Outokumpu is a global company within the stainless steel market producing both hot and cold rolled band rolls. Their main customers are producers of equipment for transportation and storage of chemicals, food and brewery industry and piping. The steel production at Avesta Works is fully integrated, which means that all the steps from raw material to product can be done on site. The three main processes are Steel mill (SM), Hot rolling mill (HRM) and Annealing and pickling line (APL). The steel mill is of the electro-steel works type and uses recycled scrap metal as raw material.

2.1 Steel mill (SM)

The first part of the production process is the steel mill. This plant consists of the processes from the scrap metal area to the hot grinding as described in Figure 2.1. In the first part of the process the scrap is taken from the raw material area and lifted by cranes into three scrap baskets. These run through a preheater which heats the metal to 300°C with help from the flue gases from the electric arc furnace (EAF). The preheating is done in order to prevent possible steam explosions from melting snow and ice in the furnace and to decrease the energy demand in the EAF.

The EAF is the most energy consuming unit at the plant and has a power demand of 90 MW. The scrap is melted by electric arcs that are created between three electrode tips and the scrap. Every charge consists of about 100 tons of scrap and the process of filling, melting and draught takes approximately one hour. The furnace also uses liquid petroleum gas (LPG) burners of 12 MW and chemical reaction energy in the parts where the electrode tips not are effective. Chemical reaction energy means oxidization of pulverized coal and reduction chemicals that cause exothermic reactions in the furnace.

At 1650°C the steel melt is tapped into an LPG preheated ladle that transports the melt to a converter. The converter reduces the carbon content in the melt from 1-1.5% to the specified value of the product (usually around 0.02%). This is done by oxidizing the carbon with oxygen gas that is bubbled through the melt. This oxidization is exothermic and supplies the unit with energy. After the oxidization the chrome content is increased by re-reducing chrome from the slag with silica and aluminium substances. This reaction also releases significant amounts of energy so parts of these substances are only added as chemical energy to ‘fuel’ the converter. Finally the sulphur content is decreased to 0.001% by adding dehydrated lime and fluorspar. The flue gases from the electric arc furnace and the converter can have a temperature up to 1500°C and are slightly cooled before being cleaned in a flue gas cleaning system.

In the ladle furnace the final adjustment before the casting continuous casting takes place. To satisfy the requested properties of the steel the temperature is regulated and alloy substances can be added. The casting of the ‘steel strand’ takes 40-60 minutes and the melt is fed into a casting box, which is pre-heated by LPG. From the casting box the melt goes down into a water-cooled chill whose actual measurements decides the dimensions of the produced steel strand. If the width of the strand needs to be changed the dimensions of the chill can be changed, but if the thickness of the strand is to be varied the whole chill need to be exchanged. While the strand is produced its surface is cooled in several steps by water. Common dimensions of a strand are a thickness of 140,160 or 200 mm and a width of 800-2100 mm.

The steel is then cut into slabs with a maximum length of 11 meters and a maximum weight of 28 tons. After the cutting the slabs go through a hot grinding area, which consists of two heavy grinding machines and two fine grinding machines. The normal operation temperature for hot grinding is 800°C although cold slabs can be ground here as well. The next step is cold grinding which consists of three grinding machines that operate outside the range of the hot grinding machines (short or crooked slabs). Some slabs are sold directly from here.

2.2 Hot rolling mill (HRM)

A simplified flowsheet of the hot rolling mill is shown in Figure 2.2. In this process the slabs from the steel mill are treated to create so called “black bands”. The first part of HRM consists of two reheating furnaces called walking beam furnaces. These are heated by LPG and the slabs exit at a temperature of 1200-1270°C so that the material is more easily processed. The flue gas from these furnaces is used for air preheating in recuperators and then used in a waste heat boiler which is connected to the district heating network. After being heated the slabs are transported into the roughing mill where the slabs are rolled down to a thickness of 20-25 mm. Depending on the requested thickness and the properties of the steel the slabs are passed 1-7 times through the roughing mill.

When the slabs have the right dimensions they are transported into the steckel mill area, which is the main process of HRM. Here the bands are passed 0-9 times depending on the requested thickness and steel properties. In the steckel the band is hooked onto one coiler on each side of the steckel itself. The band is then run though the steckel in both directions. During this process the slabs are kept hot by two coiler furnaces fuelled by LPG. The flue gas from this unit passes through burner recuperators for air preheating. Large quantities of electric power are also used in the steckel mill. The final step is to cool down the “black bands” with water, which is then cooled in a cooling tower. Some bands from HRM are sold directly and the rest are transported to the annealing and pickling line for further processing. More info about this can be found in Section 3.1.

2.3 Annealing and pickling line (APL) – L76 & Z-high

The annealing and pickling line flowsheet is shown in Figure 2.2. To create thinner bands and receive better surface properties than is possible at HRM the ‘black bands’ are run through APL to become ‘white bands’. The bands are first welded together into a continuous band and then annealed and pickled in what is called ‘Line 76’. In the annealing furnace the band is heated by WRD oil oxyfuel burners to 1200°C and then cooled with air and water. This reheating and cooling process is done to achieve the right mechanical properties throughout the whole band. The oxyfuel burners also use process steam to atomize its fuel, which is generated in a WRD oil steam boiler. Furthermore a catalytic NO_X flue gas cleaning system is installed. Here WRD oil is used to generate the heat needed for reducing NO_X and thereby cleaning the flue gas.

During the annealing a metal oxide shell can form on the bands. This shell is broken by easy mechanical stress in the descaling process. To smoothen and clean the surface of the band it is blasted before it is transported into the pickling process. The band is first pickled in an electrolytic stage and then pickled with chemicals in the ‘turbo pickling stage’. Here the band is washed in a two-step acid treatment consisting of an acid mix of hydrofluoric and nitric acid. Finally the band is controlled and then put on a roll. The bands that need more processing to become thinner or receive other surface properties are run through the cold rolling mill in the ‘Z-high line’ and then annealed and pickled again in ‘Line 76’. Approximately one third of all products produced at Avesta Works are cold rolled.

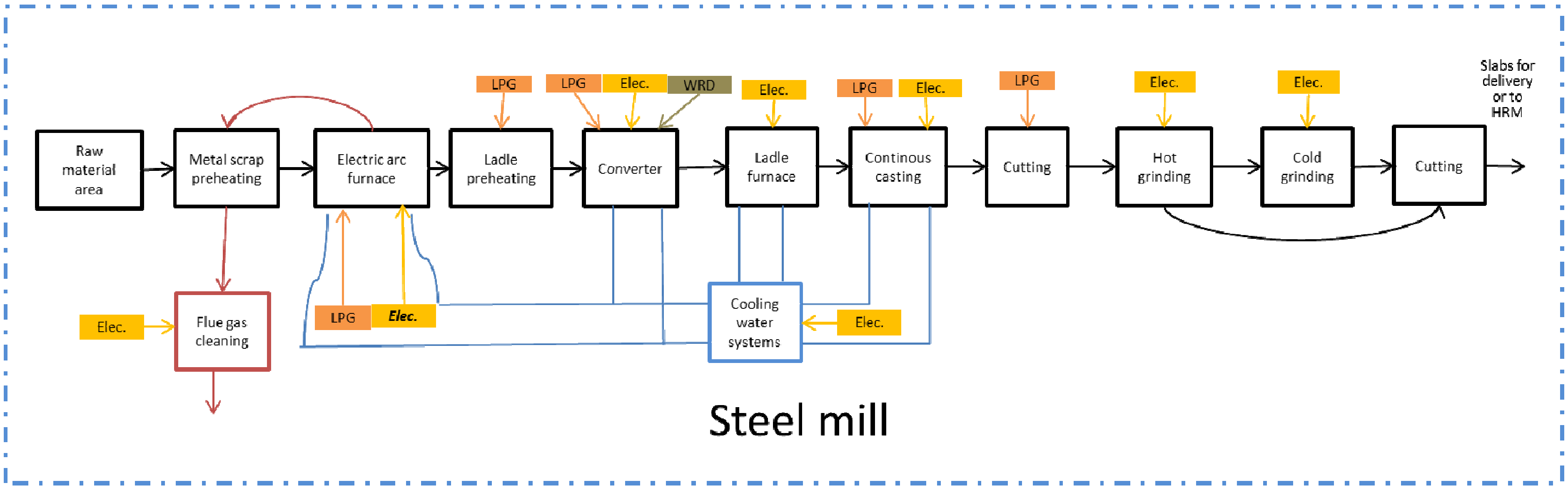

Figure 2.1 Simplified process flowsheet for the steel mill.

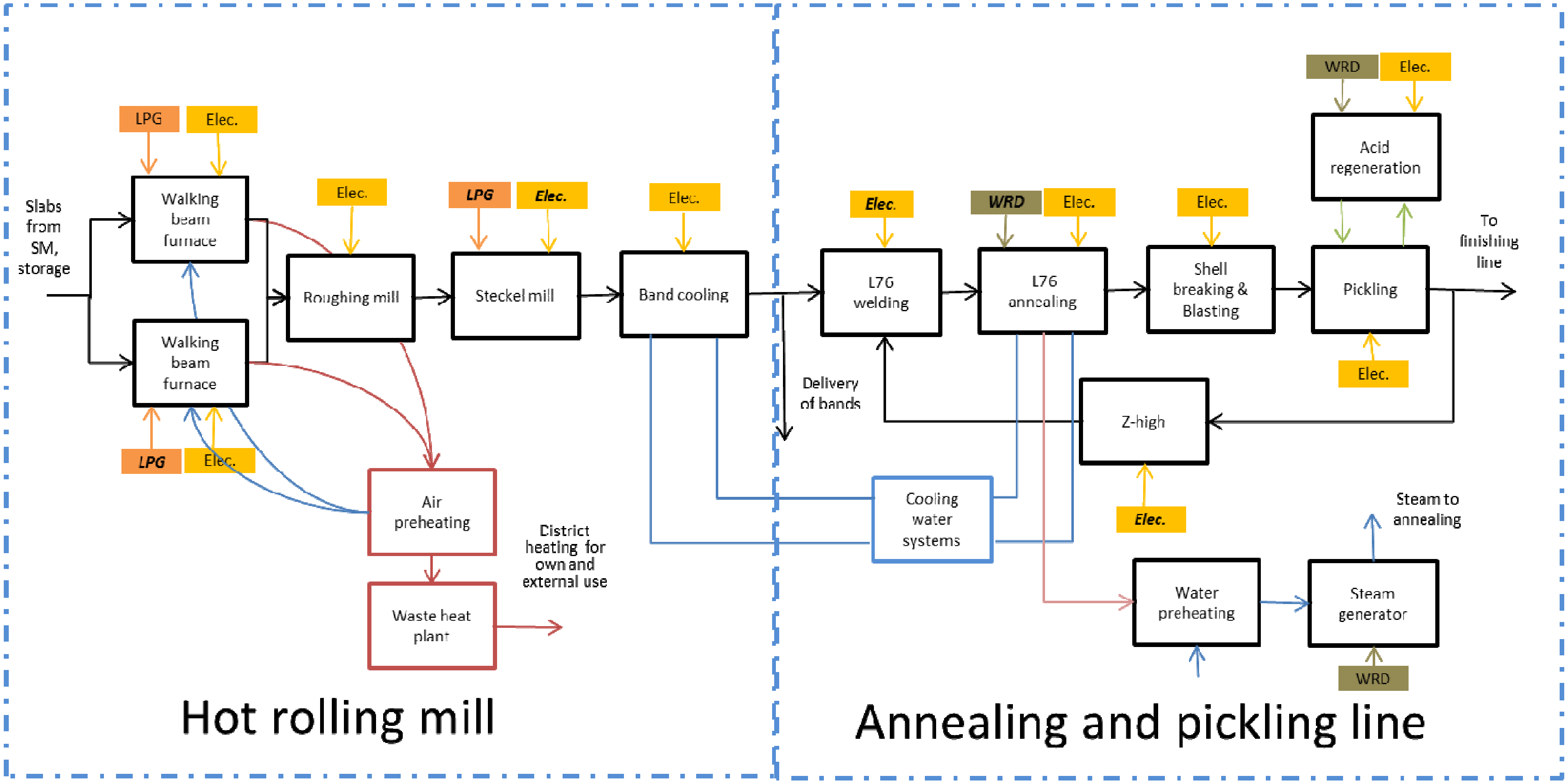

Figure 2.2 Simplified process flowsheet for the hot rolling mill and the annealing and pickling line.

3 Possible relationships between energy consumption and products

To be able to decide which process equipment to analyse in detail the annual energy consumption and the production methods of different processes were studied. This was done to find out where possible variations in the energy consumption could exist and if it would be possible to relate and quantify these variations to the produced products. In Table 3.1 and Table 3.2 electricity and fossil fuel consumption divided between different process equipment for 2010 can be seen.

Table 3.1 Total electricity consumption for 2010. (Tarantino. N, 2010)

Steel mill	**[MWh]**	**% of total**	**Hot rolling mill**	**[MWh]**	**% of total**
Electric arc furnace	178 477	52,0	Sub process P	2 798	0,8
Sub process A	11	0,0	Sub process Q	841	0,2
Sub process B	888	0,3	Sub process R	3 390	1,0
Sub process C	1 049	0,3	Sub process S	280	0,1
Sub process D	11 750	3,4	Sub process T	26 784	7,8
Sub process E	4 314	1,3	Sub process U	6 245	1,8
Sub process F	11 322	3,3	Sub process V	546	0,2
Sub process G	10 095	2,9	Sub process X	3 807	1,1
Sub process H	3 831	1,1	Sub process Y	1 465	0,4
Sub process I	13 340	3,9	Sub process Z	1 384	0,4
Sub process J	16 516	4,8	**Sum**	**47 540**	13,8
Sub process K	1 549	0,5	**APL**		
Sub process L	5 396	1,6	Sub process W	1 845	0,5
Sub process M	731	0,2	Sub process AA	2 760	0,8
Sub process N	484	0,1	Sub process AB	1 666	0,5
Sub process O	2 886	0,8	Sub process AC	9 961	2,9
Sum	**262 639**	76,5	Sub process AD	6 634	1,9
			Sub process AE	10 301	3,0
			Sum	**33 167**	9,7

Table 3.2 Total fossil fuel consumption for 2010. (Tarantino. N, 2010)

LPG Steel mill	**[MWh]**	**% of total**	**LPG Hot rolling mill**	**[MWh]**	**% of total**
Sub process AF	10 133	4,3	Sub process X	38 964	16,6
Sub process AG	14 758	6,3	Sub process Y	152 212	64,7
Sub process AH	1 449	0,6	Sub process AL	10 003	4,3
Sub process AI	4 936	2,1	**Sum**	**201 179**	85,5
Sub process AJ	1 417	0,6	**WRD-oil L76**	**[MWh]**	
Sub process AK	1 417	0,6	Sub process AM	94128	91,2
Sum	**34 110**	14,5	Sub process AN	1829	1,8
			Sub process AO	7228	7,0
			Sum	**103 185**	100,0

Out of the total energy use electricity and fossil fuel constitutes approximately half each. The LPG consumption is about 70% of the total fossil fuel consumption. All of the furnaces on site used to be fuelled by oil. The original walking beam furnace at HRM was built in 1940 and was not replaced until 1992 when the new steckel mill was installed. By this time LPG was a cheaper fuel and was perceived as more modern, with better emission characteristics than oil. The annealing furnace at L76 was built in 1976 when oil was still the most common fuel. There have been discussions if the furnace should be running on LPG instead, but this change has not been made yet.

3.1 Product flow

The product flow at Avesta works is rather complicated since products leave the production process at many different places to be delivered to different 'customers'. After the slabs are cast in the continuous casting they can take several ways though the production system. The steel that is not processed through APL is sent to Outokumpu's other sites in Degerfors, Nyby - Eskilstuna, Newcastle or 'pressplate'-Avesta for further processing. During 2010 a small number of slabs were sent to Outokumpu in Tornio. A summation of these customers can be seen in Table 3.3. The slabs can be sent away either directly after the continuous casting, after the hot grinding, after the cold grinding or after HRM. This quite complex product flow can be seen in Figure 3.1.

Table 3.3 Different customers, product codes and possible treatment at HRM.

Customer	Code	Treated at HRM
Newcastle	ASP	no
Degerfors	HPRD - Slabs	no
Degerfors	HPRD - 'run program 5'	yes
Degerfors	HPRD - 'run program 2'	yes
Pressplate	MPPP	yes
Nyby, Eskilstuna	NYBY	yes
Tornio	TORNIO	no
APL	KBR	yes

The slabs that are processed at APL are always prepared at HRM first. If the slabs are longer than seven meters and approved after the hot grinding (HG) they are sent directly to HRM. If the slabs are shorter than seven meters they are instead processed in the cold grinding (CG), before further processing in HRM. The third alternative is if they are processed in HG and not approved, they are also processed in CG.

Some of the slabs which are sent to Degerfors are delivered directly without any grinding treatment or processing in HRM (flow A in figure). Other slabs are treated in the HG only and then sent away (flow B in figure) and some are treated in both HG and CG and then sent away (flow C in figure). Slabs to Degerfors that are processed in the HRM plant can be treated in either HG or CG or in both (first flows E & F and then flow D in figure). In Nyby tubular products are produced and all slabs that are sent here from Avesta are treated in the HRM unit (flow D in figure). For products to both of these customers the same criteria for processing in HG and CG as above apply.

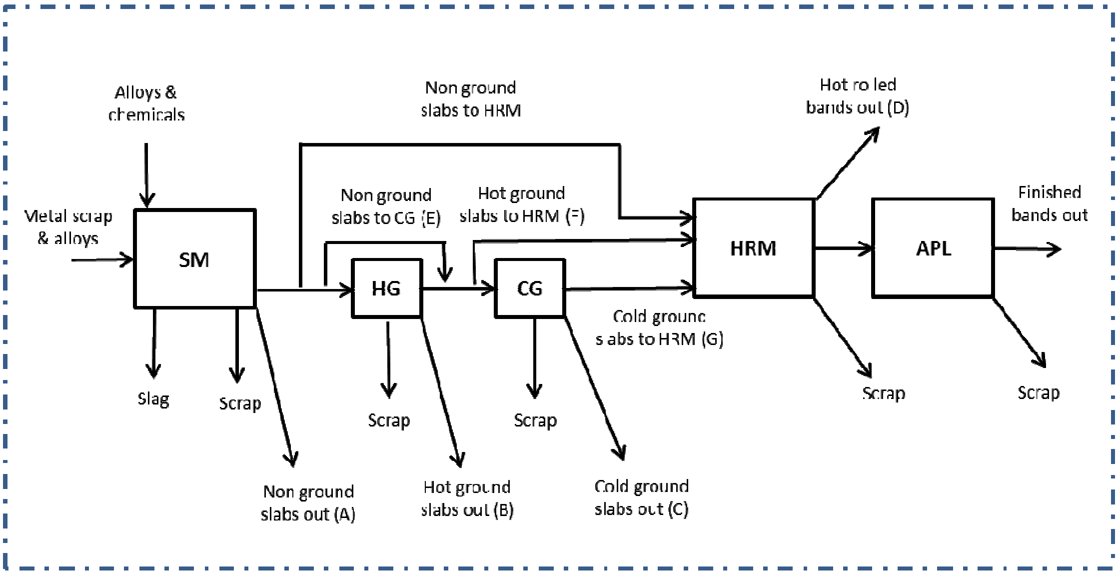

Figure 3.1 Flow of products in the production process.

Every month about four charges are produced that are sent to Newcastle. None of these slabs are treated in HRM and the same criteria for processing in the grinding equipment applies as for all other products.

The complex production pattern with products to different end customers could result in differences in energy consumption. The process logs were used to take inventory of the different flows of material in each process and can be seen in Table 3.4. Most bands go to APL (KBR) and a majority of the bands that are sent to Degerfors (HPRD) are not hot rolled at HRM. Furthermore the amount of hot rolled bands that go to Nyby is higher than the amount of the same bands of the steel mill. This can be explained by the fact that slabs could have been produced during 2009 and then been rolled during 2010.

Table 3.4 Product flows for different 'customers'.

	Out of steel mill [ton/year]	**Into hot grinding [ton/year]**	**Into hot rolling mill [ton/year]**
ASP	4 522	989	0
HPRD	45 661	30 649	8 049
KBR	254 718	104 374	249 412
MPPP	1 757	82	1 331
NYBY	75 922	58 808	81 335
TORNIO	86	0	80
Sum	382 666	194 901	341 852

3.2 Oxygen usage

Oxygen gas is used in three process parts at Avesta Works. In the EAF, oxygen and coal is blown into the furnace by lance manipulators to create slag bubbles. In the converter oxygen gas is blown into the melt to reduce the carbon content during formation of carbon monoxide. At L76, oxygen is used in the oxyfuel burners of the annealing furnace.

The oxygen is produced offsite by AGA Gas AB, Avesta. This production unit produces oxygen, nitrogen and argon by cryogenic air separation. The process consists of a separation column that separates the air to desirable purities. This is done under high pressure created by large electric compressors. The average electricity consumption for this process is 0.75 kWh/Nm^3 (Rasmuson. A-K, 2011).

3.3 Annealing and pickling line (APL)

The end products from APL are divided into different groups depending on the surface properties of the band. These surface property groups are named 1,2,3,4,5,6. During 2010 about 97% of all bands processed were products with surfaces 1, 2 and 3. Based on this the other surfaces were excluded from the analysis.

The same band can be run through the process with different treatment programs depending on the thickness of the incoming band or if the band is being reprocessed due to an unwanted product variations. The two most common and important programs are called GLR and GLF and constitute 95% of the runs made at L76. Therefore focus will be put on analyzing these two programs. GLR is a pre-treatment program that is used if the requested final thickness of the band is low. GLF is the final run where the product is finished. If the steel is cold rolled, this is done in between the GLR and GLF runs.

The blasting and the pickling are not the largest energy consumers but these probably constitute a significant product related variations since they are not used at all for some products. These processes together with the difference if the steel is cold rolled in Z-high or not was therefore seen as the most important energy aspects of the process.

The oil consumption of the annealing furnace is assumed to be dependent on the residence time of the bands in the furnace. Furthermore reprocessing of the bands is important since then the bands have to be heated more than once in the furnace. The oil consumption of the NO_X cleaning and the steam boiler is also assumed to have small variations with different products.

3.4 Hot rolling mill (HRM)

The main differences between the products at HRM are the steel type and the dimensions of both the incoming slabs and the outgoing bands. Depending on these variables the slabs are processed with a different number of passes through both the roughing mill and the steckel mill. Furthermore, there are a few different ‘run programs’ through the process; 1,2,5,6. ‘Run program 1’ is the most common program where the slab runs through the whole process. Some slabs have dimensions and ‘difficult’ mechanical properties which imply that they have to be run two or in some special cases three times through the process. These are first run through ‘run program 6’ where the slabs/bands pass through the roughing mill but not the steckel mill. All bands are finally treated in ‘Run program 1’.

‘Run program 5’ and ‘Run program 2’ are bands that are sent to Degerfors (HPRD). The ones in program 2 go through both the roughing and the steckel mill, but are cut up into plates in the steckel and leave the process from the side of 'the line'. Bands in program 5 are just processed in the roughing mill. Apart from these differences bands that are treated with programs 1 and 6 can be sent to APL or Nyby, depending on the type of product. Some bands in program 1 are also sent to 'pressplate' (MPPP). A summation of these run programs can be seen in Table 3.5.

Table 3.5 Run programs at HRM.

Run Program	Customer	Roughing mill	Steckel mill
1	APL, NYBY or MPPP	X	X
2	Degerfors (HPRD)	X	X
5	Degerfors (HPRD)	X	-
6	APL or NYBY	X	-

The steckel mill and the roughing mill are the two largest electricity consumers at the hot rolling mill. Furthermore these two process parts have a connection both to thickness and steel type. So focus was here set on these two processes and the number of passes and runs done through them.

3.5 Steel mill (SM)

In the steel mill the most important energy related difference between the products is the type of steel that is produced. Other factors that also have an effect on the energy consumption is the length of the waiting times between the different charges (batches) in the process and to which degree the melt in the charge is "deslagged" before treatment in the ladle furnace. If the slag layer is too thin the heat losses from the charge will be larger and if the layer is too thick further processing will consume more energy.

As seen in Table 3.1 the EAF consumes 52% of all electricity at Avesta Works (68% of the electricity at the steel mill). Various steel types have different residence time in the electric arc furnace. Steel types that are 'heavier', high temperature resistant steel for example, need longer processing time since they contain a larger share of alloys like chromium that require more energy to melt.

The converter does not consume a lot of electricity since the reduction of the carbon content is a very exothermic reaction and 'fuels' the process. The requested content of carbon and other elements in the steel affects the amount of added chemical energy and oxygen needed for oxidization.

The ladle furnace might show some differences in the electricity consumption between different steel types. Since the ladle furnace is the final adjustment before the casting it is affected by what has been done earlier in the EAF and the converter and by the accuracy of the operator during the "deslagging process". Therefore it is probably harder to relate these differences to a specific steel type.

The difference in energy consumption between the products in the rest of the continuous casting is can be difficult to document except for the stirring equipment. But this only constitutes a small part of the total consumption. It should be noted that the electricity consumption of the continuous casting cooling water system is logged under 'continuous casting power' and not under 'cooling water'.

The use of LPG at the steel mill (except for the LPG used in the EAF) does not have a strong connection to the different products. The LPG is mainly used for preheating of equipment like the ladle; the converter and the casting box in the continuous casting. The need for preheating depends on if the production is stopped due to maintenance or problems so it is hard to relate this use of LPG to the products.

Especially in the EAF and the converter the addition of carbon and metals are of interest. The reason is that when these substances are oxidized a lot of energy is released to the process which substitutes heating with electricity and fossil fuel. The oxidization of carbon does of course also have a contribution to the CO_2 emissions. More information about the thermo chemical reactions in the EAF and the converter can be found in Appendix E.

4 Allocation methods

The general purpose of the allocation methods was to relate the energy consumption which was logged per switchgear and hour for electricity [kWh/h] or volume and hour for fossil fuel data [Nm^3/h] to the process logs. This to be able to calculate the key values for the analysis and the calculation tool which is the specific energy consumption [kWh/ton] for each sub process. The strategy for the electricity was to calculate a residence time for a certain product during a certain hour in a process part and multiply this with the consumption of the related switchgear during this certain hour. Because of the difference in residence time between the different processes the methodologies differ from each other.

4.1 Annealing and pickling line (APL)

In the process log for L76 the time that each band is inserted into the furnace (the front end) was the only time information given. Therefore the exiting times of the bands had to be approximated. The production process is continuous, which means that a good approximation was that as soon as one band is exiting the furnace to enter the ‘line’ (all processes after the furnace) the next band is fed into the furnace. Thereby the exiting time from the furnace for a band could be approximated with the time when the next band is inserted into the furnace. Furthermore the ‘line’ is the part of the process that limits the production rate so the time in the furnace is set by the production rate of the ‘line’. Thereby the residence time on the ‘line’ could be approximated by the time in the furnace. This is illustrated for two bands A and B which are run through the annealing and pickling line in Figure 4.1. For more details on the calculation procedure see Appendix A.1.

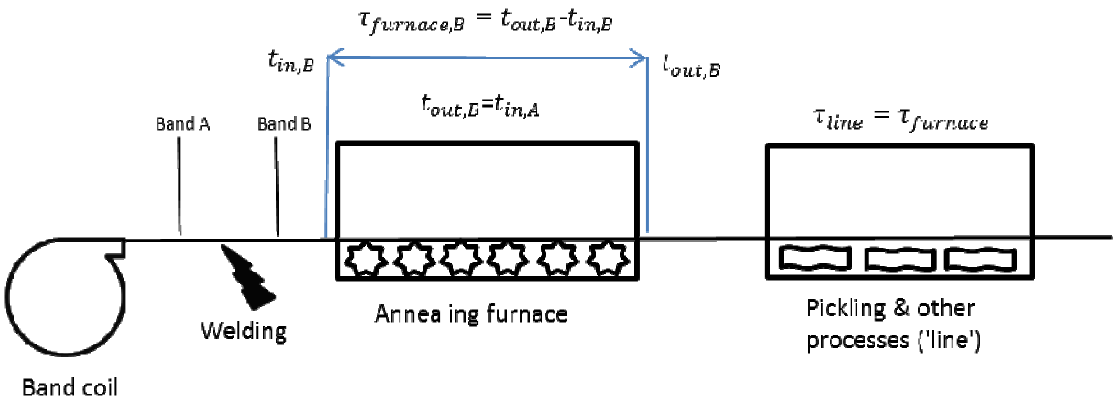

Figure 4.1 Residence times in the annealing and pickling line.

The calculations for Z-high was done in a similar way as for L76. The difference was that the exact residence times were available in the process log and that the residence times were longer. The residence time for each hour was matched with the electricity consumption for each hour. The calculations for each band were done separately and then imported into the L76-calculations so that Z-high could be seen as sub process of APL, even though it is process of its own in reality.

The electricity data was logged per switchgear so it was necessary to investigate which equipment that is connected to which switchgear. The switchgears were then sorted into different groups representing the process parts. Switchgears that represented process equipment that are non-variable or small energy consumers were usually set in the group “other”. The switchgear groupings can be found in Appendix B. For Z-high all the switchgears were simply lumped together into one group since no other grouping seems to be done on site.

The specific WRD oil consumption of the annealing furnace was logged for each band. So no allocation methodology had to be developed for this physical quantity. The oxygen consumption for the oxyfuel burners, the oil consumption for the catalytic NO_X reduction and the steam boiler were allocated in the same way as for the electricity.

4.2 Hot rolling mill (HRM) - Electricity

In the process log for HRM three different times of interest could be found: The exiting time for the slabs from the walking beam furnaces, the time when the band reaches the steckel mill and the time when it is ready in the steckel mill. This made it possible to calculate an estimate of the residence times in the roughing mill and the steckel mill for each band. For the detailed calculations see Appendix A.2.

The other process parts such as lightning and roller conveyors were harder to connect to a residence time in the same way so a different method was used for this equipment. Here all the bands that exit the furnaces at a certain hour simply shared the electricity consumption for this hour. This was seen as a good approximation since the average residence time on the whole line is 7 min and the average waiting time between that the band is finished and the next slab is exiting the furnace is 10 min. The switchgear grouping for HRM can be found in Appendix B.

4.3 Walking beam furnace (WBF) - LPG

The problem with investigating the energy variations related to product properties in the WBF:s compared to other process equipment was that more than one product is in the system at the same time. This makes the allocation of the hour logged LPG data more complex. Heating by convection and radiation are quite complex processes some simplifications had to be done. The furnaces contain several burners and combustion zones and the temperature profile as the slabs pass through the furnace is not linear. The first simplification made was that the heat absorption of each slab is linear during each whole hour so that the temperature increase is linear for each hour.

It was decided that residence time of the slabs in the furnace would be a good way to allocate the LPG consumption. The results from these calculations were a bit strange since they showed that there was no clear correlation between the slab weight and LPG consumption as seen in Figure 4.2. The slab weight should have an influence on the LPG consumption since heavier slabs need to be heated more. Because of these results the allocation method had to be further developed.

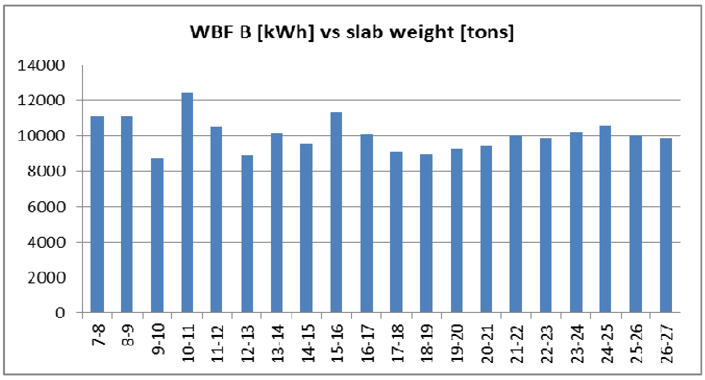

Figure 4.2 LPG consumption for WBF B, based on residence time only.

The amount of absorbed energy in the slabs can be described according to equation 4.1. The difference in exiting temperature between the slabs is quite small (~40°C) compared to the actual exiting temperature (~1260°C), so the enthalpy can be seen as constant. Based on this the second assumption made was that the slab weight is the only parameter that significantly affects the energy absorption of the slabs. So the model was now based on residence time multiplied by slab weight. For the detailed calculation procedure of this model see Appendix A.3.

$$\Delta Q_{slab} = m_{slab} \cdot \left(H_{steel,T_{out}} - H_{steel,T_{in}}\right) \tag{4.1}$$

4.4 Heat balance for Walking beam furnace B

The results from the investigation of the LPG consumption of the walking beam furnaces gave one result that was particularly interesting. It was the relationship between the production rate at HRM and the specific LPG consumption. As observed in Figure 4.3 the specific consumption decreases rapidly at lower production rates. At higher production rates the specific consumption seems to decrease slightly. It would have been interesting to investigate this more in detail and see if and how efficiency varies.

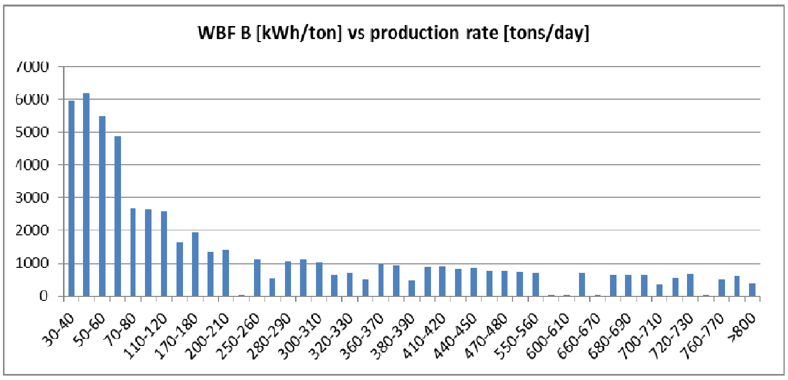

Figure 4.3 Daily specific energy consumption for WBF B for different daily production rates.

It was decided that a good way to investigate this was to set up a heat balance for the furnace. Also identification of improvements of the furnace might be possible through this analysis. Data was obtained from the process log for the furnace, where airflow, fuel flow, cooling water flow, the O_2 concentration in the flue gas and the furnace pressure and temperatures for all flows could be found. Unfortunately the measurement of the flue gas flow had been out of order so this data was missing. Therefore the flue gas flow had to be calculated. Data which was logged approximately every second minute was gathered for April 2010. This data was then aggregated into daily averages for velocities and summed for e.g. fuel amount data. The goal was to solve the heat balance for each day based on the average values. A schematic of the furnace heat balance can be seen in *Figure 4.4*. The temperatures in the figure are average temperatures for April (except for combustion air and the slabs entering the furnace which were assumed to be equal to the air temperature outside of the furnace). The reference temperature of the system was set to 0°C since the data for the LPG was given for this temperature.

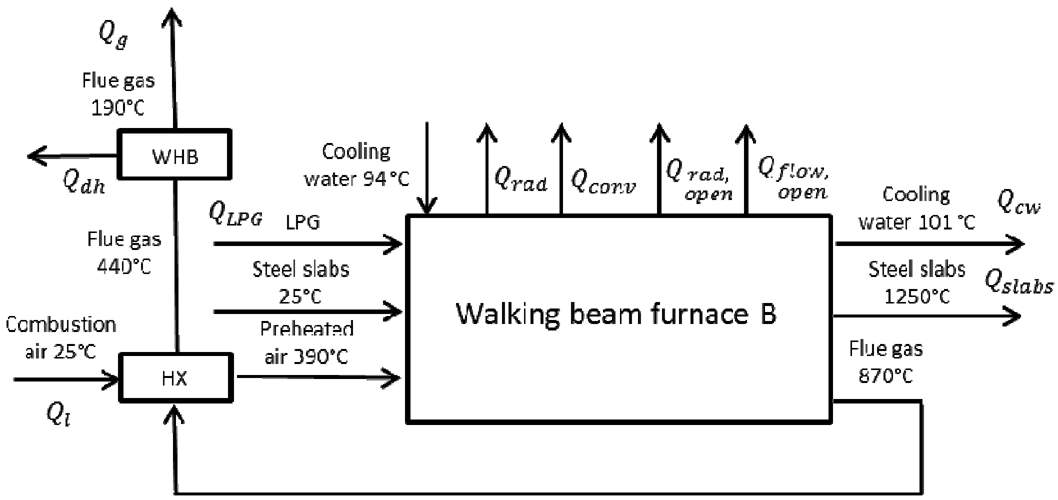

Figure 4.4 Heat balance for WBF B.

The preheating of the air in the heat exchanger was assumed to have an efficiency of 100% so that the heat exchanger can be seen as a part of the furnace. After the air preheater the flue gases are cooled in a waste heat boiler (Q_{dh}), which is connected to the district-heating network.

The radiation (Q_{rad}) and the convection (Q_{conv}) from the outside of the furnace were assumed to take place from all four sides of the furnace and from the top of the furnace. The terms $Q_{rad,open}$ and $Q_{flow,open}$ are the radiation losses and the losses from air flow out of the furnace when the windows of the furnace are opened to insert or take out slabs from the furnace. The conduction from the furnace through the floor of the building was neglected. The heat balance for the whole furnace can be seen in equation 4.2. A description of how each of these terms was calculated can be found in Appendix C.

$$Q_{LPG} + Q_l = Q_{slabs} + Q_{cw} + Q_g + Q_{dh} + Q_{rad} + Q_{conv} + Q_{rad,open} + Q_{flow,open} + Q_{diff} \quad (4.2)$$

To evaluate the additional losses the difference in the energy balance (Q_{diff}) and the efficiency of the furnace was calculated. The difference was defined according to equation 4.3. Then the efficiency was calculated as the ratio between the energy added to the slabs and the energy going into the furnace according to equation 4.4. Note that the energy to the district heating is not included here.

$$Q_{diff} = \sum Q_{in} - \sum Q_{out} \tag{4.3}$$

$$\eta_{furnace} = \frac{Q_{slabs}}{Q_{LPG} + Q_l} \tag{4.4}$$

4.5 Coiler furnaces - LPG

The LPG consumption for the coiler furnaces was not logged on site at all. Instead the consumption was estimated from historical data before 1 Jan 2004. This estimated data was also only broken down into months. The consumption in the coiler furnaces is only 4.2% of the total LPG consumption. Based on this fact together with the low preciseness of the data a method similar to the one used for the electricity consumption in the steckel and the roughing mills was developed. This method can be found in Appendix A.5.

4.6 Steel mill – Electricity

The available electricity data for the steel mill already had the switchboxes divided into different sub process groups so no grouping had to be done in connection to allocating the data.

4.6.1 Electric arc furnace

The electricity consumption of the EAF connected to the melting power was available directly in the process log so no allocation method had to be evaluated.

The EAF has some side processes (auxiliaries and preheating), which are logged per switchgear. These were allocated to each charge in the same way as for the electricity at APL. The difference that a higher number unique hours were included since the residence time was longer. 99% of the charges processed in the EAF had a residence time which was ten hours or less. Therefore it was decided that electricity data for ten full unique hours was to be included in the analysis. The charges are processed one at a time so the residence times for each hour and charge were calculated and then connected to the electricity consumption for this hour. The details on this method can be found in Appendix A.6.

4.6.2 Converter, ladle furnace and continuous casting

The same procedure as for the EAF auxiliaries was used for the converter, the ladle furnace and continuous casting. There was one difference though, the number of included full unique hours. Based on statistics of the residence times for each processed charge it was decided that the converter needed four full hours, the ladle furnace four full hours and the continuous casting two full hours.

4.6.3 Flue gas system

The flue gas system at the steel mill is connected to both the EAF and the converter and can be seen in *Figure 4.5*. Flue gas leaves both processes through the roof and during some process steps via a direct extraction. Note that the booster fans in the figure belong to the EAF preheating system electricity consumption wise. The largest electricity consumers of the flue gas system are the fans. Therefore it was assumed that the share of the electricity consumption for the EAF and the converter could be approximated with the share of the total flue gas flow for these two processes. More details on this can be found in Appendix A.7.

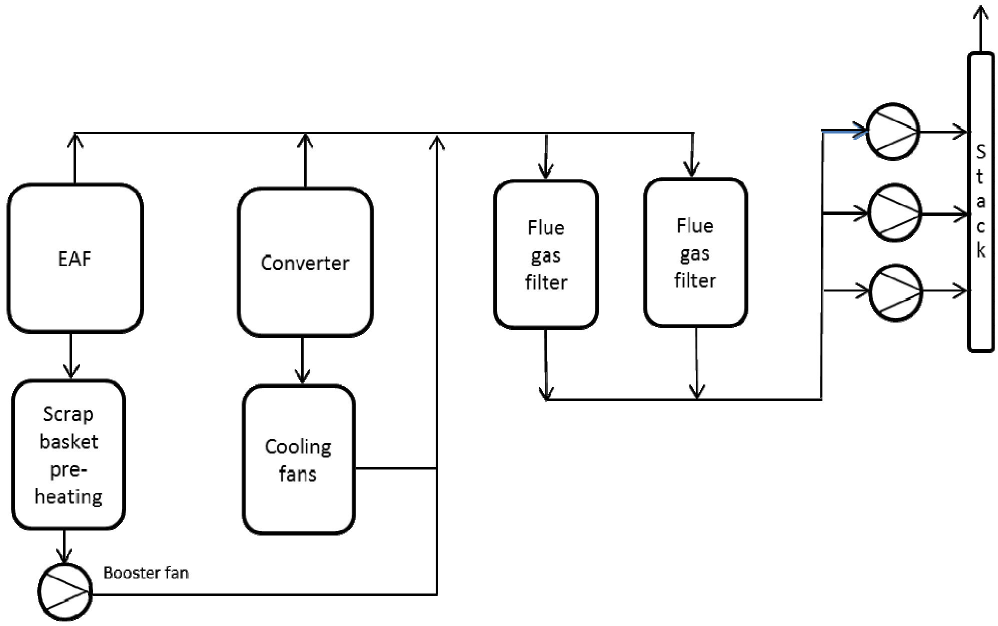

Figure 4.5 Schematic of the flue gas system in the steel mill.

4.6.4 Cooling water system

The cooling water system at the steel mill is divided into four sub systems:

- EAF
- Converter
- Ladle furnace
- Continuous casting.

The cooling water to the EAF cools the furnace walls, the burners, the vaults and the flue gas channel. The cooling water to the converter cools the flue gas channel but not the walls of the process. The ladle furnace cooling system is connected to the cooling of the ladle lid. Apart from this an emergency cooling system exists. The cooling water system of the continuous casting is connected to many different processes. Some of these are cooling of machinery, cooling of the chill and spray cooling of the casting arch where the strand is cast. The electricity consumption of this cooling water system is logged under 'continuous casting' and was not included in the calculations here.

The whole cooling water system is logged in one switchgear which includes mostly pumps. Therefore the pump power for each of these three processes (EAF, converter & ladle furnace) was calculated together with the share of the total power. With these shares the residence time for each slab in each process could be connected to the electricity consumption. The details on the pumps of the cooling water system and the calculation procedure can be seen in Appendix A.8.

4.6.5 Hot grinding and cold grinding

The hot grinding is a process that has a very short residence time, about seven minutes per slab and run. The residence time was estimated from the time the slab enters the grinding machine (the only time given in the process log) and the average grinding speed for the corresponding steel type. There are several grinding machines connected to the same switchgear so several slabs can be in the 'process' at the same time. Therefore the electricity was allocated in the same way as done for the steckel mill and roughing mill at HRM. A weight factor based on the residence times during each hour was calculated for each slab. From here the electricity consumption could be calculated.

For the cold grinding neither inserting time nor exiting time was given in the process log. Due to this it was not possible to allocate with the same accuracy as for the hot grinding. In the process log the number of "upper surface" and "under surface" transfers was given for each slab. So the total number of grinding transfers was used to allocate the electricity to each slab. The total electricity consumption was divided by all surface transfers and this value was multiplied by the numbers of transfers for each slab.

4.6.6 Lighting

The lighting is a bit different at the steel mill compared to APL and HRM. The steel mill has two different categories for lighting, one for each department. Since both departments have two process steps where each charge has its residence time, the electricity consumption of the lighting had to be allocated with respect to the sum of these residence times. The 'summed' residence time gave a higher consumption than the real consumption since the 'summed' residence time is larger than the total time during a year. Therefore the consumption for each charge was normalized by dividing it with the ratio between the calculated and the measured consumption. Also note that there is other miscellaneous equipment connected to this switchgear so all of the electricity consumption is not lighting.

4.7 Steel mill – Oxygen, chemical energy and LPG

The oxygen consumption and the chemical additives were logged per charge in the process logs for the EAF so no allocation method had to be developed. The amount of chemicals reacted that can be regarded as energy addition was estimated as the difference between the total input in the steel mill and the content of the species in the cast steel strand. More info on these chemical reactions can be found in Appendix E.

The LPG consumption in the steel mill was only logged monthly for the different consumers. Therefore the LPG was allocated to the different steel types per processed weight since the consumption doesn't have any connection to a production related parameter that could be quantified easily (see section 3.5).

5 Calculation scenarios

5.1 Standstill and idling energy

All three departments on site are not in production during the whole time of the year. There is usually a 14-day vacation stop in the middle of July and other planned and unplanned production stops occur due to maintenance or other problems. Furthermore a lot of the process equipment is still running in idling mode even though no products are processed. This means that just connecting the electricity or fossil fuel consumption to the process log data would not include the whole annual consumption.

To take care of this matter the hours which did not include production (t_{ss}) were identified and the electricity consumption was connected to these hours. This was approximated by identifying the hours where no products was entering the process for the processes with a short residence time (APL and HRM). For the processes with longer residence time (WBF and the steel mill) the hours that did not have any slabs processed, entering or exiting the process were seen as non production hours. The consumption for each hour was then summed together to receive the annual standstill consumption (W_{ss}) according to equation 5.1. An analysis of the stand still energy energy consumption is found in Chapter 7.

$$W_{ss} = \sum_i (t_{ss} \cdot W_i) \tag{5.1}$$

5.1 Selected energy usage indicators

Apart from the standstill energy there was also an issue with products that had been processed many times. There was a possibility of looking at either the energy consumption per run or all energy accumulated to the final product. Furthermore it had to be decided if the energy consumption per run [kWh/run] or the specific energy consumption [kWh/ton processed] was to be analyzed. These two options together with the choice of including the standstill energy or not gave eight possible cases for analyzing the relation between product and process parameters and the energy consumption.

From here it was decided that the influence from process and products variations on the energy consumption would be analyzed with the specific energy per run as basis (processed weight) and that the standstill energy should not be included. This applies for all data presented in Chapter 6. For HRM the slab weight has a minor impact on the results, so the nonspecific consumption was analyzed [kWh/slab]. When constructing the final calculation tool the specific energy consumption is the parameter of special interest so it was used for all processes [kWh/ton]. Furthermore the annual standstill energy was included separately and the energy consumption from all runs accumulated to the final product.

6 Identification of parameters that affect the energy consumption

In this chapter the calculated energy consumption from the allocation methods will be presented for each sub process and each steel type. The purpose is to show which production and product related parameters that affect the energy consumption. A summary of these parameters is presented in Section 6.8. The different steel types produced at the site are:

- Duplex steel
- Steel with high content of molybdenum, chromium or other alloys
- High temperature resistant steel
- Steel types that does not fit into other categories
- Standard steel
- Titanium stabilized steel

Due to the secrecy of specific data for each steel type the letters A,B,C,D,E and F are used to represent the them. All data presented here is average data within each parameter group for 2010. For example data for the steel type 'A' is an average value of all possible surfaces and thicknesses within this group. First of all the total energy consumption calculated from the allocation method will be compared with the measured data for 2010. This to verify the plausibility of the allocation methods. The results will be presented for each sub process separately, beginning from the annealing and pickling line and then backwards in the process. For a reminder on the different process parts it is recommended to review Chapter 2 before reading this section.

Since the analysis is statistic and different intervals of a parameter can contain data with differences in other parameters the correlations contain some 'noise'. Because of the large number of available combinations of variables and process equipment to analyze, all of them could not be presented here. Only the combinations which showed a clear correlation to the energy consumption are presented. These constitute about 50% of the available combinations.

6.1 Annealing and pickling line (APL) – Electricity

The calculated total annual electricity consumption for APL and a comparison with the actual consumption for 2010 can be seen in Table 6.1. This shows that the developed allocation methodology gives reasonable results, at least when the standstill energy is included.

Table 6.1 Comparison between annual calculated and actual electricity consumption for APL in 2010.

	Total without stand still [MWh]	**Total without stand still [%]**	**Total with stand still [MWh]**	**Total with stand still [%]**	**Measured [MWh]**	**Measured [%]**
APL	27 884	84,1	32 893	99,2	33 168	100,0

6.1.1 L76

In this section the calculated energy consumption for L76 is presented. A separate analysis of Z-high is found in Appendix H.1. The calculated data for difference surface treatment programs could not be presented due to secrecy. At L76 16 090 runs were done and 11 289 bands were processed with a total weight of 239 521 tons during 2010. Out of these runs made 69.5% were GLF treatment program runs and 24.5% were GLR treated.

The specific total electricity consumption for APL together with the average residence times and production rates for different steel types can be seen in Table 6.2. 'D' and 'C' steel has almost the double consumption compared to 'B' and 'E'. The consumption of the different process parts at APL shows the same pattern as the total consumption for the various steel types.

In Figure 6.1-Figure 6.2 the specific electricity consumption for different residence times and production rates can be seen. There is a strong connection between both these parameters and the electricity consumption. To show the strongest influence the residence time was plotted against the production rate as seen in Figure 6.3. This relation looks very similar to Figure 6.2. Thereby the production rate seems to be the most important parameter which affects the residence time and therefore the electricity consumption. This indicates that the reasoning in Section 4.1 is correct.

Table 6.2 Specific total electricity consumption, residence times and production rates for different steel types.

Steel type	Tot [kWh/ton]	Residence time in furnace [hrs]	Production rate [ton/h]
D	93,76	0,288	50,11
C	88,97	0,419	53,38
F	79,18	0,392	56,56
A	74,36	0,319	63,47
E	50,08	0,269	92,87
B	43,99	0,290	93,18

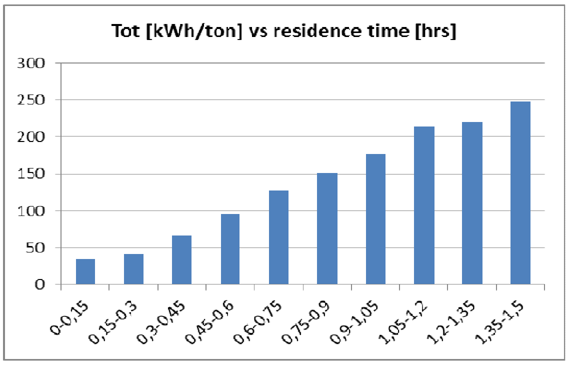

Figure 6.1 Total specific electricity consumption in relation to residence time.

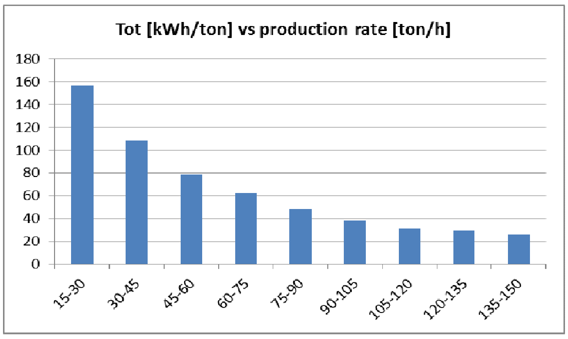

Figure 6.2 Total specific electricity consumption in relation to production rate.

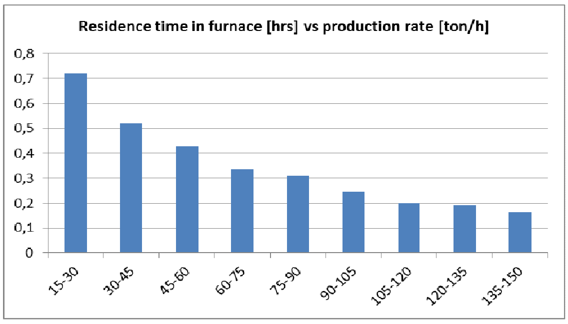

Figure 6.3 Residence time in furnace in relation to production rate.

The relation between total specific electricity consumption and thickness of the exiting band can be seen in Figure 6.4. Thinner bands have a higher consumption and this relation looks the same for all process parts at APL except for the blasting equipment. This can probably be explained by the fact that the production rate is higher for thicker bands. It is also important to remember that thinner bands are usually run through the process more than once, so the energy consumption of the final product will be even higher. A similar relation can be seen for the band width in Figure 6.5. This can be explained by the production rate which increases with the band width.

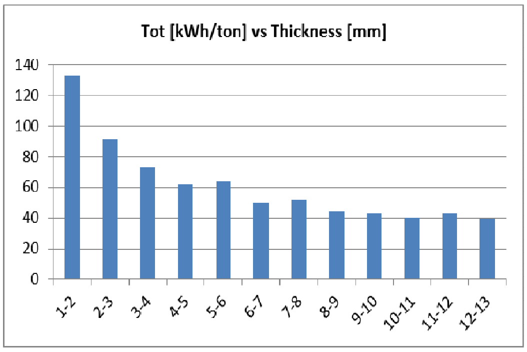

Figure 6.4 Total specific electricity consumption in relation to thickness.

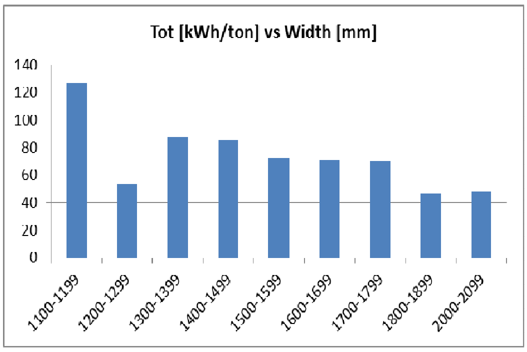

Figure 6.5 Total specific electricity consumption in relation to width.

6.2 L76 – WRD oil & oxygen

The allocation of the oil consumption worked rather well as seen in Table 6.3, where a comparison between the calculated and measured annual oil consumption can be seen.

Table 6.3 Comparison between calculated annual and actual oil consumption for L76 in 2010.

	Total without stand still [MWh]	Total without stand still [%]	Total with stand still [MWh]	Total with stand still [%]	Measured [MWh]	Measured [%]
WRD oil	93 033	90,2	100 010	96,9	103 185	100,0

In Table 6.4 the oil consumption and the energy consumption for producing oxygen for different steel types can be seen. The steel types ‘F’ and ‘A’ have the highest and ‘B’ the lowest oil consumption for the annealing furnace. Furthermore the steam boiler and the catalytic NO_X-reduction do not follow this pattern. The explanation is that the steam boiler is connected to the pickling equipment with a heat exchanger. If the steel is ‘easily’ pickled the reaction rate is higher and more heat is developed. So for easily pickled steel the need combustion in the steam boiler is lower. Important to point out when comparing Table 6.4 and Table 6.2 is that the energy need for producing oxygen is significant, about 50% of the total electricity consumption for APL.

Table 6.4 Specific oil and oxygen energy consumption in relation to steel type.

Steel type	Oil, annealing furnace [kWh/ton]	O_2, annealing furnace [kWh/ton]	Oil, steam boiler [kWh/ton]	Oil, catalytic NO_X [kWh/ton]
F	282,4	40,6	19,4	4,4
A	279,8	42,9	17,7	4,4
D	278,6	45,7	23,2	5,2
C	258,2	40,4	24,0	5,0
B	241,6	35,4	7,3	2,8
E	236,6	35,7	7,3	2,8

In Figure 6.6 and Figure 6.7 the specific oil consumption and energy need for producing oxygen can be seen for different production rates. The consumption decreases slightly with increasing production rates. This since the ‘base consumption’ is divided to a larger processed weight when the production rate increases. The trend looks the same for the steam boiler and the NO_X cleaning, but the decrease is steeper. This correlation between oil consumption and the production rate does also correspond well with other parameters such as residence time, band thickness and band width. Lower production rates give higher residence times and thereby higher consumption. Thinner and wider bands have lower production rates and therefore higher consumption.

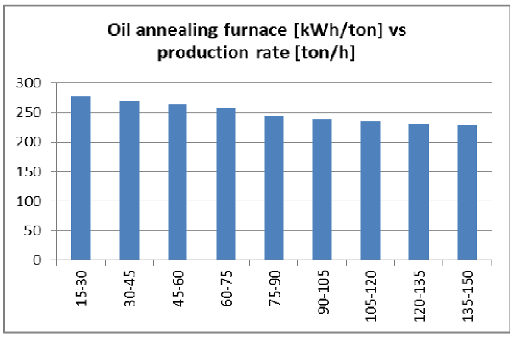

Figure 6.6 Specific WRD oil consumption in annealing furnace in relation to production rate.

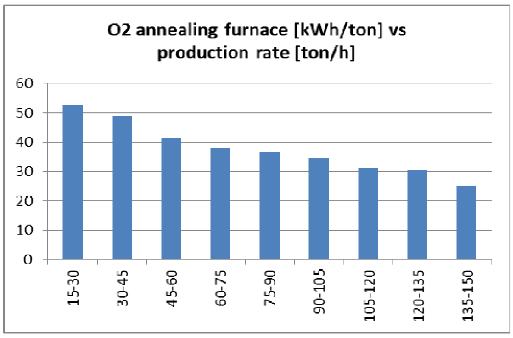

Figure 6.7 Specific oxygen energy consumption in annealing furnace in relation to production rate.

The relation between the oil consumption in the annealing furnace and the steam boiler is investigated in Table 6.5. The oil consumption in the annealing furnace increases slightly as the production rate increases. The opposite happens with the steam boiler, and the decrease is steep. This is explained by the heat exchanging between the annealing furnace and the steam boiler. If more heat is released with the flue gases from the annealing furnace, the need for combustion in the steam boiler decreases.

Table 6.5 Connection between WRD oil consumption in the annealing furnace and the steam boiler in relation to production rate.

Production rate [ton/h]	**WRD Oil annealing furnace [kWh/band]**	**WRD Oil steam boiler [kWh/band]**
15-30	4896	887,5
30-45	4833	534,3
45-60	5144	359,8
60-75	5044	257,0
75-90	5297	182,9
90-105	5435	132,3
105-120	5338	92,7
120-135	5341	85,0
135-150	5116	57,8

6.3 Hot rolling mill (HRM)– Electricity

A comparison between the calculated annual and the measured annual electricity consumption for HRM can be seen in Table 6.6. Here the allocation methodologies seem to have enough accuracy.

Table 6.6 Comparison between calculated annual and actual electricity consumption for HRM in 2010

	[MWh/year]	%
Calculated without standstill	35 164	74,0
Calculated with standstill	47 171	99,2
Measured	47 540	100,0

In total 16 802 slabs with a weight of 341 852 tons were processed in 17 219 runs at HRM during 2010. In Table 6.7 and Figure 6.8 the total electricity consumption for HRM (all run programs together), the steckel mill consumption and the total consumption for each of the run programs is presented for different steel types. For a reminder of the different run programs, see section 3.4. 'D' seems to have the lowest consumption per run but the average number of runs is higher than for the other steel types. This is connected to the higher portion of these slabs that have to be processed with 'run program 6' which has a lower energy consumption since the steckel is not running. In the end the slabs that are processed with 'run program 6' will have a higher consumption since they are processed two or three times through the process. The difference between the steel types for 'run program 1' is smaller. So the main difference between various is if the steel is run through the process more than once with 'run program 6'or because of reprocessing.

The breakdown between the run programs for the roughing mill can also be seen in Figure 6.9. The difference in energy consumption between 1 and 6 in the roughing mill is quite large but not as large as the difference in total electricity consumption between the programs, as seen in Table 6.7. Thereby the largest difference electricity wise between the programs is that the steckel mill is running or not. This does also correspond well with the large difference between 'run program 2' and 'run program 5'. For a reminder on the run programs, see Table 3.5.

Table 6.7 Electricity consumption in relation to steel type and 'run program' .

Steel type	**Tot [kWh/slab]**	**Steckel mill [kWh/slab]**	**Number of runs/slab**	**Tot (run pr. 1) [kWh/slab]**	**Tot (run pr. 2) [kWh/slab]**	**Tot (run pr. 5) [kWh/slab]**	**Tot (run pr. 6) [kWh/slab]**
C	2 067	1 241	1,019	2 114	1 851	643	915
D	1 765	883	1,479	2 141	-	829	822
F	2 043	1 133	1,025	2 101	-	729	1 244
A	1 883	1 040	1,252	2 151	-	684	694
B	2 098	1 191	1,018	2 106	1 924	777	-
E	2 000	1 094	1,024	2 071	1 887	697	-

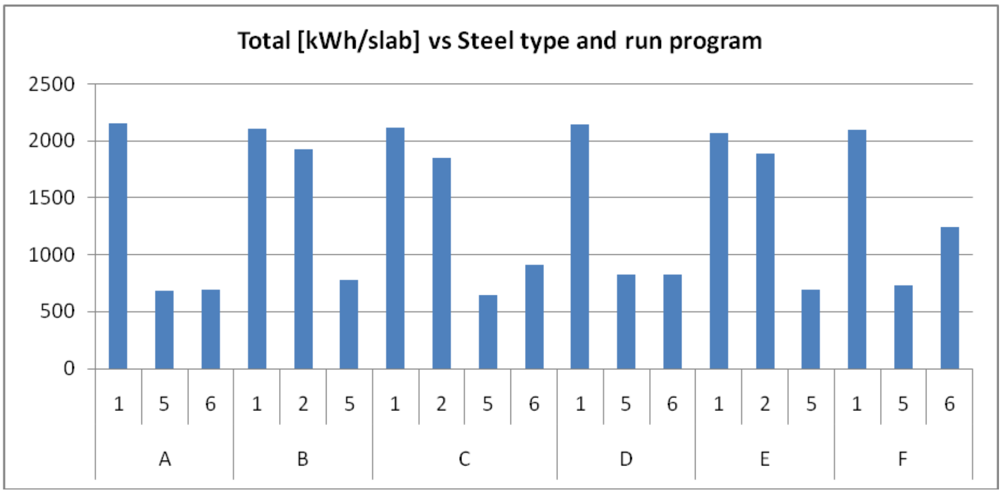

Figure 6.8 Total electricity consumption in relation to steel type and 'run program'.

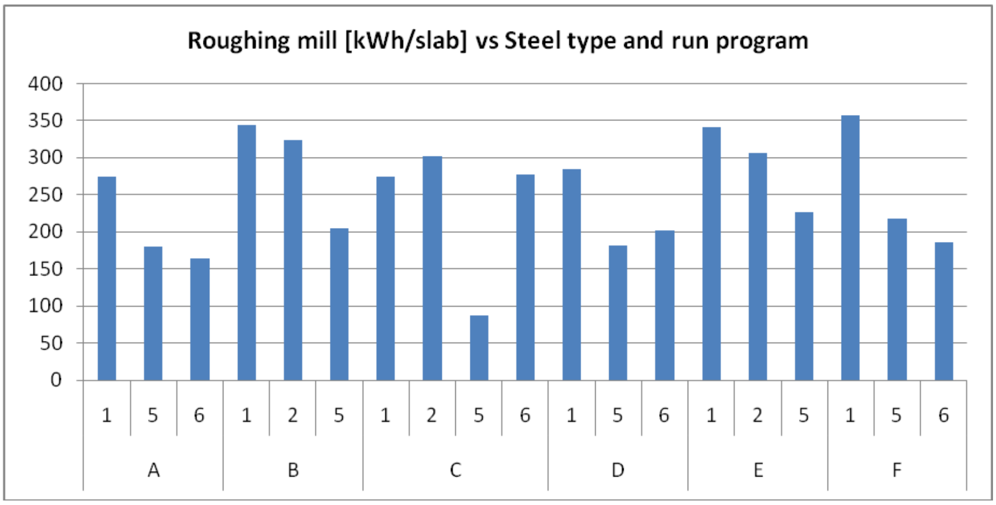

Figure 6.9 Roughing mill electricity consumption in relation to steel type and 'run program'.

In Figure 6.10 the relation between the total electricity consumption and the thickness of the finished band can be seen. Worth to notice is that the thicknesses >14mm are bands that are in 'run program 6' so these bands don't leave HRM with this thickness. Apart from this a vague trend can be seen that thinner bands have a higher consumption.

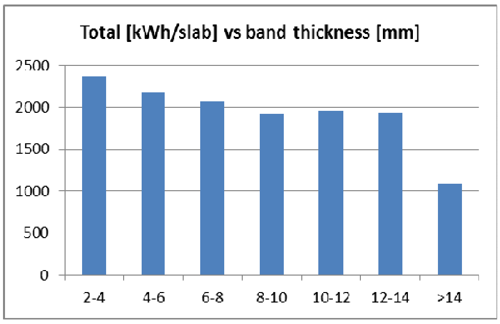

Figure 6.10 Total electricity consumption in relation to band thickness.

6.3.1 Steckel mill & Roughing mill

The influence from residence time and number of passes made in the steckel and the roughing mill is investigated further in Figure 6.11 - Figure 6.16. The electricity consumption of the steckel mill has a clear connection to both the residence time and the number of passes made. It is important to note is that the energy consumption per pass is higher for the first passes made in the steckel mill. As can be seen in Figure 6.13 the number of passes increases with the residence time apart from the >8min group. However, only 2 % of the processed bands belong to this group.

The electricity consumption for the roughing mill does also increase with the residence time and the number of passes, as seen in Figure 6.14-Figure 6.15. Note that there was only one band with 8 passes through the roughing mill, which explains the ‘outlier’ in Figure 6.15. The same correlation between number of passes and residence time for the steckel mill can be found in Figure 6.16. Less than 1% of the bands have a residence time more than 3.5 minutes so this data could also be seen as outliers. The electricity consumption for different end customers is available in Appendix I.1.

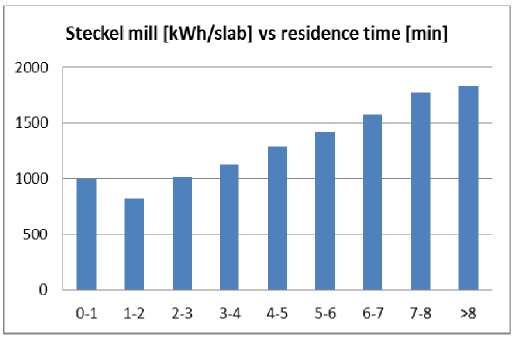

Figure 6.11 Steckel mill electricity consumption in relation to residence time.

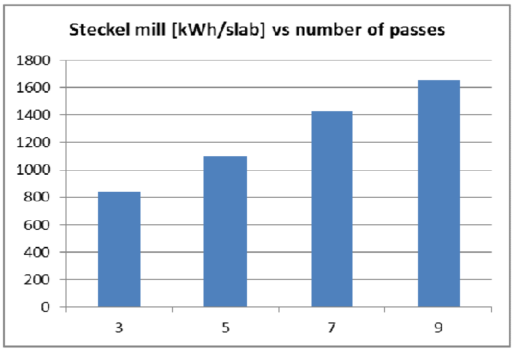

Figure 6.12 Steckel mill electricity consumption in relation to number of passes.

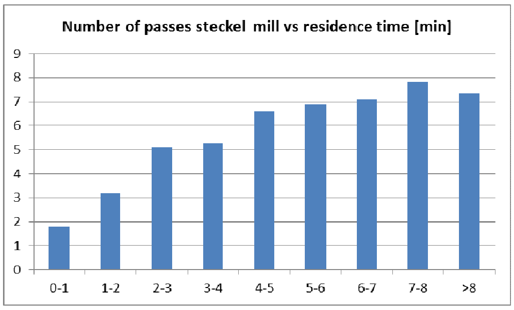

Figure 6.13 Steckel mill number of passes in relation to residence time.

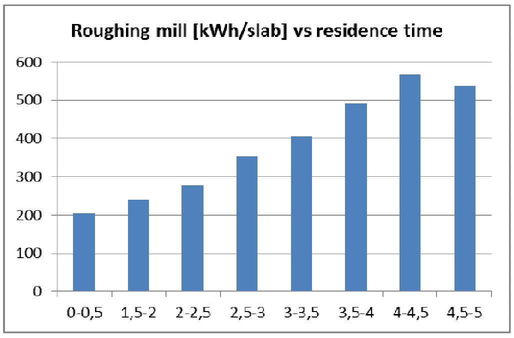

Figure 6.14 Roughing mill electricity consumption in relation to residence time.

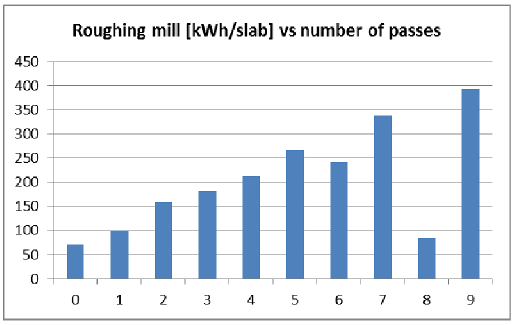

Figure 6.15 Roughing mill electricity consumption in relation to number of passes.

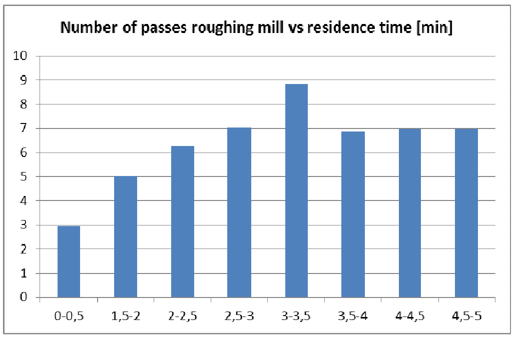

Figure 6.16 Roughing mill number of passes in relation to residence times.

6.4 Walking beam furnaces (WBF) - LPG

The allocation methodology developed for the LPG consumption in the walking beam furnaces had a high accuracy as can be observed in Table 6.8.

Table 6.8 Comparison between calculated and actual LPG consumption for walking beam furnaces in 2010.

	WBF B [MWh/year]	WBF A [MWh/year]	WBF B [%]	WBF A [%]
Calculated without standstill	137 518	33 813	90,3	86,8
Calculated with standstill	153 165	39 314	100,6	100,9
Measured	152 212	38 964	100,0	100,0

The LPG consumption for different steel types is presented in Table 6.9. ‘E’ has the highest average LPG consumption per produced slab in both furnaces and ‘D’ has the lowest one. The average LPG consumption per slab is higher in WBF B than in WBF A, which indicates that WBF A has a higher efficiency. Please remember from Chapter 3 that the consumption of WBF B is almost four times as high as WBF A and that the number of operation hours is significantly higher. WBF A was in production for 1698 hours during 2010 and WBF B for 4776 hours.

Table 6.9 LPG consumption for WBF B & A in relation to steel type.

Steel type	WBF B LPG [kWh/slab]	Slab weight [ton]	WBF A LPG [kWh/slab]	Slab weight [ton]
E	10 619	21,3	9 993	22,4
B	10 487	21,8	9 814	21,8
C	10 402	18,7	8 827	18,9
F	9 515	19,3	8 365	17,8
A	8 283	15,7	8 109	17,6
D	6 831	13,0	6 553	12,9

The slab weight has a strong influence on the energy consumption in the furnaces. Figure 6.17 - Figure 6.18 shows the increased energy consumption in relation to slab weight. The average slab weight is the highest for ‘E’ steel and ‘B’ for both WBF B and WBF A as seen in Table 6.9. These steel types also have the highest average LPG consumption. ‘D’ has the lowest LPG consumption in both furnaces. The LPG consumption follows the slab weight when looking at Table 6.9 with one exception and that is for ‘C’ and ‘F’ in WBF B.

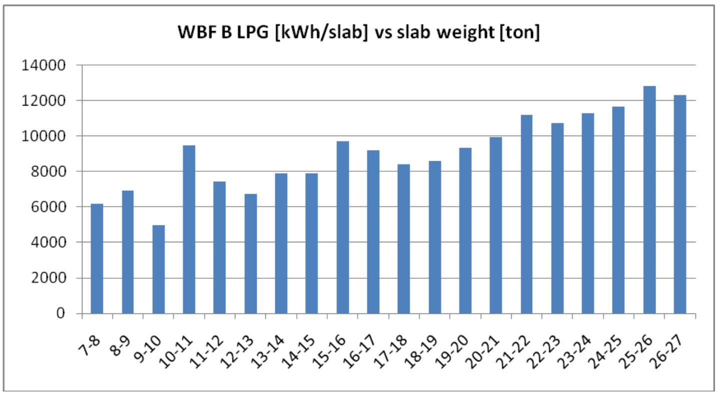

Figure 6.17 LPG consumption of WBF B in relation to slab weight.

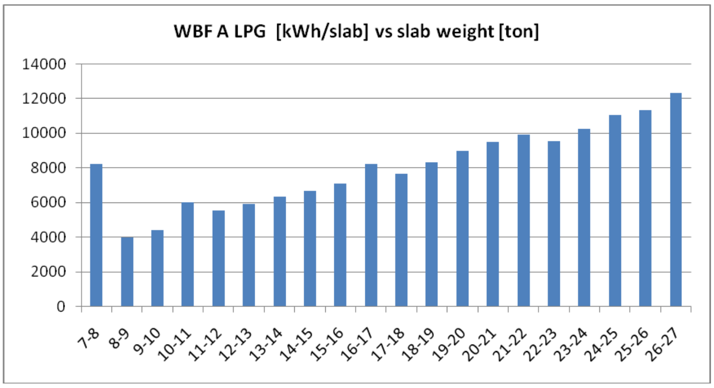

Figure 6.18 LPG consumption of WBF A in relation to slab weight.

The residence time in the furnaces seems to have a slight impact on the energy consumption as seen in Figure 6.19. Only a weak correlation can be observed for the most common residence times (<6 hours). Only 3.5% of all slabs are processed longer than 6 hours so the statistics for these slabs are not representative.

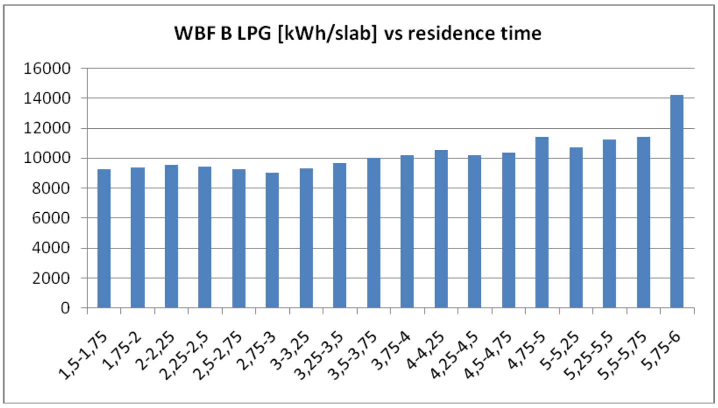

Figure 6.19 LPG consumption of WBF B in relation to residence time.

Due to the high consumption of fossil fuel in the WBF:s and a suspicion about high standstill losses an investigation about the production rate’s impact on the energy consumption was done for WBF B. The specific energy consumption was investigated in connection to production rate as seen in Figure 6.20. The consumption decreases quickly when the production rate increases and seems to decrease linearly for higher production rates. This indicates that the production rate is one of the most important factors that affect the energy consumption. The very low production rates with high specific energy consumption are not that common and do probably mostly represent start-up and shut down periods. To investigate the energy consumption of WBF B better and to find out if the efficiency of the furnace varies as much as the statistical analysis indicated, the heat balance calculations were done. These results are available in section 6.4.1.

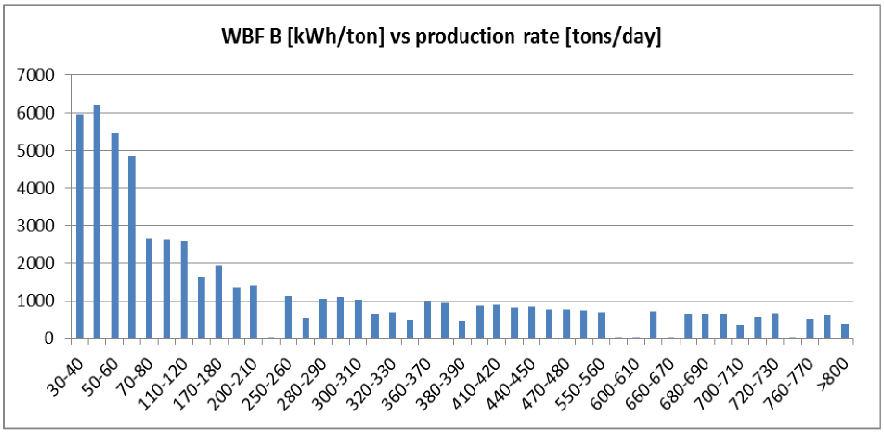

Figure 6.20 Daily specific energy consumption of WBF B in relation to daily production rate.

6.4.1 Heat balance for WBF B

During April 2010 1591 slabs with a total weight of 32 088 tons were heated in WBF B. The results from the heating balance calculations for WBF B can be seen in Table 6.10. The average efficiency of the furnace is lower than 50% and the various losses are significant. The flow losses from the windows are probably underestimated since they were based on the time the windows are fully opened and the time for opening and closing the windows was not included.

The difference term in the energy balance is also quite significant, 11.9%. This indicates that there must be other losses which are not included in the heat balance. Air leakage out of the furnace could constitute a big share of these losses since there were several spots where one could see into the furnace. Furthermore the thermo graphic studies showed high temperatures (500-600°C) around fittings and openings which indicates air leakage. Since there were two days in April without production the efficiency was calculated with these days both included and excluded. The reason was to see if standstill affects the efficiency remarkably . As can be seen the efficiency drops about 1 percentage point due to the days without production.

The furnace efficiency for different production rates is presented in Figure 6.21. This efficiency only includes the heat transferred to the slabs and not the heat delivered to the district heating network. The efficiency rises quickly at low production rates and seems to flatten out around 55% for the higher production rates. This pattern explains why the specific energy consumption of the walking beam furnace is so high for lower production rates (see Figure 6.20) so the results in section 6.4 are reasonable. Additional results and analysis done connected to the heating balance can be found in Appendix C.6.

Table 6.10 Heat balance terms of WBF B, April 2010.

Term	**[MWh]**	**% of total in**
Air into furnace	164,1	0,964
LPG into furnace	16 855	99,0
Total energy in	**17 019**	100,0
Energy to slabs	7 892	46,4
Cooling water losses	2 430	14,3
Flue gas losses	1 491	8,76
Waste heat boiler losses (district heating)	2 061	12,11
Radiation losses from furnace walls	596,4	3,50
Convection losses from furnace walls	2 405,0	14,13
Flow loss from charging side	205,2	1,21
Flow loss from discharging side	303,4	1,78
Radiation loss from charging windows	1,893	0,011
Radiation loss from discharging windows	5,979	0,035
Total losses	**7 095**	41,7
Total energy out	**14 987**	88,1
Difference in-out	2 032	11,9
Number of slabs into furnace	1 591	-
Total slab weight [ton]	32 088	-
Average efficiency (days without production excluded) [%]	-	**47,3**
Average efficiency [%]	-	**46,4**

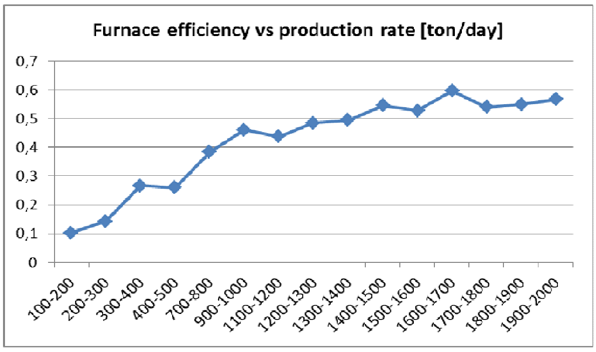

Figure 6.21 Furnace efficiency in relation to daily production rate.

6.5 Coiler furnace – LPG

Since the LPG consumption of the coiler furnaces only was allocated based on the annual consumption no deeper analysis of this was done. The results for different steel types are available in Appendix H.2.

6.6 Steel mill – Electricity

The preciseness of the allocation methods was investigated and as observed in Table 6.11 the calculated annual energy consumption for the steel mill corresponds quite well with the measured annual consumption. The difference between 'without standstill' and 'with standstill' is large for the converter and the continuous casting. The difference between these two numbers is so small for the ladle furnace since almost all the electricity is consumed by the electrodes in the furnace which have no consumption during standstill mode.

The process logs obtained from the steel mill only contained a few parameters that could be connected to the energy consumption. Furthermore it was hard to track variations in energy consumption since the production pattern is dependent on the preceding processes as stated in Section 3.5. Due to these two facts the analysis of the energy consumption of this department became insufficient. Some results will be presented even though explanations have not always been found. Therefore a large share of the results are to be found in Appendix F. It was possible to calculate in data for the calculation tool as planned though. Short comments on the cooling water system can be found in Section 6.6.2.

Table 6.11 Comparison between calculated annual and actual energy consumption for the steel mill in 2010.

	Total without Stand still [MWh]	**Total without stand still [%]**	**Total with stand still [MWh]**	**Total with stand still [%]**	**Measured [MWh]**	**Measured [%]**
Steel mill (without EAF melt power)	62 473	83,8	72 989	98,0	74 514	100,0

6.6.1 EAF melting power

In the electric arc furnace (EAF) the steel types 'F' and 'A' have the highest specific electricity consumption while 'B' and 'E' have the lowest one as seen in Table 6.12. The absolute difference between the steel types is large compared to other components since the consumption of the EAF is so large. The first parameter that was investigated against the electricity consumption was the weight of the material in the charge. In Figure 6.22 a quite fair correlation can be observed. Even the specific electricity consumption seems to have a correlation to the charge weight as seen in Figure 6.23.

Results for scrap density and chromium content constitue proprietary knowledge and are therefore not presented in this report. These parameters are however not of high importance for the analysis of the process.

Table 6.12 EAF specific melting power consumption and charge weight in relation to steel type.

Steel type	**EAF [kWh/ton]**
F	455,4
A	446,7
C	445,8
D	428,1
B	420,8
E	417,2

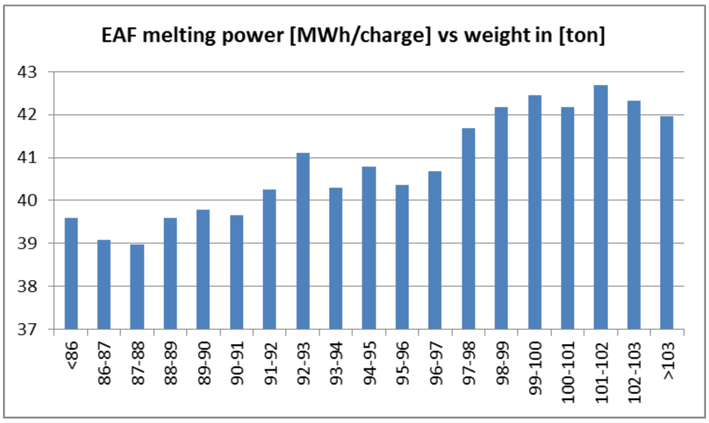

Figure 6.22 EAF melting power consumption in relation to charge weight.

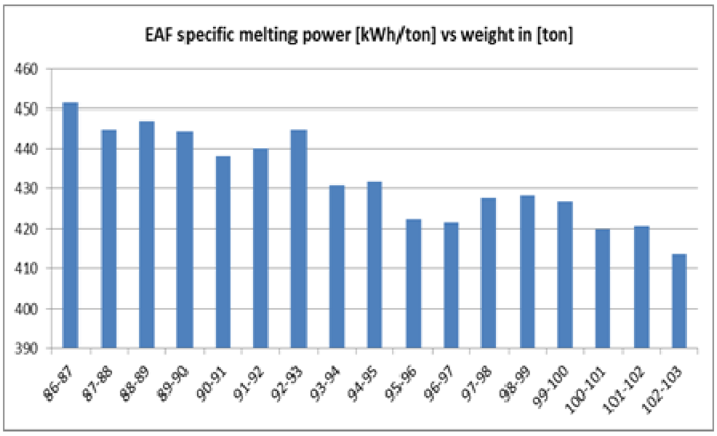

Figure 6.23 EAF specific melting power consumption in relation to charge weight.

6.6.2 Cooling water systems

A survey of the cooling water systems had to be done to allocate the electricity use of these processes. During this survey it was discovered that there might be a potential both for load controlling these systems and eliminating stand still energy use.

The pumps of the cooling water system that cools the flue gas channels connected to the EAF and the converter are running at constant speed during both production and non-production hours. The full cooling demand for the flue gas channel in the converter is only present during direct extraction which is only done about 10% of the production time. When not direct extracting flue gas the cooling demand is about 90% lower (Hansson. M, 2005). So there should probably be a potential for saving quite a lot of electricity by regulating the cooling water flows to better match the cooling demand. The consequence of failing to meet the cooling demand in the flue gas channel is a blowout which could be very costly so the regulation would have to be very precise and robust. The regulation of the cooling of the EAF flue gas system would probably be easier to implement since the consequence of not meeting the cooling demand is not as serious.

The cooling water system at the continuous casting is also only partly demand controlled. All the pumps of this system were mapped and can be found in Appendix A.8. Some pumps are only running when a strand is cast but most of them are running at constant speed all the time to keep the system stable. This process could probably be controlled so that the cooling demand is met more accurate. Doing such an analysis in detail was not the objective of this project though.

6.7 Steel mill – LPG, oxygen and chemical energy

6.7.1 LPG

In the EAF the LPG consumption was logged per charge. The data is presented in Table 6.13. As also can be noticed, the share of LPG of the total energy consumption (electricity and LPG) in the EAF follows the same trend. For the rest of the equipment in the steel mill no analysis in connection to the different steel types was made as mentioned in section 4.7. The results for this other equipment can be seen in

Table 6.14

Table 6.13 Specific LPG consumption of the EAF in relation to steel type.

Steel type	EAF LPG [kWh/ton]	EAF LPG [kWh/charge]	EAF LPG [%] of El+LPG
D	25,0	2 254	5,5%
E	24,5	2 404	5,5%
B	23,9	2 331	5,4%
C	23,3	2 090	5,0%
F	23,2	2 250	4,8%
A	21,6	2 098	4,6%

Table 6.14 Specific LPG consumption for the other equipment in the steel mill.

Equipment	LPG [kWh/ton]
Sub process a	38,6
Sub process c	12,9
Sub process b	3,8
Sub process d	3,7
Sub process e	3,7

6.7.2 Energy for oxygen production & chemical energy

The energy consumption related to oxygen usage and the used chemical energy (the amount of chemicals added to the steel) is propriertary product information and can therefore not be presented in this report. No deeper analysis of these parameters was done however.

6.8 Summary of parameters that affect the energy consumption

Here the important product properties and production parameters that affect the energy consumption is listed.

L76 (electricity):

- Steel types has a strong influence
- Production rate has a strong influence

- How many times the band is run through the process has a strong influence.
- Surface has an apprecable influence
- Thickness has an appreciable influence
- Width has some influence

L76 (WRD oil):

- Steel types has a slight influence
- Production rate has a strong influence

Z-high (electricity):

- Steel type does not have an influence
- Number of passes made has a strong influence
- Thickness has an appreciable influence

HRM (electricity):

- Run program & end customer has a strong influence
- Number of passes in steckel & roughing mill has a strong influence
- Thickness has a slight influence

HRM (LPG):

- Steel type has a strong influence
- Production rate has a strong influence
- Slab weight has a strong influence
- Residence time has a slight influence

EAF:

- Steel type has a large (absolute) influence
- Charge weight has some influence
- Chromium content has a large (absolute) influence
- Scrap density has a slight influence

7 Analysis of standstill energy consumption

To identify the process parts with a potential for energy savings the standstill energy for each process part is presented. In the APL plant, 3245 hours or 37% of the year were hours without production. As presented in Table 7.1 the total stand still share of the electricity consumption at APL is about 12 %. The treatment line has a bit higher standstill consumption. Both the oil to the steam boiler and the catalytic NO_X reduction had rather high standstill consumption. There has already been a lot of work done to decrease the standstill consumption at L76, so focus was put on the other processes.

A standout is Z-high though, which has a rather high stand still consumption (22%). A study of the different types of production stops was done to investigate this. The longest stop is the summer vacation stop during the second half of July. There are also production stops every second weekend. During regular production the total average electricity consumption was 1.560 MWh/h in 2010. The corresponding numbers for maintenance stops and the summer stop were 0.440 and 0.300 MWh/h, respectively. The Switchgear A111 constitutes the major consumption during the stops. So an investigation could be carried out which equipment that is connected to this switchgear and if it could be turned off during the stops to save electricity.

Table 7.1 Standstill energy consumption for APL.

Process part	**Stand still percentage [%]**
Electricity	
Treatment line	17,52
Inlet	9,20
Electrolyte pickling	0,87
Blasting	1,44
Total L76	12,26
Z-high	21,90
O2 energy	5,91
Oil	
Steam boiler	42,52
Cat NOx	31,91
Annealing furnace	3,68

The standstill energy consumption at HRM was almost a quarter of the annual consumption as can be seen in Table 7.2. 3884 hours (44%) during 2010 were non production hours and the standstill percentages were generally higher here than at APL. The steckel is the largest consumer and has a high standstill share. Furthermore the power transformer and the plate hall have rather high standstill consumption. But these processes are not directly connected to the production process in the same way, so the figures could be misleading. The standstill LPG consumption of the walking beam furnaces is quite small. It is probably larger for WBF A since this furnace has a higher consumption during start-up and shut down.

Apart from the summer stop there are shorter stops due to maintenance and stop in production every second Thursday and every second weekend at HRM. When in production the total electricity consumption at HRM is approximately 6.0 – 7.0 MWh/h. During the summer vacation stop most of the equipment is shut off, but the consumption of the steckel mill switchgears; A121, A126 and A216 is still quite high: 1.7 - 1.8 MWh/h. For both the stops during Thursdays and weekends the electricity consumption is around 3 MWh/h. A potential for saving in connection to both of these types of stops.

Table 7.2 Standstill energy consumption for HRM.

Process part	**Stand still percentage [%]**
Electricity	
Total	24,64
WBF A	20,34
WBF B	25,80
Rollers	13,64
Roughing mill	11,50
Steckel Mill	24,09
Lighting	42,11
Oxide shell washing	17,99
Power transformer 6	37,18
Plate hall	38,28
Band roll cooling	30,26
LPG	
WBF B	10,22
WBF A	13,99

The standstill energy consumption of the steel mill is presented in Table 7.3. As seen the continuous casting, the converter and the cooling water systems have the largest share of standstill consumption. The steel mill has maintenance stops every second Thursday. During these stops the total electricity consumption was around 6.0 MWh/h. For the summer vacation stop this number is 3.4 MWh/h and for regular production this is around 10 – 11 MWh/h when excluding the EAF melt power. This means that there might be a possibility to shut off more equipment, especially during shorter stops.

Table 7.3   Standstill energy consumption for the steel mill.

Process part	**Stand still percentage [%]**	**Number of stand still hrs**
Electricity		
Steel mill auxiliaries & preheating	8,373	1211
Converter	19,268	1935
Ladle furnace	0,701	1920
Continuous casting	27,202	2812
Flue gas system	3,973	1153
Cooling water system	15,050	1122
Hot grinding (filter & lighting included)	34,962	4500

8 Analysis done with calculation tool

The construction of the calculation tool was carried out with the results in Chapter 6 as basis. The parameters affecting the energy consumption that would be possible to quantify in an annual production mix were identified as: customer, run program, steel type and surface. All possible combinations of these parameters were identified in the process logs and each of these combinations were seen as a separate product. As stated earlier the main purpose of the calculation tool is to predict the energy consumption for a certain annual production mix. The in-data to the tool is the requested amount (ton) of each product and the final thickness of the band (only for KBR). For all calculations done the average thickness within each product group during 2010 was used.

The calculation tool uses the specific energy use calculated with the allocation methods described in chapter 4. The difference is that the energy use is accumulated from each run made to the final end product. With this data the energy use in each sub process, the total energy use and emissions are calculated. For the calculation of emissions internal fuel data (Mogard. S, 2009) together with emission data for average Nordic electricity mix (Jernkontorets Energihandbok, 2010) was used.

8.1 Total energy use for different steel types and products

The calculation tool was initially used to calculate the total (from steel mill to annealing and pickling line) specific use of electricity, WRD oil and LPG as well as the total specific CO_2 emissions. This was done by setting up a production scenario with one ton of each product. The purpose was to find out which products that are the largest consumers of each energy carrier and the largest sources to CO_2 emissions. The results from this analysis is seen in Table 8.1 - Table 8.4, where the ten products with the highest consumption of each energy carrier is shown.

As seen in Table 8.1 the largest electricity consumption is for 'D' and 'C' steel. The steel type seems to be the most important parameter. It is hard to distinguish if the surface or the run program is the second most important parameter. Run program 6 a higher consumption than run program 1.

Table 8.1 Total specific electricity consumption for different products.

Customer	Run program	Steel type	Surface	Electricty [kWh/ton]	Average number of runs at L76
KBR	6	D	3	1 654	2,12
KBR	1	D	3	1 541	2,12
KBR	6	C	3	1 509	2,07
KBR	6	C	2	1 507	2,31
KBR	1	C	3	1 458	2,07
KBR	6	F	3	1 457	2,32
KBR	1	C	2	1 456	2,31
KBR	6	A	3	1 390	2,07
KBR	1	F	3	1 365	2,12
KBR	6	D	1	1 350	1,08

The specific oil consumption varies more than the electricity consumption for different steel types as seen in Table 8.2. Generally ‘special’ steel has a higher consumption than ‘standard’ steel, but the surface seems to be a parameter with stronger influence. Since the oil consumption is not affected by the ‘run program’ this parameter is excluded from the table. Just like the for electricity consumption bands that are processed more than once through L76 have a higher consumption. This coincides well with the average number of runs made through L76.

Table 8.2 Total specific oil consumption for different products.

Customer	Run program	Steel type	Surface	WRD Oil [kWh/ton]	Average number of runs at L76
KBR	6	F	3	914	2,32
KBR	6	D	3	909	2,12
KBR	6	A	3	849	2,07
KBR	6	C	2	810	2,31
KBR	6	C	3	799	2,07
KBR	1	B	3	684	2,03
KBR	1	B	2	657	2,01
KBR	1	E	2	605	1,90
KBR	6	A	2	553	1,70
KBR	6	F	1	422	1,10

The specific LPG consumption varies significantly and is mostly dependent on the run program as seen in Table 8.3. ‘Run program 6’ gives a high consumption since the slabs are heated in the furnace twice. The HPRD slabs with ‘run program 5’ have a very high residence time in the WBF which explains this high value. ‘Surface’ is excluded from this table since the LPG consumption has no relation to the surface. Due to the fact that oil and LPG are the largest sources of CO_2 emissions the products with high consumption of these fuels have high emissions. This is observed in Table 8.4.

Table 8.3 Total specific LPG consumption for different products.

Customer	Run program	Steel type	LPG [kWh/ton]
HPRD	5	C	4 122
KBR	6	F	1 793
KBR	6	D	1 762
KBR	6	C	1 353
KBR	6	A	1 340
NYBY	6	C	1 046
HPRD	5	A	962
KBR	1	D	840
KBR	1	C	817
HPRD	5	D	797

Table 8.4 Total specific CO_2 emissions products.

Customer	Run program	Steel type	Surface	CO_2 [Ton/ton]
HPRD	5	C	-	1 114
KBR	6	F	3	920
KBR	6	D	3	912
KBR	6	A	3	791
KBR	6	C	2	787
KBR	6	C	3	782
KBR	6	F	1	760
KBR	6	D	1	741
KBR	1	F	3	706
KBR	1	D	3	702

8.2 Prediction of energy use for changes of the production mix

Finally the calculation tool was used to show the difference in energy consumption between different annual production mixes. This since Outokumpu most likely will focus on producing more 'special' steel in the future.

8.2.1 Base case

First a scenario with the production mix of 2010 was done to verify the accuracy of the calculation tool. This scenario was based on the weight data from the process logs together with the yields for each steel type for 2010. The yields were taken from the internal key indicators of Avesta Works. The delivered weight from each process was calculated as the product of the incoming weight and the yield. An exception was the steel mill where the delivered weight was available in the process log. These calculations do not reflect the production of 2010 perfectly but with enough accuracy for this analysis.

Two problems occurred when doing the final energy calculations for APL. Since the bands with other surfaces than 1, 2 and 3 were excluded from the analysis the energy consumption of these bands was missing in the calculated total annual energy consumption. Therefore this energy had to be included as a separate summed item. Furthermore, energy is consumed when L76 is fed with bands that are used as 'connection bands' between different product bands or 'maintenance/standstill bands', which are fed into the line during production stops. These two band types are called HOL and DRA, respectively. The total annual energy consumption for these two groups was also included as separate items in the calculation tool. The amount of maintenance bands processed during a year is probably not affected by a change in production mix, so the energy consumption will not be affected. The HOL-bands are used to connect two bands to each other and mainly used for 'special' steel products. So a larger share of 'special' steel bands in the production mix would increase this consumption. The summed electricity consumption of the HOL-bands during 2010 was only 400 MWh so a slight increase of the number of HOL-bands would not affect the total results that much.

8.2.2 Future production scenarios

In the first future scenario the produced weight of 'special' steel from APL (KBR) was increased with 50% compared to the 2010 mix. The production of 'standard' steel was decreased with the same amount so that the total produced weight would be the same for all scenarios. For the second scenario the amount of 'special' steel to the other customers was increased with 50% compared to 2010. These two cases are referred to as '50% KBR' and '50% Other', respectively. The share of 'special' steel for the three different cases are 35.6%, 42.5% and 45.6% respectively. So the actual increase of produced 'special' steel is 7 and 10 percentage points, respectively. The input data for these two cases is found in Appendix G.

8.2.3 Results

The results from the calculations for these cases can be seen in Table 8.5. The energy consumption of the base case coincides well with the measured data for 2010 (compare with Table 3.1 and Table 3.2). There are two exceptions to this; the log data for the EAF melt power did not coincide with the data in the internal energy report, so the electricity of the steel mill lacks ~4 800MWh compared to the measured data. The second exception is L76, where the calculations are highly dependent on the thickness of the produced bands. Using the average thickness does most likely underestimate the energy consumption for all processes here since the relation between the specific energy consumption and the thickness is not linear.

Table 8.5 Energy consumption for production scenarios.

		Base case 2010	**50% KBR**	**50% Other**
APL	L76 Electricity [MWh]	21 307	23 103	21 307
	Z-high Electricity [MWh]	10 301	10 607	10 301
	WRD Oil [MWh]	98 833	102 148	98 833
	Oxygen [MWh]	13 387	13 834	13 387
HRM	Electricity [MWh]	47 125	48 072	47 318
	LPG [MWh]	198 399	201 040	202 115
Steel mill	Electricity [MWh]	253 998	257 108	256 409
	LPG [MWh]	32 477	32 730	32 664
	Oxygen [MWh]	7 683	7 879	7 906
	Chemical [MWh]	151 421	154 872	155 252
	CO_2 from C [ton]	21 820	22 626	22 565
Total	Electricity [MWh]	332 731	338 891	335 335
	WRD Oil [MWh]	98 833	102 148	98 833
	LPG [MWh]	230 876	233 770	234 779
	Oxygen [MWh]	21 070	21 713	21 293
	Chemical [MWh]	151 421	154 872	155 252
	Tot CO_2 [tons]	135 095	138 104	137 010

The absolute and the percental increase in consumption of different energy carriers for the two cases are presented in Figure 8.1 and Figure 8.2 (compared to the base case). Keep in mind that the actual total increase of 'special' steel produced is not 50% (see section 8.2.2). The largest absolute increase is the LPG at HRM and it is larger for the '50% Other' case. This is because of the products to Degerfors, which are heated in the WBF for a very long time. The largest percental increase is for the electricity and oil consumption at APL. This shows that APL has largest the difference between 'standard' and 'special' steel products.

Overall, the energy consumption of the steel mill is affected the least (percental) by a production mix change. Producing more 'special' steel affects the consumption of oxygen and chemicals the most. The total increase in energy consumption is larger for '50% KBR' even though the absolute increase in produced weight of 'special' steel is larger in the '50% Other' case. The products not delivered to KBR are processed at other sites though, so the total consumption/emissions for this case is different.

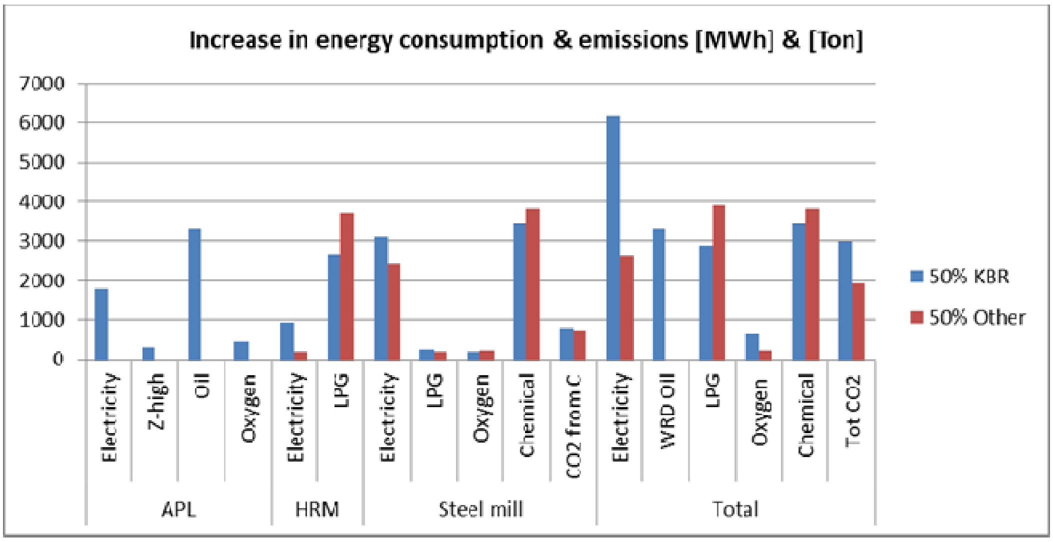

Figure 8.1 Absolute increase in energy consumption for production scenarios.

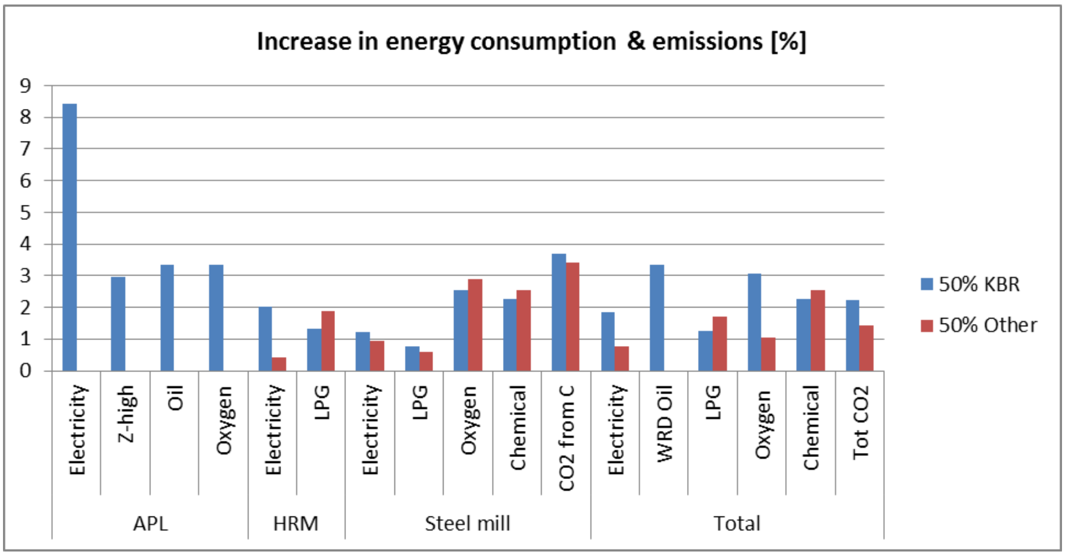

Figure 8.2 Percental increase in energy consumption for production scenarios.

9 Conclusions and recommendations

The energy consumption differs significantly between various steel products. The most important product properties that affect the energy consumption are steel type (especially ‘standard’ versus ‘special’), surface and thickness. For most production processes residence time, if reprocessing has to be done and slab/charge weight are important production parameters affecting the energy consumption. For L76 the production rate is the most important process parameter which is related to the energy consumption. At HRM, the run program used and the number of passes in the steckel and roughing mill are the most important parameters. For the WBF:s the production rate determines the specific LPG consumption. The amount of chromium in the scrap mix is the most important parameter that affects the melting power in the EAF.

The energy consumption and the CO_2 emissions of all of the main processes on site will increase appreciably if more ‘special’ steel is to be produced. Especially if this increase is for products that are treated at all three departments on site. By far the largest percental increase in energy consumption is the electricity of L76. The largest absolute increases are WRD oil at L76, LPG in the WBF:s and the electricity of the steel mill.

Since the specific energy consumption will increase with a higher share of ‘special’ steel in the production mix this has to be communicated in connection to PFE. With help from this master thesis this matter can more easily be discussed with the Swedish Energy Agency.

A potential for energy savings exists at several sub processes on site. This is related to shutting equipment off when not in production during for example maintenance stops and summer stops. The most important processes in this matter are the steckel mill and Z-high. A recommendation is that a thorough investigation of the equipment connected to the steckel mill switchgears and their on/off regulation is done. The same applies for many of the processes at the steel mill. Furthermore HRM could develop their energy logging systems in a way similar to what has been done at L76. This would be helpful for keeping track of the energy use and finding possible improvements when used by a person with deep knowledge about the production processes.

A better regulation of the cooling water systems for both the continuous casting and the cooling of the flue gas channels in the steel mill could decrease their energy consumption. This work would probably need help from an expert in the area who is interested in energy related matter.

The WBF:s are the largest fossil fuel consumers on site and the production rate in these affects the energy consumption and the efficiency significantly (for furnace B). One way to decrease the energy consumption would be to try to plan the production so that the production rate is maximized while still only keeping one furnace running. Furthermore the air leakage from the furnace together with the combustion air flow control and measurement system should be investigated further. This since significant unknown losses from the furnace and a very varying oxygen concentration in the flue gas were found.

The energy consumption related to oxygen use on site is significant, almost as large as the electricity consumption at L76. So saving oxygen can (indirectly) decrease energy use and emissions.

The price setting process of different steel products that is used today could be improved by including some energy related parameters. Especially fossil fuel could be included with help from this master thesis and/or existing process logs.

The analysis done of the steel mill in this project did not go as deep as wished for, partly because of lack of data. Especially the factors that affect the electricity consumption of the processes after the EAF and which equipment that is connected to each switchgear could be investigated further.

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Appendix A – Details on allocation methods

Here a more thorough description of the allocation methods for the energy data will be presented. Note that subscript *i* is for a value that is connected to an hour and subscript *x* for a specific slab/band in all equations.

A.1 Annealing and pickling line (APL) - Electricity

Since the logged electricity data is unique for each hour the residence time ($\tau_{furnace}$) had to be connected to the right hour from the electricity log. Most of the bands had a residence time which was less than 0.6 hours and almost 99% of the bands had a residence time lower than 2 hours. So it was decided that electricity data for two separate unique hours should be included in the calculations; the residence time for the inserting hour ($\tau_{x,in}$) and the exiting hour ($\tau_{x,out}$) as stated in equation A.1 and equation A.2. Since the residence time had to be connected to the correct hour the 'whole hour' that the slabs are inserted into ($t_{x,ins}$) and exiting the furnace ($t_{x,exit}$) had to be identified. Then the total electricity consumption per slab could be calculated by equation A.3. Examples of these times used can be found in Table A.1.

$$\tau_{x,in} = (t_{x,ins} + 1hr) - t_{x,in} \quad \text{(A.1)}$$

$$\tau_{x,out} = t_{x,out} - t_{x,exit} \quad \text{(A.2)}$$

$$W_x = \tau_{x,in} \cdot W_{i,ins} + \tau_{x,out} \cdot W_{i,exit} \quad \text{(A.3)}$$

A.1.1 Treatment of production stops

One problem with this allocation method would be production stops. Since the residence time was calculated from the inserting time into the furnace a production stop will give the last band before the production stop a very large residence time. To take care of this matter the data for the exiting hour was corrected by setting the residence time for the exit hour to 1.5 if the total residence time was higher than 2 hours. This is illustrated in Table A.1.

Table A.1 Data correction for production stops.

$t_{x,in}$	$t_{x,out}$	$\tau_{x,furnace}$	$t_{x,ins}$	$t_{x,exit}$	$\tau_{x,in}$	$\tau_{x,out}$
Inserting time	**Exiting time**	**Residence time furnace [hrs]**	**Inserting hour**	**Exiting hour**	**Residence time insert hour [hrs]**	**Residence time exit hour [hrs]**
2010-08-03 13:13	10-08-03 15:55	2,70	10-08-03 13:00	10-08-03 15:00	0,7691	1,5000
2010-08-26 23:50	10-08-27 00:14	0,40	10-08-26 23:00	10-08-27 00:00	0,1628	0,2375
2010-08-21 07:18	10-08-21 07:31	0,22	10-08-21 07:00	10-08-21 07:00	0,2195	0,0000
$If\ \tau_{x,furnace} > 2hrs \quad \tau_{x,out} = 1,5hrs$						

A.2 Hot rolling mill (HRM) - Electricity

The residence times in the steckel and the roughing mill (τ_x) were calculated according to equation A.4 and equation A.5. The residence times for all bands during a certain hour were then summed together to a total residence time during a certain hour (τ_i). Then the share the total residence time during each hour (S_x) for each band was calculated. This share was multiplied with the electricity consumption connected to the certain hour to calculate the consumption for the band according to equations A.6-A.8. The same procedure was used for the roughing mill

One problem occurred for the bands processed with 'run program 5' and 'run program 6'. The calculated electricity consumption for the roughing mill was based on the time the band reaches the steckel mill. Since this time was not given for these bands the consumption in the roughing mill could not be calculated. So in this case the weight factor for the roughing mill and thereby the electricity consumption was estimated from an average residence time for the corresponding steel type in 'run program 1'. The same was done for the weight factor for the steckel mill for 'run program 2' bands since the ending time in the steckel was not given for these bands.

$$\tau_{x,roughing} = t_{x,in,steckel} - t_{x,out,furnace} \quad (A.4)$$

$$\tau_{x,steckel} = t_{x,out,steckel} - t_{x,in,steckel} \quad (A.5)$$

$$\tau_{i,steckel} = \sum_x \tau_{x,steckel} \quad (A.6)$$

$$S_x = \frac{\tau_{x,steckel}}{\tau_{i,steckel}} \quad (A.7)$$

$$W_x = S_x \cdot W_i \quad (A.8)$$

A.3 Walking beam furnaces (WBF) - LPG

From the process log information about inserting time, exiting time and slabs weight was given. The first thing that had to be identified was which hour the slab was inserted into the furnace and how much time the slab spent in the furnace during this 'inserting hour' ($t_{x,in}$). Then the whole hours that the slab had been in the furnace had to be identified. Finally the exiting hour ($t_{x,out}$) was identified as well as how much time the slab spent in the furnace during this 'exiting hour'. An example of this calculation procedure for the inserting hours, exiting hours and whole hours is shown in Table A.2. Here information about four slabs going into the furnace during the same hour is given. The residence times during the inserting hour and exiting hour were calculated according to equation A.9 and equation A.10.

Table A.2 Example of residence times in WBF

CGS	Inserting time furnace	Exiting time furnace	Slab weight [tonnes]	Hour in	Part of hour in	Hour exit	Part of hour exit	# of hrs	Hour 1	Hour 2
403354-3	10-10-23 06:08	10-10-23 09:01	20,49	06:00	0,864	09:00	0,029	2	07:00	08:00
403355-1	10-10-23 06:32	10-10-23 09:16	21,13	06:00	0,453	09:00	0,278	2	07:00	08:00
403453-2	10-10-23 06:47	10-10-23 09:31	20,91	06:00	0,210	09:00	0,528	2	07:00	08:00
403453-4	10-10-23 06:59	10-10-23 09:46	20,91	06:00	0,010	09:00	0,777	2	07:00	08:00

$$\tau_{x,in} = (t_{x,ins} + 1hr) - t_{x,in} \quad \text{(A.9)}$$

$$\tau_{x,out} = t_{x,exit} - t_{x,out} \quad \text{(A.10)}$$

Then weight factors for each slab (G_x) for inserting, whole and exiting hours were calculated as the product of residence time and slab weight according to equations A.11 - A.13. Finally the weight factors for all slabs that were in the furnace during an hour were summarized to a weight factor unique for each hour (G_i) as stated in equation A.14.

$$G_{x,in} = m_x \tau_{x,in} \quad \text{(A.11)}$$

$$G_{x,i} = m_x \tau_x = m_x \text{ since } \tau_x = 1 \forall i \quad \text{(A.12)}$$

$$G_{x,out} = m_x \tau_{x,out} \quad \text{(A.13)}$$

$$G_i = \sum_x G_{x,in} + \sum_x G_{x,i} + \sum_x G_{x,out} \quad \text{(A.14)}$$

In Figure A.1 an example hour is shown where 16 slabs are heated in the furnace. Slabs A-D are inserted into the furnace during this hour, slabs E-H are treated during their first whole hour in the furnace, slabs I-L are treated during their second whole hour in the furnace and slabs M-P are exiting the furnace during this hour. For each of these slabs the weight factor is also given.

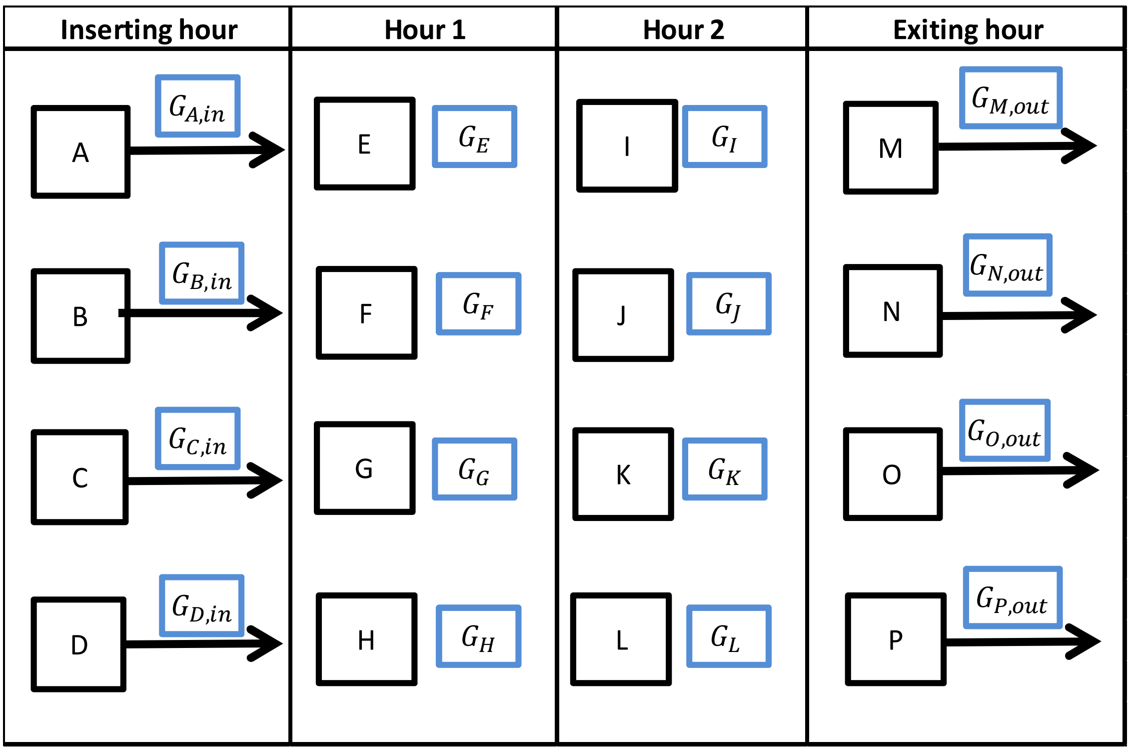

Figure A.1 Schematic description of the calculation procedure for one hour in WBF.

From the weight factor for the unique hour an energy weight factor (C_i) was calculated for each unique hour according to equation A.15. When the energy weight factors for each hour during the whole year had been calculated the LPG consumption for each slab and each hour it was treated in the furnace was calculated ($E_{x,in}$), (E_x) and ($E_{x,out}$) according to equations A.16-A.18. These values were then summarized to total energy consumption for each slab ($E_{x,tot}$) as stated in equation A.19.

$$C_i = \frac{E_{i,LPG}}{G_i} \tag{A.15}$$

$$E_{x,in} = C_i \cdot G_{x,in} \tag{A.16}$$

$$E_x = \sum_1^n C_i G_{x,i} + ... + C_n G_{x,n} \tag{A.17}$$

$$E_{x,out} = C_i \cdot G_{x,out} \tag{A.18}$$

$$E_{x,tot} = E_{x,in} + E_x + E_{x,out} \tag{A.19}$$

A.5 Coiler furnaces - LPG

First the sum of all residence times for all bands during a month in the steckel mill was calculated and then the share of the residence time was calculated for each band. This share was then multiplied with the monthly consumption to calculate the consumption for each band. This procedure can be seen in equations A.20-A.22. The same problem as for the electricity of the steckel mill occurred here. Since the slabs processed with 'run program 2' did not have a exiting time from the steckel mill the residence time for these slabs had to be estimated from the average for each steel type in 'run program 1'.

$$\tau_{i,steckel} = \sum_x \tau_{x,steckel} \tag{A.20}$$

$$S_x = \frac{\tau_{x,steckel}}{\tau_{i,steckel}} \tag{A.21}$$

$$E_x = S_x \cdot E_{i,LPG} \tag{A.22}$$

A.6 Steel mill - Electricity

These calculations were carried out in the same way as for the annealing and pickling line as presented in section A.1. An example of a charge with a residence time of two full hours can be seen in Table A.3. The calculations were carried out in a similar way as for APL according to equations A.23-A.26. One thing was different here though: the waiting time between the charges in each process step. This waiting time was usually less than an hour and therefore would not be included in the standstill hours. Each charge was simply allocated this rest time in the calculation.

Table A.3 Example of residence times in the converter.

$t_{x,in}$	$t_{x,out}$	$\tau_{x,furnace}$	$t_{x,ins}$	$t_{x,exit}$	$\tau_{x,1}$	$\tau_{x,2}$
StartTimeAOD	**EndTimeAOD**	**Time in AOD**	**Hour in**	**Hour out**	**Hour 1**	**Hour 2**
2010-02-25 22:56	2010-02-26 01:20	2,39	2010-02-25 22:00	2010-02-26 01:00	2010-02-25 23:00	2010-02-26 00:00

$$\tau_{x,in} = (t_{x,ins} + 1hr) - t_{x,in} \quad \text{(A.23)}$$

$$\tau_{x,out} = t_{x,out} - t_{x,exit} \quad \text{(A.24)}$$

$$\tau_{x,i} = 1 \forall i \quad \text{(A.25)}$$

$$W_x = \tau_{x,in} \cdot W_{i,ins} + \sum_i (\tau_{x,i} \cdot W_i) + \tau_{x,out} \cdot W_{i,exit} \quad \text{(A.26)}$$

A.7 Flue gas system

The flue gas flows for the EAF and the converter are measured every second but not logged and saved for more than 3 months back. Therefore suitable data from 2010 for this investigation was not available. Instead the average set points for the flows during different production phases were used. From these the share of the total flue gas flow was evaluated for the converter and the EAF. These were calculated as 74% and 26 % for the EAF and converter, respectively. It was assumed that all production phases use an equal amount of time. This is probably not perfectly true, but no data for this time distribution was available.

For each hour during the year the electricity consumption of the flue gas system for both the EAF and the converter was calculated. Four different cases were available for this calculation and these can be seen in Table A.4. From here the total electricity consumption was calculated for each charge based on its residence times in the EAF and the converter as done in section A.6.

Table A.4 Calculations of flue gas system electricity consumption.

Case	Electricity consumption EAF [% of hourly consumption]	Electricity consumption converter [% of hourly consumption]
EAF & Converter running	76	24
EAF running	100	0
Converter running	0	100
None running	50	50

A.8 Cooling water system

The pumps of the cooling water systems can be seen in Table A.5. The design power and then the electric power of the pumps were calculated according to equation A.27 and equation A.28 because this data could not be found in the pump specifications. The electric efficiency of the pumps was assumed to be 95%.

The shares for each process was calculated as the sum of the power of all pumps in the process divided by the total pump power for the whole cooling water system. The shares, which can be seen in Table A.6, were then used to calculate the electricity consumption for the four different processes during each hour of the year. The total electricity consumption was calculated as the sum of the three processes.

$$P_{pump} = q \cdot \rho \cdot g \cdot h \tag{A.27}$$

$$P_{el} = \frac{P_{pump}}{\eta_{pump}} \tag{A.28}$$

Table A.5 Pumps in cooling water system of the EAF, converter and ladle furnace.

Pump system	**Flow [m3/h]**	**'Lifting height' [mVp]**	**Design power [kW]**	**% of design power**	**Running power [kW]**	**Number of pumps**	**Number of pumps running**	**Total power [kW]**	**Running time**
EAF Cooling	650	81	143,4	70%	100,4	4	3	317,0	Year round
Converter Cooling	710	72	139,3	70%	97,5	4	3	307,8	Year round
Ladle Furnace Cooling	300	60	49,0	70%	34,3	2	1	36,1	Year round
Booster pumps to emergency cooling	120	40	13,1	-	-	2	0	0	In emergency

Table A.6 Shares of pump power in the cooling water system.

Process	**Percent of pump power**
EAF	47,96%
Converter	46,57%
Ladle Furnace	5,47%

Table A.7 Pumps in cooling water system of the continuous casting.

Pump system	**Flow [m3/h]**	**'Lifting height' [mVp]**	**Design power [kW]**	**% of design power**	**Running power [kW]**	**Number of pumps**	**Number of pumps running**	**Total power [kW]**	**Running time**
P1 A - Reservoir pump	-	-	30	100%	30	1	0	0	Now & then
P1 B - Reservoir pump	-	-	30	100%	30	1	0	0	Now & then
P3 - Cooling of machinery	-	-	81,5	100%	81,5	4	3	244,5	Year round
P7 A-C - Cooling of strand	-	-	110	100%	110	3	2	220	During casting
P5 A-C - Spray cooling casting arch	-	-	75	100%	75	3	2	150	During casting
11 A-C - Cooling of chill	-	-	90	75%	67,5	3	2	135	Not during winter
12 A-C - Cooling towers	-	-	90	75%	67,5	3	2	135	Not during winter
P4 A-B - Other cooling	-	-	90	100%	90	2	1	90	Year round
P31 - Pumps for flooding	-	-	-	-	-	-	-	-	In emergency
P6 - Emergency cooling	-	-	-	-	-	-	-	-	In emergency

Appendix B – Switchgear groupings

Table B.1 Switchgear groups for APL.

Switchgear ID	Equipment	Group
A201	Strömsnäs pump water	Not included
A205	Treatment line	Treatment line
A206	Treatment line	Treatment line
A207	Electrolyte	Pickling
A208	Inlet	Inlet
A209	Blasting	Blasting
A210	Inlet	Inlet
A211	Inlet	Inlet
A212	Inlet	Inlet
A213	Lighting	Other
A214	Acid Regeneration	Not included
A215	Reserve	Not included

Table B.2 Switchgear groups for HRM.

Switchgear ID	Equipment	Group
A104	Switchgear 9	WBF B
A108	Oxide shell washing	Other
A109	Lighting	Other
A110	Walking beam furnace A	WBF A
A111	Walking beam furnace B	WBF B
A121	Steckel	Steckel mill
A123	Switchgear 9 (kraftrafo)	Other
A124	Switchgear (plåthall)	Other
A125	Switchgear 2	WBF A
A126	Switchgear 1 (Horizontal)	Roughing mill
A127	Reserve	Not included
A128	Help-power steckel	Steckel mill
A129	Reserv	Not included
A15	Hasplar Undergrupp 216	Steckel mill
A16	Delningssax Undergrupp 217	Steckel mill
A17	DC-drifter Undergrupp 218	Steckel mill
A201	Reserve	Not included
A206	Reserve	Not included
A207	Vertical roughing	Roughing mill
A208	Horizontal roughing	Roughing mill
A209	Horizontal roughing	Roughing mill
A211	Roller conveyors roughing	Roller conveyors
A212	Horizontal roughing	Roughing mill
A213	Reserve	Not included
A214	Reserve	Not included
A215	Roller conveyors	Roller conveyors
A216	Steckel main motor	Steckel mill
A218	Rollers conveyors roughing	Roller conveyors
A219	Rollers conveyors roughing	Rollers conveyors
G31	Compressor spooling	Other

Appendix C – Heat balance for WBF B

C.1 LPG, combustion air and slabs

The energy added by the LPG was calculated from equation C.1. The added energy to the slabs in the furnace (going out from the furnace) was simply calculated as the enthalpy difference between incoming and outgoing slabs according to equation C.2. The temperature of the exiting slabs varied from 1250-1300°C. It was assumed that the steel enthalpy varies linearly in this interval. Energy in the combustion air was calculated according to equation C.3 since the reference temperature was set to 0°C.

$$Q_{LPG} = V_{LPG} \cdot \rho_{LPG} \cdot H_{LPG} \tag{C.1}$$

$$Q_{slabs} = m_{slabs} \cdot (H_{steel,1250\,°C} - H_{steel,25\,°C}) \tag{C.2}$$

$$Q_l = V_{l,v} \cdot \rho_l \cdot H_{l,25\,°C} \tag{C.3}$$

C.2 Cooling water, flue gas and district heating losses

The cooling water losses were calculated from the flow in each cooling zone and the temperature difference between ingoing and outgoing cooling water according to equation C.4. The specific heat capacity of the cooling water was assumed to be constant with regard to temperature.

$$Q_{cw} = m_{cw} \cdot C_{p_{cw}} \cdot (T_{cw,in} - T_{cw,out}) \tag{C.4}$$

The problem with the flue gas losses was that the flue gas flow was not known, so the flue gas flow had to be calculated from ingoing airflow and theoretical combustion principles (Mörtstedt. S-E, 1962). Complete combustion of LPG takes place according to equation C.5. Then the theoretical air demand, the specific theoretical air demand, the specific real air demand and the air excess ratio were calculated as in equations C.6-C.9.

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O \tag{C.5}$$

$$V_{l,0} = \frac{V_{LPG} \cdot \rho_{LPG}}{M_{LPG}} \cdot \frac{5}{1} \cdot \frac{M_{O_2}}{\rho_{O_2}} \cdot \frac{1}{[O_2]_l} \tag{C.6}$$

$$l_0 = \frac{V_{l,0}}{V_{LPG}} \tag{C.7}$$

$$l_v = \frac{V_{l,v}}{V_{LPG}} \tag{C.8}$$

$$\lambda = \frac{l_v}{l_0} \tag{C.9}$$

From here the theoretical amount of different species (y) in the flue gases was calculated. These were then summed together for the total theoretical flue gas amount. An example of this calculation for CO_2 can be seen in equation C.10. This calculation was done for all species (y). Then the theoretical and actual specific flue gas amounts could be calculated as in equation C.11 and equation C.12.

$$V_{CO_2,0} = \frac{V_{LPG} \cdot \rho_{LPG}}{M_{LPG}} \cdot \frac{3}{1} \cdot \frac{M_{CO_2}}{\rho_{CO_2}} \tag{C.10}$$

$$g_0 = \frac{\sum_y V_{y,0}}{V_{LPG}} \tag{C.11}$$

$$g_v = g_0 + (\lambda - 1) \cdot l_0 \tag{C.12}$$

Now the composition of the flue gases had to be calculated to be able to estimate the enthalpy of the flue gases. First the amount of oxygen going into the furnace was calculated and then the amount of oxygen oxidized during combustion. Finally the amount of the flue gas species could be calculated as well as the molar concentration of each species. This was done according to equations C.13-C.19.

$$n_{O_2,in} = V_{l,v} \cdot [O_2]_l \cdot \frac{\rho_{O_2}}{M_{O_2}} \tag{C.13}$$

$$n_{O_2,oxidized} = n_{O_2,in} - V_{g,v} \cdot [O_2]_g \cdot \frac{\rho_{O_2}}{M_{O_2}} \tag{C.14}$$

$$n_{O_2,g} = n_{O_2,oxidized} - n_{O_2,in} \tag{C.15}$$

$$n_{CO_2,g} = n_{O_2,oxidized} \cdot \frac{5}{3} \tag{C.16}$$

$$n_{H_2O,g} = n_{O_2,oxidized} \cdot \frac{5}{4} \tag{C.17}$$

$$n_{N_2,g} = n_{O_2,in} \cdot \frac{1}{[O_2]_l} \tag{C.18}$$

$$[y]_g = \frac{n_{y,g}}{\sum_y n_{y,g}} \tag{C.19}$$

From the molar concentrations the final enthalpy of the flue gas could be calculated according to equation C.20. The average temperature of the flue gases varied between 150 and 300°C. It was assumed that the enthalpy varied linearly in each 100°C interval so that the enthalpy could be calculated with 1°C preciseness. Finally the flue gas loss could be calculated with equation C.21.

$$H_g = \sum_y [y]_g \cdot H_{y,g} \tag{C.20}$$

$$Q_g = V_{g,v} \cdot H_{g,T_g} \tag{C.21}$$

The district heating losses were calculated with the enthalpies of the flue gas before and after the waste heat boiler according to equation C.22.

$$Q_{dh} = V_{g,v} \cdot (H_{g,T_{WHB,in}} - H_{g,T_{WHB,out}}) \tag{C.22}$$

C.3 Radiation and convection losses

To calculate the radiation and the convection losses from the furnace it was modelled as a rectangular cuboid. The dimensions were measured from blueprints: length 22.5m, width 13.8m and height 6.8 m. The average temperatures of the surfaces had to be estimated. This was done from thermo graphic measurements done for the sides of the furnace in March and April 2009. Thermo graphic measurements were done in February 2011 to estimate the temperature of the discharging side of the furnace. No measurements of the charging side could be done so this temperature was set equal to the discharging side.

The temperature of the roof was measured with a contact thermometer and varied depending on where the measurement was done. It was also rather low so the temperature of the side of the furnace was measured to see if the thermometer was calibrated correctly. The average temperatures can be seen in Table C.1 along with the areas of the different sides.

Table C.1 Temperatures and surface areas for WBF B.

	Average temperature [°C]	**Area [m2]**
Left side	126,7	157,3
Right side	146,2	157,3
Charging side	194,3	92,1
Discharging side	194,3	92,1
Top	125	291,4

The radiation losses were calculated by assuming that the furnace is a gray surface, that the incident radiation from the air to the furnace can be neglected and that the area of the surrounding air is significantly larger than the area of the wall (so that the view factor is 1). This assumption together with Stefan Boltzmann's law gives us equation C.23 which has to be solved for each surface (Welty J-R et al., 2001). The total radiation losses are then the sum of all the surfaces. The furnace walls were painted with aluminium paint so the emissivity of the walls was set to 0.5.

$$Q_{rad} = A \cdot \varepsilon_{furnace} \cdot \sigma \cdot (T_s^4 - T_\infty^4) \tag{C.23}$$

The convection losses were calculated with the same areas and temperatures. The convection was assumed to be natural convection from vertical and horizontal plates. The Nusselt number was calculated according to equation C.24 and equation C.25 for vertical and horizontal plates respectively (Welty J-R et al., 2001). From the Nusselt number the convective heat transfer coefficient and then the convective losses from each surface were calculated according to equations C.25 - C27.

$$Nu_L = \left(0{,}825 + \frac{0{,}387 Ra_L^{1/6}}{\left[1 + (0{,}492/\Pr)^{9/16}\right]^{8/27}} \right) \quad \text{(C.24)}$$

$$Nu_L = 0{,}14 \cdot Ra^{1/3} \quad \text{(C.25)}$$

$$h_{conv} = \frac{Nu_L \cdot k}{L} \quad \text{(C.26)}$$

$$Q_{conv} = h_{conv} \cdot A \cdot (T_s - T_\infty) \quad \text{(C.27)}$$

C.4 Airflow losses from windows

The losses involved when air flows out of the windows can be calculated by assuming that the flow can be approximated with incompressible and reversible flow. Thereby the flow from the windows can be calculated with Bernoulli's equation (Welty J-R et al., 2001). The pressure in the furnace was known so the pressure difference could easily be calculated. The reference point is set so that the elevation in both points will be zero. Thereby the velocity out from the windows could be calculated by equation C.28 and the energy loss from the windows from equation C.29. The enthalpies of the flue gas in the furnace were based on the composition calculated in section C.2 and a flue gas temperature of 800°C on the charging side and 1250°C on the discharging side.

To be able to calculate the total losses during each day a few more factors needed to be estimated. First the time the windows are opened when the slabs are charged and discharged from the furnace was needed. This was measured to 25 seconds for charging and 30 seconds for discharging. The windows measure 0.6x11.8m for both the charging and the discharging side. A small part of this area is blocked by the equipment that charges/discharges the equipment in the furnaces. Thereby 90% of the geometrical area was seen as effective flow area. To calculate the total losses the flow energy loss was multiplied with the opening time with the amount processed slabs during each day.

$$v_g = \sqrt{\frac{2 \cdot \Delta p}{\rho_{g,T_g}}} \quad \text{(C.28)}$$

$$Q_{flow,open} = v_g \cdot A \cdot (H_{g,T_g} - H_{g,25^\circ C}) \quad \text{(C.29)}$$

C.5 Radiation losses from windows

The radiation from the gas when the windows are open was calculated in the same way as for the radiation from the furnace walls in section C.3. The emissivity of the flue gases was calculated according to equation (C.30) and the methodology suggested by (Welty J-R et al., 2001). The mean beam length (L) was estimated by seeing the radiating volume as a space between infinite parallel planes and taking the average between the height and the width of the windows. Also here 90% of the geometrical area was seen as effective radiating area.

$$\varepsilon_{tot} = \varepsilon_{H_2O} + \varepsilon_{CO_2} - \Delta\varepsilon \quad \text{(C.30)}$$

C.6 Additional results from heat balance

The daily LPG consumption as well as all daily loss terms are of course rising with increasing production rate (not presented here). Interesting to notice is that the cooling water losses are quite constant though, as seen in Figure C.1. This could indicate that the cooling water flow could be controlled better if the cooling demand is not constant. The radiation losses from the windows are not presented since they are so small.

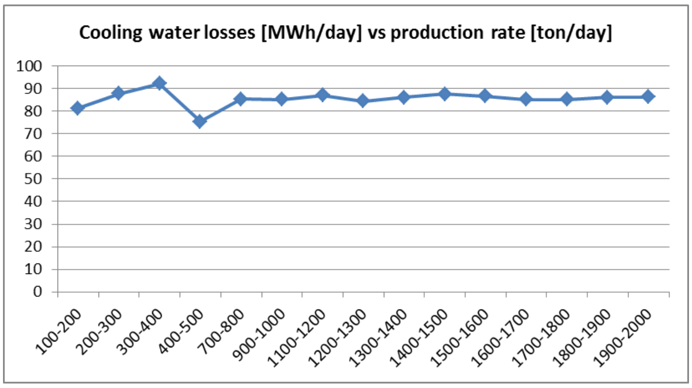

Figure C.1 Cooling water losses in relation to daily production rate.

As shown in Figure C.2 the specific LPG consumption drops quickly with increased production rate and then flattens out. The total losses follows the same pattern as observed in Figure C.3. The specific difference between the ingoing and outgoing energy to the furnace is shown in Figure C.4 and as can be seen the unknown losses decreases with increasing production rates. The conclusion is that a higher production rate is better since the losses are lower and the efficiency higher. Another important aspect is that the flue gas losses are higher during the summer months since there is no district heat production and therefore a higher flue gas stack temperature.

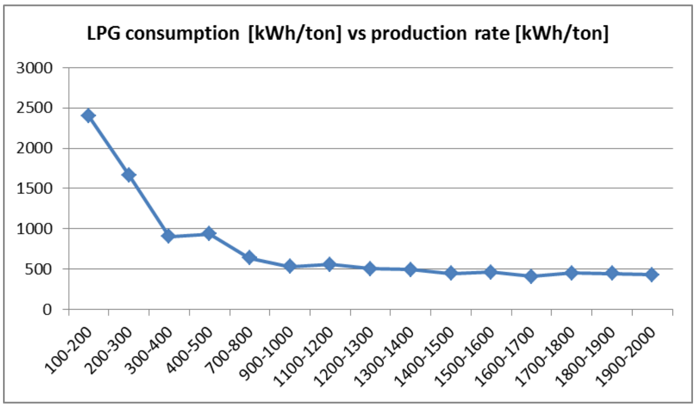

Figure C.2 Specific LPG consumption in relation to daily production rate.

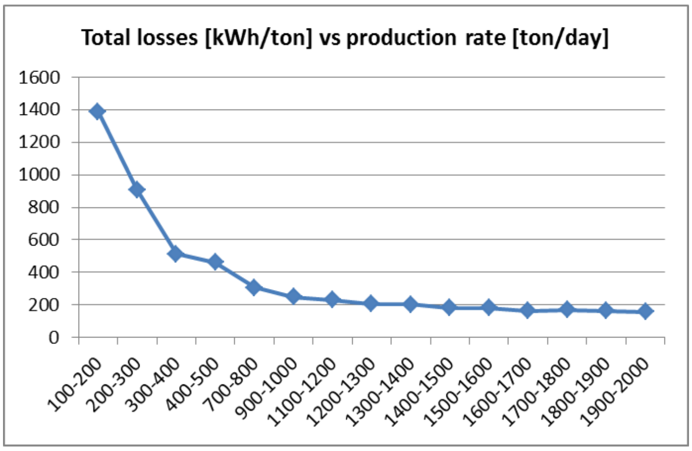

Figure C.3 Total specific losses in relation to daily production rate.

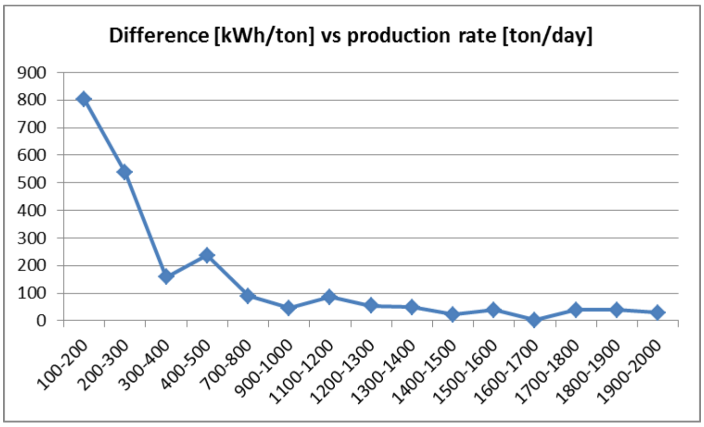

Figure C.4 Specific difference in-out of energy balance in relation to daily production rate.

Finally the air excess ratio was investigated. As seen in Figure C.5 the excess of air is quite high at low production rates and declines with increasing production rate. The air excess ratio is lower than 1 at high production rates. This means that the combustion would take place at sub stoichiometric conditions (not complete combustion) and carbon monoxide could form. 10 out of 25 data points (days) belongs to this category. This is highly unlikely, a more possible explanation is that the measurement system of the air flow into the furnace is not working properly. The fact that the air excess ratio varies so much could indicate that control system of the air flow is not working perfectly. This could be looked over together with the air flow measurement system.

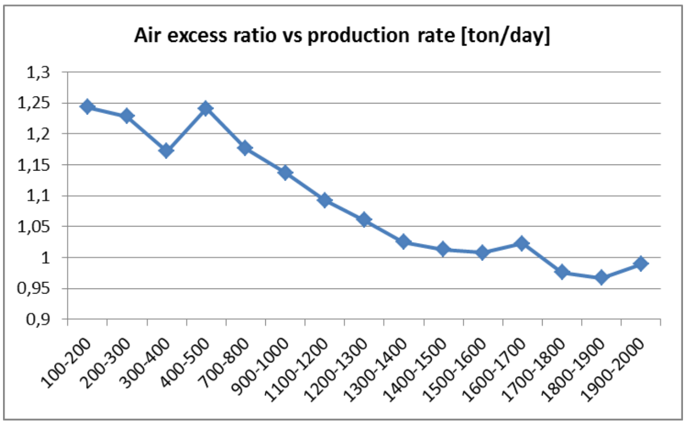

Figure C.5 Air excess ratio in relation to daily production rate.

Appendix E – Thermo chemical reactions

In both the EAF and the converter the carbon is oxidized to carbon monoxide at high temperatures. The carbon monoxide is later oxidized to carbon dioxide in the flue gas channels according to equation E.1 and equation E.2.

$$2C+O_2 \rightarrow 2CO \quad \text{(E.1)}$$

$$2CO+O_2 \rightarrow 2CO_2 \quad \text{(E.2)}$$

The amount of carbon that is oxidized can be calculated as: the carbon inputs to the charge minus all carbon that the cast strand contains. The carbon input is calculated from the carbon content in the metal scrap, alloys additives, carbon losses from the carbon electrodes and other carbon containing chemicals. The calculation of CO_2 emissions from material input is based on the same carbon amounts. Note that one kg of carbon gives 3,667 kg of carbon dioxide.

When oxygen is blown into the melt to create slag bubbles and to reduce the carbon content an undesired reaction takes place where the chromium reacts to chromium oxide as seen in equation E.3. Then there is equilibrium between carbon and chrome oxide according to equation E.4. The amount of chromium oxide is reduced at high temperatures and low CO pressures. To minimize the CO pressure in the converter argon and nitrogen gas are added to force the equilibrium to the right.

$$3Cr+2O_2 \rightarrow Cr_3O_4 \quad \text{(E.3)}$$

$$4C+Cr_3O_4 \Leftrightarrow 4CO+3Cr \quad \text{(E.4)}$$

Still some chrome oxide always forms and to reduce this undesired product silicone, aluminium or titanium are added to reduce the chrome oxide to as in equations E.5-E.7. In these reactions silicone oxide, aluminium oxide and titanium oxide are formed according to equations E.8-E.10 and a lot of heat is released due to the exothermic nature of the reactions. The reaction enthalpies of these reactions were taken from calculations done on site (Rosenqvist. T, 1970) and can be seen in Table E.1.

Table E.1 Reaction enthalpies for additives.

Species	Reaction Enthalpy [kWh/ton]
Carbon	3 050
Silica	8 947
Aluminium	8 622
Titanium	5 475

$$Cr_3O_4+2Si \rightarrow 2SiO_2+3Cr \quad \text{(E.5)}$$

$$3Cr_3O_4+8Al \rightarrow 4Al_2O_3+9Cr \quad \text{(E.6)}$$

$$3Cr_3O_4+8Ti \rightarrow 4Ti_2O_3+9Cr \quad \text{(E.7)}$$

$$Si+O_2 \rightarrow SiO_2 \quad \text{(E.8)}$$

$$4Al+3O_2 \rightarrow 2Al_2O_3 \quad \text{(E.9)}$$

$$4Ti+3O_2 \rightarrow 2Ti_2O_3 \quad \text{(E.10)}$$

Appendix F – Additional results Steel Mill

F.1 Flue gas system & Cooling water system

The electricity consumption for the flue gas system for different steel types can be seen in Table F.1. Since the calculation of the electricity consumption was based on average data for the whole year for two different processes no deeper analysis was done here.

Table F.1 Specific electricity consumption in the flue gas system in relation to steel type.

Steel type	Flue gas system [kWh/ton]
A	36,5
C	33,6
F	33,3
D	33,1
E	31,6
B	31,3

Just like for the flue gas system the cooling water system allocation method was based on the residence times in three different processes, so a deeper analysis was not possible. The specific electricity consumption for different steel types is presented in Table F.2.

Table F.2 Specific electricity consumption of the cooling water system in relation to steel type.

Steel type	Cooling water system [kWh/ton]
A	26,0
C	23,8
D	23,1
F	21,8
E	21,1
B	21,0

F.2 Hot grinding & cold grinding

The specific electricity consumption in the hot grinding unit can be seen in Table F.3. The highest specific consumption is for ‘B’ and the lowest is for ‘F’. An investigation of how the residence time in the grinding machine is affecting the electricity consumption was done but no clear correlation can be observed in Figure F.1. When it comes to the different steel types no correlation connected to the grinding time can be observed though. The specific electricity consumption for the cold grinding unit can be observed in Table F.4. In the cold grinding unit ‘A’ has the highest specific consumption while ‘B’ has the lowest one.

Table F.3 Specific electricity consumption of the hot grinding in relation to steel type.

Steel type	Hot grinding [kWh/ton]	Time in grinding [min]
B	23,1	7,6
D	21,5	7,0
A	20,7	6,7
E	19,2	9,2
C	18,7	7,4
F	17,7	7,1

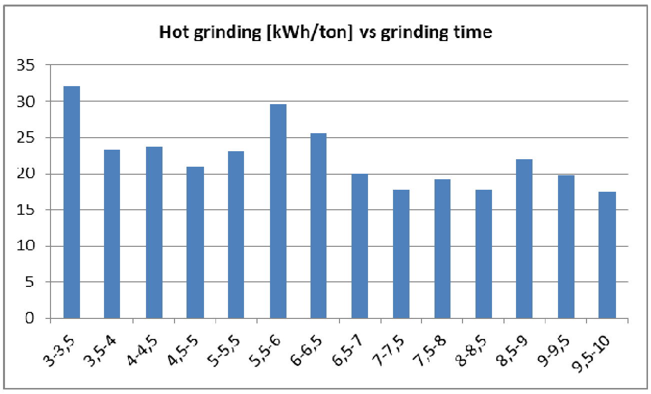

Figure F.1 Specific electricity consumption of the hot grinding in relation to grinding time.

Table F.4 Specific electricity consumption of the cold grinding in relation to steel type.

	Cold grinding [kWh/ton]	Nr. of upper surface transfers	Nr. of under surface transfers
A	42,9	2,00	2,00
D	41,3	1,88	1,65
E	37,1	2,16	2,18
F	33,9	1,93	1,91
C	30,2	1,83	1,69
B	28,8	1,65	1,65

F.3 EAF auxiliaries and scrap preheating

As seen in Figure F.2 the electricity consumption for the auxiliaries and the scrap preheating for the EAF have a connection to the residence time in the EAF. When looking at different steel types and corresponding electricity consumption and residence times this correlation does not apply. As seen in Table F.5 'B' and 'E' has the highest residence times but the lowest consumption. Overall the variation between different steel types is not that large. Another important parameter that was identified is slab weight. As can be observed in Table F.6 the specific energy consumption and the absolute energy consumption decreases with increasing charge weight.

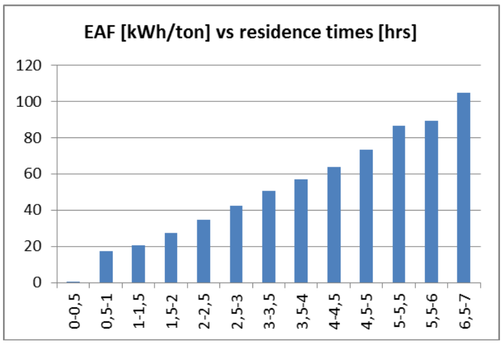

Figure F.2 Specific electricity consumption for auxiliaries and scrap preheating in the EAF in relation to residence time.

Table F.5 Specific electricity consumption for auxiliaries and scrap preheating in the EAF in relation to steel type.

Steel type	EAF [kWh/ton]	Residence time [hrs]
A	32,9	1,710
F	32,5	1,903
C	31,5	1,807
D	31,3	1,837
E	31,2	2,313
B	31,0	2,139

Table F.6 Specific electricity consumption for auxiliaries and scrap preheating in the EAF in relation to produced weights per charge.

Produced weight per charge [ton]	EAF [kWh/ton]	EAF [kWh/charge]	Residence time in EAF [hrs]
60-70	50,91	3 405,26	2,25
70-80	40,13	2 990,62	1,94
80-90	33,49	2 898,71	2,49
90-100	27,92	2 645,20	1,71
100-110	24,78	2 580,69	1,60
110-120	21,33	2 393,51	1,49
120-130	17,78	2 171,49	1,39

F.4 Converter

The correlation between the residence time in the converter and the electricity consumption can be seen in Figure F.3. The consumption increases as the residence time increases. As seen in Table F.7 this corresponds well with the steel types; a higher residence time gives a higher consumption. The difference between different steel types is more clear here. The specific but not the absolute electricity consumption decreases with increasing charge weights. This relation can be seen in Table F.8 but the residence time does not follow the absolute energy consumption.

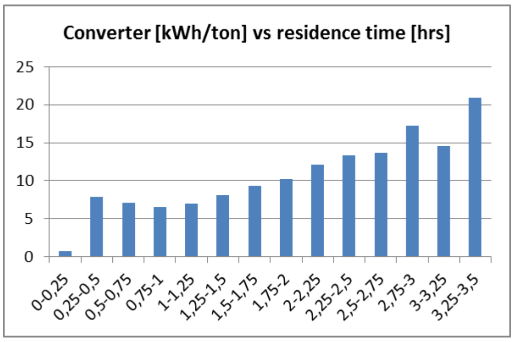

Figure F.3 Specific electricity consumption for the converter in relation to residence time.

Table F.7 Specific electricity consumption and residence times in the converter in relation to steel type.

Steel type	Converter [kWh/ton]	Residence time [hrs]
A	10,3	1,528
C	9,1	1,494
D	8,4	1,407
F	7,7	1,191
E	7,2	0,886
B	7,0	1,058

Table F.8 Specific electricity consumption and residence times in the converter in relation to produced weights per charge.

Produced weight per charge [ton]	Converter [kWh/ton]	Converter [kWh/charge]	Residence time in Converter [hrs]
60-70	11,24	747,10	1,37
70-80	8,85	661,11	1,12
80-90	8,19	709,27	1,27
90-100	7,17	679,74	1,19
100-110	6,50	678,30	1,17
110-120	5,95	668,03	1,18
120-130	5,21	639,91	1,15

F.5 Ladle furnace

The ladle furnace's electricity consumption increases as the residence time of the charge increases as seen in Figure F.4. Just like for the EAF auxiliaries no clear pattern could be found when looking at residence times of different steel types. As can be seen in Table F.9, for example 'B' has the lowest residence time but the third highest consumption. Also note that 'E' has a higher consumption. This is explained by the fact that a special type of slag with a higher weight is used for this steel type. Thereby a larger mass has to be treated in the ladle furnace. The energy consumption and residence times for different charge weights is presented in Table F.10. Both the specific, the absolute electricity consumption and the residence time decreases with the charge weight.

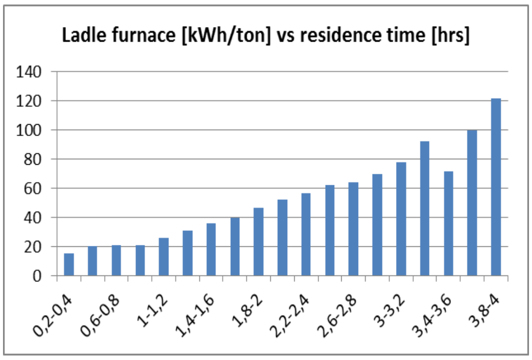

Figure F.4 Specific electricity consumption for the ladle furnace in relation to residence time.

Table F.9 Specific electricity consumption and residence times in the ladle furnace in relation to steel type.

Steel type	Ladle furnace [kWh/ton]	Residence times [hrs]
E	38,0	1,146
A	32,1	1,184
B	29,1	0,998
C	28,6	1,082
F	22,7	1,050
D	21,8	1,126

Table F.10 Specific electricity consumption and residence times in the ladle furnace in relation to produced weights per charge.

Produced weight per charge [ton]	Ladle furnace [kWh/ton]	Ladle furnace [kWh/charge]	Residence time in Ladle furnace [hrs]
60-70	48,47	3 273,83	1,41
70-80	42,92	3 200,23	1,36
80-90	28,86	2 498,80	1,13
90-100	26,37	2 503,50	0,97
100-110	18,18	1 892,94	0,62
110-120	17,50	1 968,63	0,61
120-130	16,13	1 973,85	0,60

F.6 Continuous casting

The electricity consumption of the continuous casting for different residence times does not have a correlation as can be seen in Figure F.5. A relation between these two parameters can neither be found when looking at different steel types as presented in Table F.11. The difference between the steel types is small but 'B' and E' has a lower consumption than the other steel types. An increasing charge weight decreases the electricity consumption as seen in Table F.12. The influence from the width and the thickness of the cast strand was also investigated but no correlation could be found

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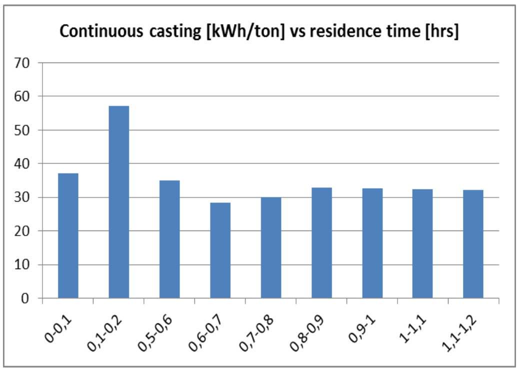

Figure F.5 Specific electricity consumption for the continuous casting in relation to residence time.

Table F.11 Specific electricity consumption and residence times in the continuous casting in relation to steel type.

Steel type	Continuous casting [kWh/ton]	Residence time [hrs]
A	36,9	0,751
C	33,4	0,763
F	33,4	0,769
D	31,3	0,857
E	30,6	0,755
B	28,2	0,704

Table F.12 Specific electricity consumption and residence times in the continuous casting in relation to produced weights per charge.

Produced weight per charge [ton]	Continuous casting [kWh/ton]	Continuous casting [kWh/charge]	Residence time [hrs]
60-70	48,7	3 255	0,603
70-80	32,2	2 404	0,684
80-90	32,2	2 794	0,740
90-100	28,1	2 658	0,746
100-110	27,8	2 900	0,739
110-120	23,9	2 692	0,751
120-130	15,7	1 914	0,673

F.7 End customer data

Table F.13 Specific electricity consumption of the EAF auxiliaries in relation to end customer.

Customer	EAF [kWh/ton]
TORNIO	69,9
MPPP	36,5
NYBY	32,8
ASP	31,9
HRPD	31,1
KBR	30,9

Table F.14 Specific electricity consumption of the converter in relation to end customer.

Customer	Converter [kWh/ton]
TORNIO	12,716
MPPP	8,507
HRPD	8,308
NYBY	8,197
ASP	7,939
KBR	7,462

Table F.15 Specific electricity consumption of the ladle furnace in relation to end customer.

Customer	Ladle furnace [kWh/ton]
TORNIO	237,9
ASP	34,8
MPPP	30,9
HRPD	30,5
KBR	28,5
NYBY	27,4

Table F.16 Specific electricity consumption of the continuous casting in relation to end customer.

Customer	Continuous casting [kWh/ton]
TORNIO	45,9
MPPP	44,1
NYBY	32,4
HRPD	31,4
ASP	31,3
KBR	29,5

Table F.17 Specific electricity consumption of the flue gas system in relation to end customer.

Customer	Flue gas system [kWh/ton]
TORNIO	87,7
MPPP	40,0
NYBY	33,7
HRPD	31,9
KBR	31,7
ASP	31,5

Table F.18 Specific electricity consumption of the cooling water system in relation to end customer.

Customer	Cooling water system [kWh/ton]
TORNIO	45,1
MPPP	25,3
NYBY	23,1
HRPD	22,4
ASP	22,1
KBR	21,4

Appendix G – In data for calculation scenarios

Table G.1 Produced amounts for "50% KBR".

Customer & Run Program	Steel type	Surface	"50 % KBR" [ton]
KBR 1	C	1	24 641
		2	297
		3	15 625
	D	1	852
		3	1 549
	F	1	13 031
		3	6 847
	A	1	305
		2	250
		3	304
	B	1	79 059
		2	33 556
		3	487
	E	1	9 080
		2	2 550
KBR 6	C	1	0
		2	0
		3	0
	D	1	1 086
		3	1 973
	F	1	180
		3	94
	A	1	98
		2	80
		3	98
		Sum	**192 042**

Table G.2 Produced amounts for “50% Other”.

Customer	Run Program	Steel type	"50% Other" [ton]
HRPD	Direct delivery	C	27 124
		D	577
		F	1 718
		A	1 288
		B	4 785
		E	2 209
			37 703
	2	C	10
		B	2 847
		E	1 582
			4 440
	5	C	2 039
		D	1 158
		F	728
		A	139
		B	0
		E	298
			4 362
MPPP	1	C	779
		B	632
		B	0
			1 410
NYBY	1	C	41 650
		D	7 336
		F	14 359
		A	1 536
		B	11 874
		E	576
	6	C	48
			77 378
ASP	-	C	921
	-	B	3 322
			4 243
TORNEO	-	A	86
		Sum	**129 535**

Appendix H – Additional results for APL

H.1 Cold rolling mill – Z-high

3692 bands with a total weight of 75 794 tons were processed through the cold rolling mill - Z-high during 2010. The correlations between specific electricity consumption and number of passes made in Z-high can be seen in Table H.1. It increases with the number of passes made. The specific electricity consumption for different thicknesses of the exiting bands from the cold rolling mill is found in Table H.2. The thinner the band, the higher the electricity consumption is. The reason to these two correlations is most likely the difference in residence time. The treatment time increases with number of passes made and with decreasing thickness.

The difference in energy consumption for various steel types is rather small as seen in Table H.3. This can be explained by the small differences in residence time. Thereby the largest difference in total energy consumption between different steel types will be if bands are processed more than once.

Table H.1 Specific electricity consumption of Z-high in relation to number of passes.

Number of passes	Z-high [kWh/ton]	Residence time [hrs]
3	72,5	1,07
5	86,0	1,11
7	101,5	1,22
9	103,5	1,38
11	111,5	1,45
13	139,3	1,59
15	153,2	1,51

Table H.2 Specific electricity consumption of Z-high in relation to thickness.

Thickness [mm]	Z-high [kWh/ton]	Residence time [hrs]
1	159,1	1,83
2	140,5	1,58
3	105,9	1,35
4	93,5	1,26
5	83,1	1,23
6	70,7	1,13

Table H.3 Specific electricity consumption of Z-high in relation to steel type.

Steel type	Z-high [kWh/ton]	Residence time [hrs]
D	107,8	1,33
C	106,9	1,39
A	106,3	1,44
F	105,1	1,29
B	105,0	1,35
E	103,2	1,33

I.1 Electricity consumption HRM

The electricity consumption for different 'end customer' is presented in Table I.1. The bands that are sent to Nyby have a higher consumption than the APL bands (KBR). This can be explained by the higher number of passes done in the steckel for the Nyby-bands. The HPRD bands that have a significantly lower electricity consumption these were processed with 'run program 5' where the steckel is not running. The HPRD bands that have a higher consumption (B and E) were processed with 'run program 2' where the steckel is running. It can also be observed that the steel types/customers with low consumption have a low slab weight and therefore a low number of passes in both the roughing and the steckel mill.

Table I.1 Electricity consumption for different end customers.

Steel Type	Customer	Tot sum [kWh/slab]	Residence time roughing mill [min]	Residence time steckel mill [min]	Slab weight [ton]
C	HRPD	653,0	0,02	0,00	12,35
	KBR	2 023	2,22	4,10	19,31
	MPPP	1 898	2,07	3,93	13,26
	NYBY	2 231	2,46	5,78	18,75
D	HRPD	829,4	0,00	0,00	10,79
	KBR	1 628	1,33	1,91	12,97
	NYBY	2 168	2,43	4,97	13,39
F	HRPD	728,6	0,00	0,00	9,13
	KBR	2 039	2,83	3,71	20,42
	NYBY	2 179	2,65	4,92	17,60
A	HRPD	683,8	0,00	0,00	8,87
	KBR	1 377	1,71	2,04	15,14
	MPPP	3 011	2,57	5,37	17,89
	NYBY	2 343	2,47	6,13	17,80
B	HRPD	1 713	1,95	0,00	16,93
	KBR	2 055	2,59	3,73	22,93
	MPPP	1 772	2,18	3,04	13,02
	NYBY	2 301	2,51	5,86	17,89
E	HRPD	1 557	1,70	0,00	16,13
	KBR	2 067	2,48	3,71	22,74
	NYBY	2 155	2,40	4,85	16,33

I.2 Coiler furnaces - LPG

Table I.2 LPG consumption of coiler furnace in relation to steel type.

Steel type	LPG [kWh/slab]
C	686
A	622
S	594
F	592
D	579
E	531