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Material Flow Analysis of FeSi Furnace at Elkem Bjølvefossen

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Preface

This thesis is written as the completion of a three-year education in Material Science and Engineering at Norwegian University of Science and Technology, NTNU. In collaboration with Elkem Bjølvefossen, a Material Flow Analysis was performed during the spring term of 2020.

We would like to thank our supervisor, Gabriella Tranell, for guiding us through both the writing process and the learning experience. She supported us through all the ups and downs of our work for this thesis and was a great motivator during challenging situations.

Further, we would extend our gratitude to Mark William Kennedy and Jan-K Lutro from Elkem, for providing data and for being available for all theoretical and practical questions about the process. Thanks to Elkem Foundry for giving us the opportunity to learn more about their production and visiting the plant at Bjølvefossen.

Thanks to Romain G. Billy, Daniel B. Müller and Casper Van der Eijk for answering all questions about MFA and providing guidance.

Finally, we will thank our families and friends for supporting us through, not only this Bachelor, but also three years of education.

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Fride Müller and Heidi Andersen Grande.

Abstract

In this thesis a material flow analysis (MFA) for furnace 5 at Elkem Bjølvefossen has been carried out based on raw material and product data from 2019. The basis for distribution of major, minor and trace elements is the assumption of 100% Fe yield. A deviation of 877 tonnes silicon surplus unaccounted for, from the output, was discovered from the MFA. This can be caused by a combination of several factors such as weighing errors or incorrect analysis, among others.

The CO_2-emissions were calculated in two different ways; from a CO_2-calculation provided by Elkem and from the mass balance in the MFA. There was an insignificant difference between these numbers at 5,4 tonnes in a year, with a weekly average standard deviation of 17,5 kg. This was calculated with the average of 0,8% Al in the metal. By using an average of 0% Al in the metal, the CO_2-emissions will increase with 0,002%. With no carbon in the metal, the CO_2-emissions will increase with 0,09%.

By assuming the slag contained no iron, the average slag percentage in a year was found to be 1,82%. From this, it was possible to find the composition of the slag. The CaO percentage in the slag was found to be 8,72%, which is quite low compared to the theoretical value. This indicates inadequately reported data from the raw materials. The SiO_2 was a bit higher than the theoretical value, which might be related to the CaO deviation.

Sammendrag

Hensikten med denne bacheloroppgaven var å utføre en materialstrømanalyse for ovn 5 ved Elkem Bjølvefossen med utgangspunkt i råvaredata fra 2019. Antagelsen om 100% jernutbytte er grunnlaget for distribusjon av hoved- og sporelementer. Fra materialstrømanalysen ble det oppdaget et overskudd på 877 tonn silisium ut av ovnen. Dette avviket kan skyldes en kombinasjon av ulike faktorer som blant annet veie-feil eller unøyaktige analyser.

Utregning av CO_2 utslipp ble utført på to måter: Fra en kalkyle utført av Elkem og fra materialstrømanalysen. Det var en ubetydelig forskjell mellom de ulike tallene på 5,4 tonn i løpet av et år, med et standardavvik på 17,5 kg. Dette ble regnet ut med et gjennomsnitt på 0,8% Al i metallet. Ved å bruke et gjennomsnitt på 0% Al i metallet vil CO_2 utslippene øke med 0,002%. Ved å anta at det ikke er karbon i metallet vil CO_2 utslippene øke med 0,09%.

En gjennomsnittlig slaggprosent på 1,82% i året ble funnet ved å anta at det ikke er noe jern i slaggen. Fra dette var det mulig å finne slaggsammensetningen. Prosentandelen CaO ble funnet til å være 8,72%, som er lavt sammenlignet med den teoretiske verdien. Dette indikerer utilstrekkelige analyser fra råvarene. SiO_2 var litt høyere enn den teoretiske verdien, dette kan ha en sammenheng med avviket fra CaO.

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Abbreviations

Table 1 explain the abbreviations used in this thesis.

Table 1 Abbreviations

FeSi	Ferrosilicon
Fix C	Fixed Carbon
MFA	Material Flow Analysis
MS	Microsilica
Std.Dev	Standard deviation
‘Rensk’	Mill-scale in quartz silo

1. Introduction

Ferrosilicon (FeSi) is produced in an electric arc furnace by carbothermic reduction of a silicon- and iron source. The furnace holds a temperature of about 1300ºC-2000ºC and the liquid metal is tapped from the bottom of the furnace. The molten metal is refined and cast before cooling down, followed by crushing to a specific size. In the furnace, CO and SiO gas are produced and burned with volatile materials on top of the charge. Due to the energy released from the gas combustion, electricity is often produced from a heat recovery system, which can supply part of the electrical energy to the plant. The gas and dust are separated in the filter, and the gas leaves the chimney as cleaned gas (mainly N_2, O_2, CO_2 and H_2O). The dust, also called microsilica (MS), is sold as a by-product. There are various types of ferrosilicon, which is classified by different silicon contents, where the most common is 15%, 45%, 75% and 90% silicon (Hustad, 2018). This thesis concentrates on FeSi52 produced by Elkem Bjølvefossen from furnace 5. The raw materials consist of a silicon source (quartz), carbon source (coal, coke and woodchips) and an iron source (mill-scale). The raw materials will always contain different species of impurities, and this will affect the process. It is crucial to have a good understanding of how these impurities behave in the furnace and where they end up (Schei et al., 1998, s. 101-103).

Previous work on this topic has been done by Elkem and NTNU. Myrhaug and Tveit published "Material Balances of Trace Elements in the Ferrosilicon and Silicon Processes" (Myrhaug and Tveit, 2000) as a part of environmental investigations in 1999, and their work has been valuable for this study when investigating the paths for the trace elements. Kero, Grådahl and Tranell published "Airborne Emissions from Si/FeSi Production" (Kero et al., 2017), which has been valuable when investigating the carbon emissions. "The silicon bible"; "production of high silicon alloys" by Schei, Tuset and Tveit (Schei et al., 1998), has also been very helpful when it comes to learning about the silicon process.

1.1. Scope

The aim of this paper is to map every mass flow in and out of the furnace from 2019, including the gas treatment, to get a better understanding of the process and the mass balance for this production. Important tasks will be to investigate the major, minor and trace elements, the slag percentage and composition, the cleaned gas output and CO_2-equivalents, and also the carbon-bearing raw materials and their behaviour in the furnace. By executing a material flow analysis (MFA), it is possible to do exactly this. MFA is a method to estimate all the flows in and out of a system, and by using Sankey diagrams, the quantities and different paths for the flows is visualized in a structured way. By understanding the material flows in the system, one can operate the processes more efficiently, prevent losses, and better report emissions. Elkem Foundry has incomplete data when it comes to material flows in and out of the system and it will be essential to map this out.

The system is limited to the furnace and gas treatment (emergency stack and filter); this means that the refining, casting and crushing will not be reviewed. This thesis also limits the flows to mass flows, and the energy is not considered. Hence, the MFA is based on analytical work of raw material and product data.

2. Theoretical Background

This chapter will present the theory relevant to the results and discussion, this includes the FeSi production process (section 2.1), raw materials and their requirements (section 2.2), the behaviour of the elements (section 2.3), MFA (section 2.4) and uncertainties (section 2.5).

2.1. The FeSi Process

Silicon is produced industrially in arc furnaces by reduction of SiO_2 with carbon. Figure 1 gives an indication of what a typical plant for the production of silicon metal looks like. In addition to the raw materials carbon and quartz, there will also be additions of iron in the production of FeSi (Schei et al., 1998, s.13).

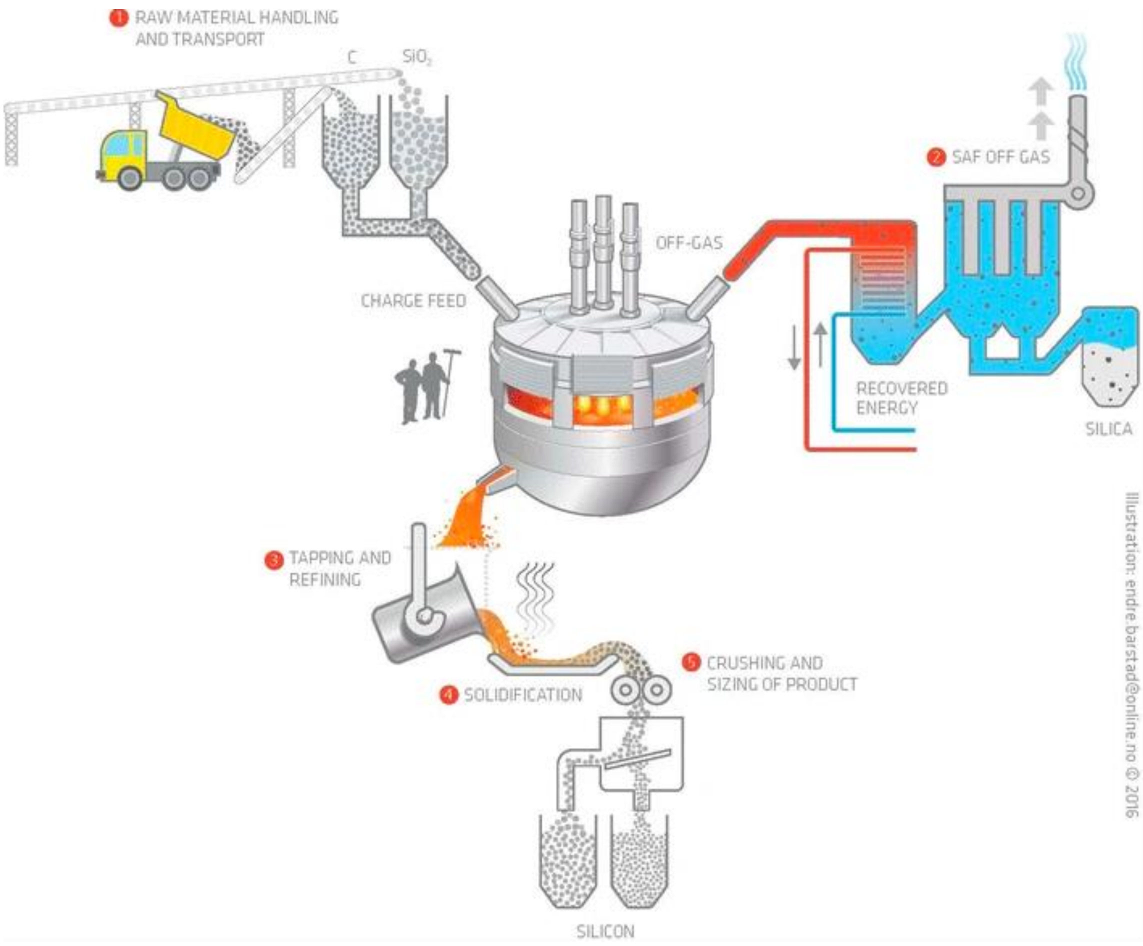

Figure 1 Principles of a modern silicon plant (Kero et al., 2017).

Theoretically the production of silicon is simple according to the reaction:

$$SiO_2 + 2\ C = Si + 2\ CO \tag{1}$$

However, the real reaction is far more complex due to a variety of reasons, but mainly loss of the gas species SiO and the high stability of SiO_2. The gases SiO and CO go through a burning process at the top of the furnace. This will result in a more accurate representation of the reaction:

$$(1 + x)SiO_2 + (2 + x)C = Si + xSiO + (2 + x)CO \tag{2}$$

$$\frac{1}{2}Fe_2O_3 + \frac{3}{2}C = Fe + \frac{3}{2}CO \tag{3}$$

$$Fe_2O_3 + C = 2FeO + CO \tag{4}$$

$$FeO + C = Fe + CO \tag{5}$$

$$xSiO + (x + 2)CO + mO_2 = xSiO_2 + (x + 2)CO_2 + (m - x - 1)O_2 \tag{6}$$

$$\begin{aligned}(1 + x)SiO_2 + (2 + x)C + (1 + x)O_2 \\ = Si + xSiO_2(silica\ fume) + (2 + x)CO_2 + heat\end{aligned} \tag{7}$$

Equation 2 and 3 describes the reaction inside the furnace, where 4 and 5 is the same as equation 3 only divided into two parts. Equation 6 describes the gas treatment process. The parameters x and m are as followed reaction parameter and air addition parameter. Equation 7 includes the reactions occurring after the furnace (Schei et al., 1998, s.14).

FeSi is produced by adding the raw materials quartz or quartzite, carbon as coal, coke and woodchips and metallic iron as mill-scale, Hot Briquetted Iron (HBI), scrap or iron oxide pellets into an electrical furnace. The high temperature makes it possible for chemical reactions to happen where the carbon reacts with oxygen and mainly produce $CO_{(g)}$, $Fe_{(l)}$ and $Si_{(l)}$. In addition to this there will also occur some formation of $SiC_{(s)}$ and $SiO_{(g)}$. Some of the most important reactions in the furnace are shown in Table 2. The production of silicon and ferrosilicon is theoretically a slag free process. However, slag is often formed and tapped together with the molten metal. The amount of trace elements in the raw material and the operation of the furnace is crucial in determining slag produced. The liquid alloy goes through a refining process to separate the slag and trace elements from the alloy. After refining the molten alloy is cast in moulds for cooling and then crushed to the specified size (Schei et al., 1998, s.15).

Table 2 Reactions in the furnace (Schei et al., 1998, s.15)

Inner zone	**Outer zone**
$SiO_{2(l)} + Si_{(l)} \rightarrow 2SiO_{(g)}$	$SiO_{(g)} + 2C_{(s)} \rightarrow SiC_{(s)} + CO_{(g)}$
$SiC_{(s)} + SiO_{(g)} \rightarrow 2Si_{(l)} + CO_{(g)}$	$2SiO_{(g)} \rightarrow Si_{(l)} + SiO_{2(l)}$

The off-gas from the production is removed by suction in off-gas ducts and lead into an energy recovery system. The heat from the gas can be used to produce electricity among other things. The cooled gas is then lead to the filters, where particles are separated out from the gas. These particles mainly consist of amorphous SiO_2, which is sold as a by-product called microsilica (MS) (Schei et al., 1998, s.15-16).

2.2. Raw Materials and Their Requirements

Elkem produce products throughout the silicon value chain from quartz to silicon, including metallurgical grade silicon, MG-Si (> 96% Si) and ferrosilicon alloys (FeSi) of different grades (FeSi55, 65, 75) (Elkem.ASA, 2020). The primary raw materials needed for the FeSi production is a silicon source (quartz, quartzite), a carbon source (coal, coke, woodchips etc.) and an iron source (scrap, mill-scale, pellets, etc.) (Schei et al., 1998, s.100-103).

2.2.1. Silicon-Bearing Raw Materials

Silicon is a metalloid with element symbol Si. Si is one of the most abundant elements in the earth´s crust, and in the natural form, mostly found as silicon dioxide (SiO_2) and silicates (Schei et al., 1998, s.13). In the solid-state, Si is a semiconductor but has the same electric conductivity as metal in the liquid state. According to EduPack, the melting point for Si is 1410 ºC, while the melting point for SiO_2 is 1713ºC* (Granta.Design.Limited, 2019).

Practically it is possible to achieve a Si alloy with less than 1-2 percent impurities and this material goes by the name metallurgical grade silicon (MG-Si). Quartz and quartzite are both used as silicon oxide sources, but there are different requirements for purity depending on the process. Generally, Si production requires a higher need for purity in the raw material than FeSi production (Schei et al., 1998, s.101).

There are various types of quartz, each with different chemistry. It is important to have a good understanding of how different parameters can affect the process, and selection of quartz is important. The range of major and minor impurities relevant to this thesis is presented in Table 3 (Aasly, 2008).

Table 3 Impurities in quartz (Aasly, 2008).

Unit	Al	Ca	Fe	Ti	Mn	K	Mg	Na
%	0,012 – 0,460	0.001 – 0,010	0,020 – 0,288	0,001 – 0,020	0,003 – 0,007	0,001 – 0,063	0,000 – 0,163	0,002 – 0,006

For the production to run smoothly, there are requirements related to the strength and size of the raw materials. The gas flow in the furnace is affected by the thermal strength of the quartz, and therefore there must not be too much quartz fines present. The size of the quartz is generally in the range of 10 to 150mm (Schei et al., 1998, s.101). Elkem Bjølvefossen mainly used two sizes of quartz for FeSi production in 2019; referred to as quartz.1 and quartz.2 in this thesis.

2.2.2. Carbon-Bearing Raw Materials

Carbon is a non-metal with element symbol C. It is found in many forms, but the most stable phase is graphite. The melting point is 3974 ºC according to EduPack, but at 1 bar pressure it will only sublimate (Granta.Design.Limited, 2019). Compounds containing carbon such as coal and coke are used as reducing agents in the production of high silicon alloys. The carbon

* The quartz will modify due to the heat in the furnace, this will not be further discussed in this thesis.

containing material decompose to an amorphous state due to the heat in the furnace and participate in the carbothermic reduction reactions. The carbon sources also react with SiO gas producing Si and releases volatiles as presented in equation 6 (Schei et al., 1998, s.102). Woodchips are also added to the charge and contributes to a more porous charge mixture along with a more even gas flow (Nordnes, 2019).

Carbon As a Reducing Agent

The reduction materials must meet the quality standards to achieve a high silicon yield, as followed. The process performance is affected by the size and the reactivity of the carbon material. Small particles might be carried into the gas outlet due to the high gas velocity in the furnace, which can lead to losing control of the carbon amount in the process. Another essential process parameter is the reactivity between the carbon source and the SiO gas from the crater; different carbon sources react differently to the SiO gas (Schei et al., 1998, s.102).

At Elkem Bjølvefossen, the primary carbon sources are coal, coke, and woodchips*. The amount of fixed carbon (fix C), volatile compounds, moisture and ash varies between the sources and is of interest to the process. Fix C is considered the main reducing agent for the SiO_2, but also for the FeO. However, volatile compounds and moisture also affect the furnace in different ways. For example, the volatile hydrocarbons contribute additional chemical energy input to the process, as well as potentially reducing the Fe_2O_3 to FeO. Coal, coke and woodchips have different concentration of fix C, moisture and volatiles (Schei et al., 1998, s.172-173). Figure 2 shows an estimate of the distribution on a wet basis.

* Elkem Bjølvefossen get their woodchip from a local supplier (Lutro, 2020).

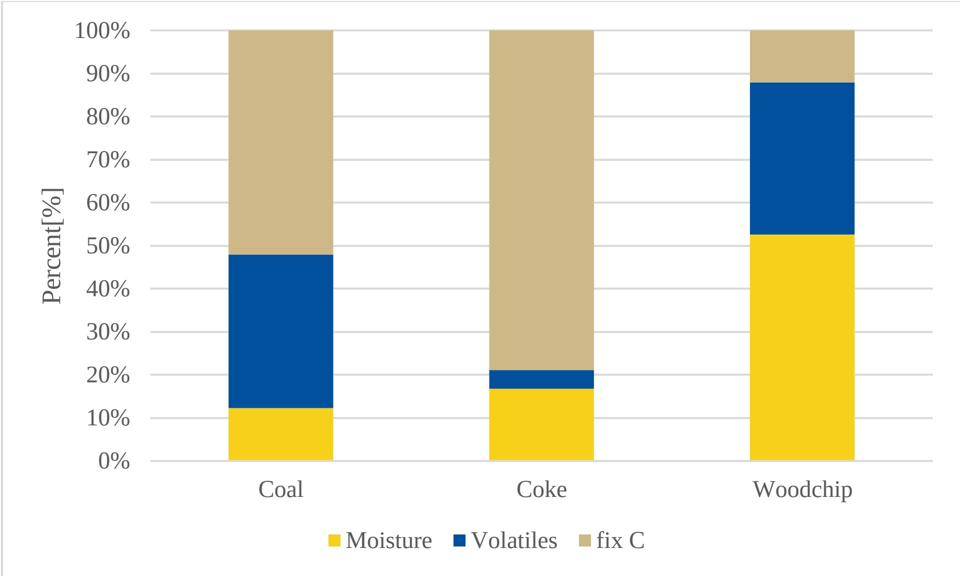

Figure 2 Estimate of distribution of moisture, volatiles and fix C in carbon materials on a wet basis(Schei et al., 1998, s.173).

Solubility of Carbon in Ferrosilicon Alloys

The solubility of carbon in ferroalloys varies with the concentration of Si and the temperature. Figure 3 shows that the carbon solubility in FeSi as a function of Si content. The figure shows an increase in C solubility up to around 25wt% Si, before it rapidly decreases with increasing Si (Schei et al., 1998, s.94).

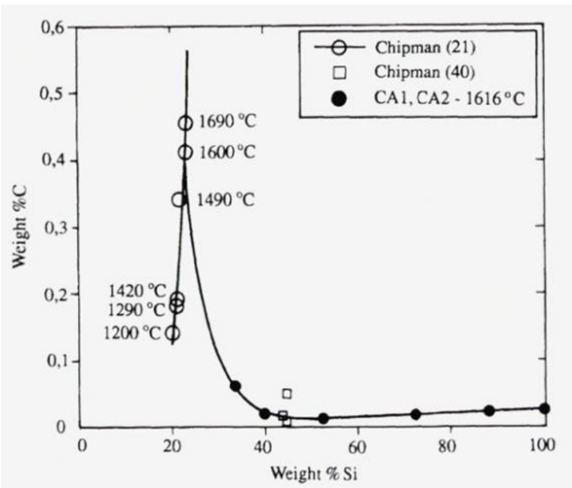

Figure 3 Carbon in FeSi alloys in equilibrium with SiC at 1616 °C (Schei et al., 1998, s.94).

Figure 4a Show the solubility of carbon in ferrosilicon alloys such as FeSi75 and FeSi65 for various temperatures. FeSi52 from Elkem Bjølvefossen contains approximately 0,8% Aluminium (Kennedy, 2019a), and Figure 4b shows the effect of aluminium on the carbon solubility in FeSi at 1550 °C.

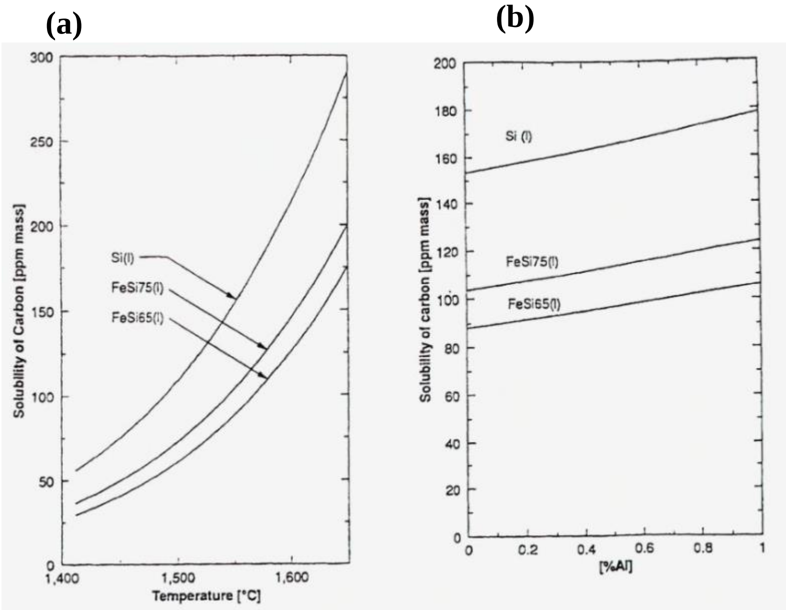

Figure 4 (a) Solubility of carbon at various temperatures. (b) The effect of aluminium at 1550 ºC (Schei et al., 1998, s.258).

The temperature at the tap-hole while tapping FeSi52 is roughly 1550 °C, and since the slight increase in silicon content from FeSi52 to FeSi65 does not have a significant impact, one can approximate the carbon solubility of FeSi52 tapped at 1550C, containing 0,8% Al. In this thesis 84 ppm is used as carbon solubility in FeSi52 with 0,8% Al.

2.2.3. Iron and Oxygen

Oxygen is supplied to the furnace system through the air at the top of the furnace charge, which combusts the SiO, CO and C_xH_y gases rising from the charge, but is also introduced via the oxide raw materials. For the FeSi process; mill-scale, iron oxide ore, HBI, or metallic iron scrap, works as an iron source. Compared to iron oxide, metallic waste reduces the need for carbon and the amount of electric energy. Still, a chemical analysis may be easier with the use of iron oxide (Schei et al., 1998, s.103). Elkem Bjølvefossen uses mill-scale as an iron source, which is partly oxidized and a consequence are a greater variation in the iron content.

2.3. The Behaviour of the Elements

Theoretically, one can predict the path of the compounds going into the furnace. Where the elements end up depend on factors such as; furnace temperature, which raw material they came from, the stability of oxides and carbides, their volatility and their solubility in liquid silicon (Myrhaug and Tveit, 2000). In Table 4, Category 1-5 represents where the various elements are expected to end up. Losses include coarse dust, diffuse emissions and losses to the environment.

Table 4 Behaviour of the elements (Myrhaug and Tveit, 2000).

Nr.	Category	Elements	Description
1	FeSi Product from tap hole	Fe, Si and additions of elements nobler than Si	The Product from the tap hole is expected to contain mostly FeSi
2	Microsilica	Si, Fe, K, Na, Mg and minor additions of other elements	The elements in MS are found as oxides
3	Slag	Si, Ca, Al, Mn, K and minor additions of other elements	Tapped with the metal as oxides
4	Cleaned gas	C, H, S, N	The cleaned gas will foremost consist of N_2, O_2, CO_2 and H_2O in decreasing order of concentrations
5	Losses	Small amount of the elements above	Microsilica losses as tapping smoke, raw material losses from handling and transport

2.3.1. Slag

Slag formation occurs in the furnace as a result of incompletely converted charge materials. Metals as oxides less noble than silicon, will form a new silicate phase in the furnace. An Ellingham diagram for some of the relevant oxides is represented in Figure 5. Hence, the slag will consist primarily of silicates of metals less noble than Si, which have a low oxide vapour pressure at the operating temperature of the furnace (Schei et al., 1998, s. 77).

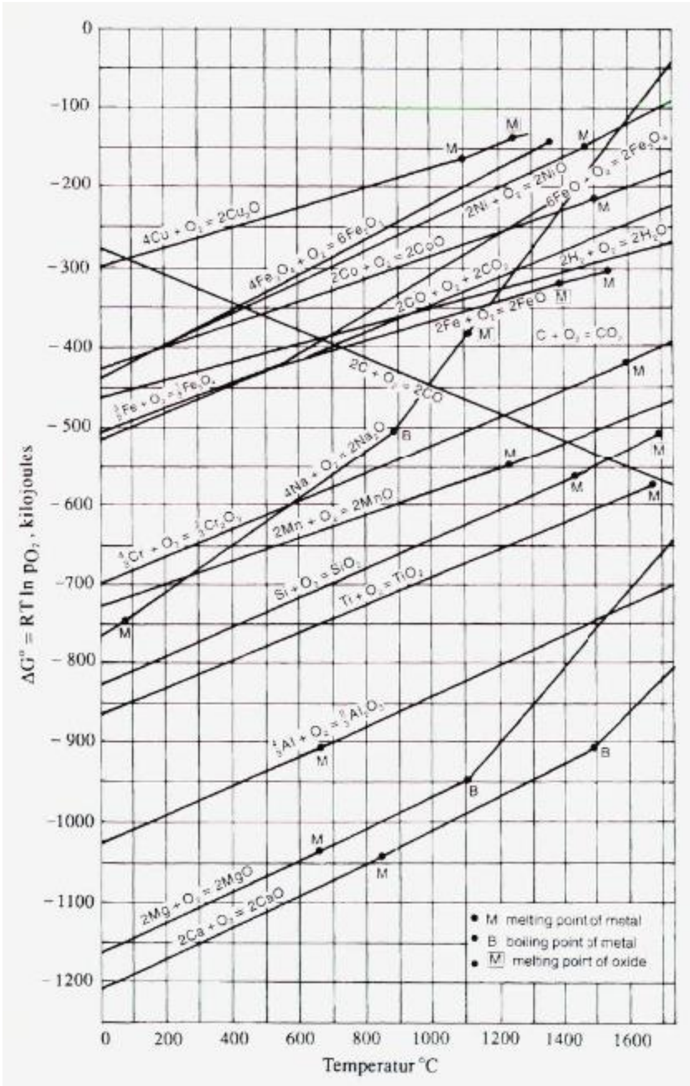

Figure 5 Ellingham diagram for the oxides of relevant additional elements (Schei et al., 1998, s.77).

The composition of the FeSi product has an impact on the slag composition and accordingly the slag density. Furnace 5 at Elkem Bjølvefossen mainly produces FeSi52, and the slag that appears will have a lower density than the product. Therefore, the slag will float on the top of the ladle and can be removed by skimming.

In the ferrosilicon process, the slag consists of large amounts of valuable materials like SiO_2 and SiC. However, amounts of impurities such as aluminium oxide (Al_2O_3), calcium oxide (CaO), and small quantities of other oxides, will be found in the slag. The Al_2O_3-CaO-SiO_2 slag system described by the phase diagram in Figure 6 shows a 2D projection of the liquidus surface (Schei et al., 1998, s.235).

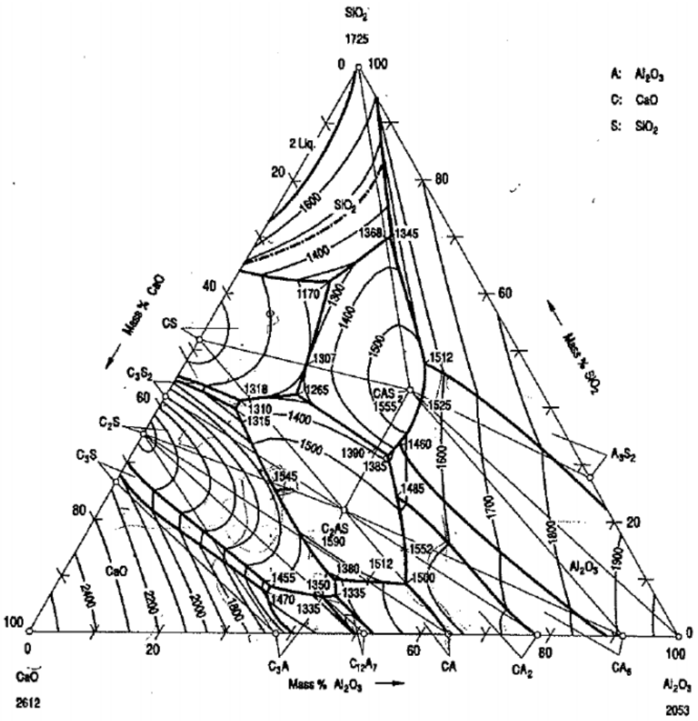

Figure 6 Phase diagram of the Al_2O_3-CaO-SiO_2 slag system (Schei et al., 1998, s. 235).

The thick solid lines represent the different phases in the system, while the thinner lines represent liquidus isotherms.

Oterkjær did a calculation in 1976 and an average slag composition for FeSi75 was found as followed.

31,5% SiO_2 – 3,8% SiC – 38,7% Al_2O_3 – 26,0% CaO

The calculations are slightly uncertain as the weight of the slag was not recorded (Schei et al., 1998, s.87). In addition, the slag will also contain minor impurities of elements such as Fe, Mn, Mg, Na and K. An example of a slag analysis from Elkem Bjølvefossen, performed in 2008, is presented in Table 5. Note that the slag analysis is from another furnace, and the product was FeSi75 (Appendix A: Output Analyses).

Table 5 Slag analysis done by Elkem Bjølvefossen in 2008 (Appendix A: Output Analyses).

	SiO_2	Al_2O_3	MgO	CaO	Fe_2O_3	Na_2O	K_2O
Range [%]	48,6 – 60,1	4,8 – 6,3	10,1 – 19,7	20,0 – 31,5	0,3 – 2,8	0,05 – 0,2	0,05 – 0,07

The Fe-impurities are reported as Fe_2O_3, but present as various oxides including FeO (Kennedy, 2020).

2.4. Material Flow Analysis (MFA)

Material flow analysis is defined as "The systematic assessment of the flows and stocks of materials within a system defined in space and time" (Brunner and Rechberger, 2004). The law of conservation of mass is based on fundamental principles of physics stating that matter cannot be created or destroyed (in the absence of nuclear reactions). Due to this, an MFA can easily be controlled using a material balance by studying all inputs, stocks and outputs of a process. MFA is an attractive tool in resource management, waste management and environmental management. This analysis will give a good indication of where the different materials end up, what goes to waste and what goes to environmental loadings. Further this analysis can be used to take actions that can prevent losses and pollution and increase utilization of materials and products in the system (Brunner and Rechberger, 2016).

In MFA terminology there is a lot of terms necessary to analyse the activity within a system. The most common terms are substance, goods, process, stock, flow and system. According to "Practical Handbook of Material Flow Analysis" by Paul H. Brunner and Helmut Rechberger (Brunner and Rechberger, 2016) these terms can be defined as shown in Table 6.

Table 6 MFA terms and definitions (Brunner and Rechberger, 2016).

Term	Definition
Substance	*A substance is any (chemical) element or compound composed of uniform units. All substances are characterized by a unique and identical constitution and are thus homogeneous*
Goods	*Goods are defined as economic entities of matter with a positive or negative economic value. Goods are made up of one or several substances*
Process	*A process is defined as the transformation, transport, or storage of materials*
Stocks	*Stocks are defined as material reservoirs (mass) within the analysed system*
Flows	*A flow is defined as a "mass flow rate." This is the ratio of mass per time that flows through a conductor.*
System	*A system is defined by a group of elements, the interaction between these elements, and the boundaries between these and other elements in space and time*

2.5. Uncertainties

Error can be defined as "The difference between an observed or calculated value and a true value" (Merriam-Webster). There are two types of errors; systematic errors and random errors. Systematic errors can appear from mis-calibrated instruments, wrong or incomplete system definition or errors in the structure/information of the experiment or data, while random errors are the remaining deviations (Müller, 2017). While doing repeated measurements of a given variable it is normal to expect some variation or errors to arise, these errors are quantified by the standard deviation (std.dev). Uncertainty is an estimate of the std.dev (Müller, 2017).

3. Approach

The approach is described in four phases; The theoretical calculations and material flows (section 3.1), the handling of the raw data, both input and output (section 3.2), visualization of the data structures, including assumptions and errors (section 3.3) and finally experimental work (section 3.4).

3.1. Theoretical Material Flow

The theoretically material flow for the furnace can be found by using equation 2 and 3. By assuming 100% Fe yield and 90 % Si yield, it is possible to calculate the fractions of raw materials needed to produce 1 tonne ferrosilicon as shown in Figure 7. With this Si yield the parameters x and m from equation 2 and 3 will be respectively 0,111 and 2,222 (Schei et al., 1998, s.169). Other assumptions used to find a theoretical material flow:

- FeSi52
- No production of SiC
- No slag, note that this is just for the theoretical balance
- No loss of any kind to the environment (dust, particles etc.)
- No stock accumulation in the process
- All the Fe is added as Fe_2O_3*

* Iron comes into the furnace as various compounds, such as Fe, FeO and Fe_2O_3 (Kennedy, 2010)

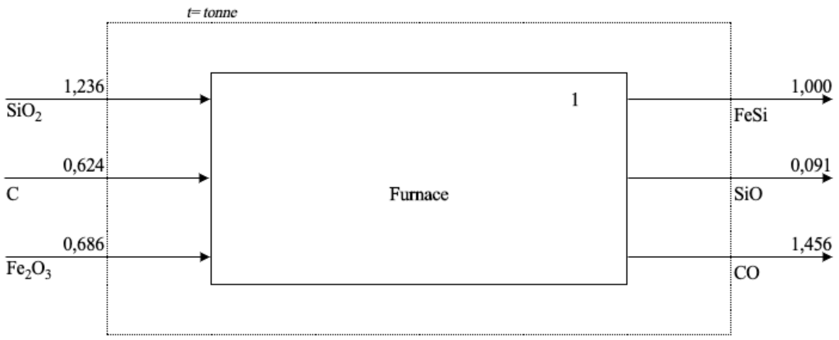

Figure 7 Schematic representation of the material flows in the furnace for the production of 1 tonne of FeSi52.

For a theoretical process there will be no loss during casting and crushing of the product FeSi. Further it is possible to find the amount of microsilica and CO_2 by using equation 6 as shown in Figure 8.

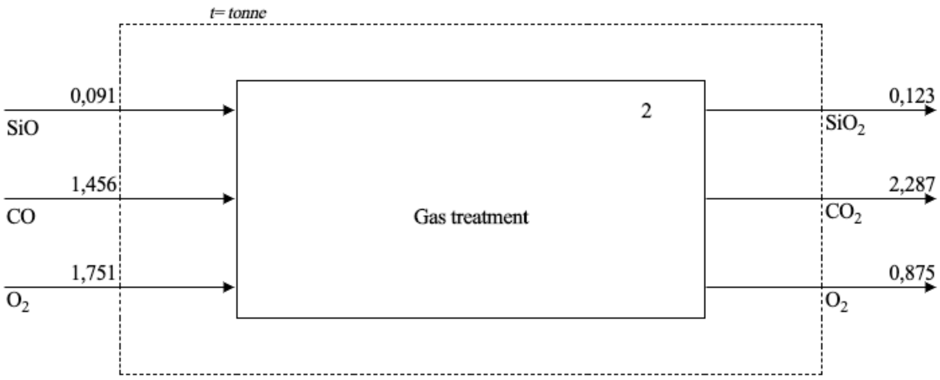

Figure 8 Schematic representation of the material flows in the gas treatment for the production of 1 tonne of FeSi52.

In Table 7 the balance of the input and output is shown for both the furnace and the gas treatment.

Table 7 Balance for furnace and gas treatment for production of 1 tonne FeSi [t]

Material balance furnace				Material balance gas treatment			
Input	**t**	**Output**	**t**	**Input**	**t**	**output**	**t**
SiO_2	1,236	FeSi	1,00	O_2	1,551	O_2	0,875
C	0,624	SiO	0,091	SiO	0,091	SiO_2	0,123
Fe_2O_3	0,686	CO	1,456	CO	1,456	CO_2	2,287
total	2,546		2,546		3,297		3,286

Figure 9 describes the theoretical material flows, calculated from production of 1tonne FeSi, of the major elements in the entire system. However, the real process will be different due to impurities and state of the raw materials, losses of particles and gas, slag formation, SiC formation, etc. It is worth mentioning that most of the off-gas is N_2, but this element is not studied closely in this thesis.

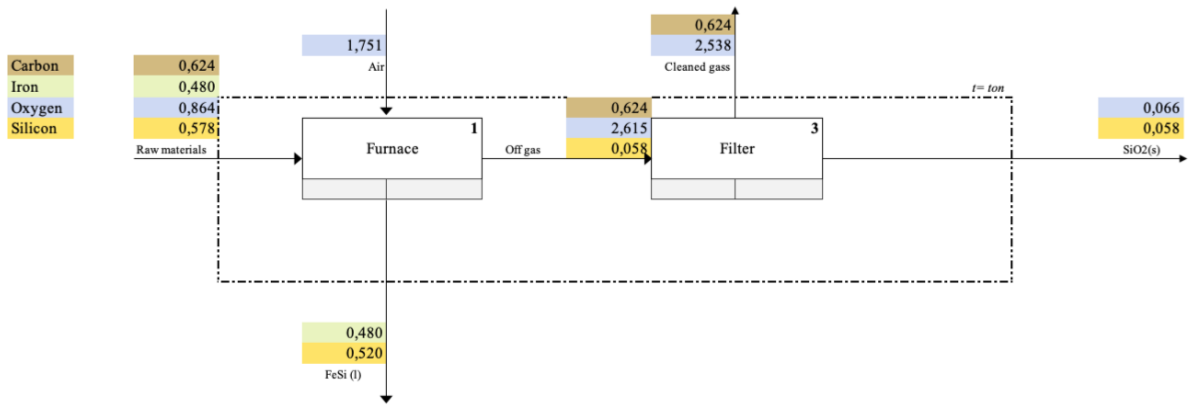

Figure 9 Schematic representation of the major element flow in the system, calculated from production of 1 tonne FeSi.

3.2. Raw Data

The furnace data sent from Elkem contained batch number, timestamps (daily basis), mass flows, and composition of the raw material and tapped metal. Elkem analyses every batch of raw material, except for the woodchips. Most of the data is from 2019, but some are from earlier years. A timeline visualizing the different batches through a year is presented in Figure 10.

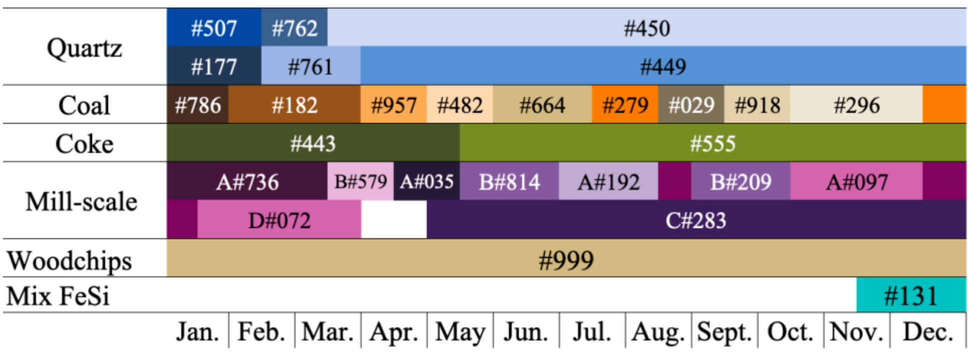

Figure 10 Timeline of different batches used in 2019

At the highest resolution, the data was analysed weekly; at the lowest resolution, the system was analysed for the whole year of 2019. The main material flows are the raw materials input and the tapped metal output. Flows like the off-gas, microsilica product, off-gases, and other minor flows (slag and dust) also occur. The raw material composition data was calculated from oxides to pure elements. This made it easier to quantify the system for different element layers and show the results in Sankey diagrams.

When analysing the input and output, days with less than 90% operating time were disregarded. This method resulted in 333 operative days in a year, which was used to find the average data on a weekly basis for the weeks with less than seven operating days. The major elements include carbon, iron, silicon and oxygen, while the minor elements include aluminium, calcium, manganese and hydrogen. Some trace elements are also analysed, such as potassium, magnesium, sodium, sulphur, phosphorous, titanium, nitrogen and chloride.

3.2.1. Input

The chemical analysis for the raw materials mill-scale, quartz and carbon-bearing materials is available in Appendix B: Chemical Analyses of Raw Materials.

Quartz

For the quartz, the data came in separate assays, furnace data (Kennedy, 2019a); where batch number and weighed input on a daily basis was available, and composition data; analysis of the composition in different batches on a monthly basis. The composition for quartz used in this paper consist of an average for a period of five months. This is because of the minor variations from batch to batch, and the fact that the composition data was not connected to a specific batch number.

Carbon

For the carbon materials most of the data was available in the furnace data (Kennedy, 2019a) . Some of the composition data for the minor and trace elements was available in a separate assay from 2018 (SGS, 2018). The woodchip data was a typical analysis of spruce from “phyllis.nl,” which included composition data for major, minor and trace elements (Phyllis2, 2020). This analysis was used as an average through the entire year. For electrode paste, the input weight was available in furnace data, while composition data came from literature (Campello-García et al.). To find the amount of fix C from the raw materials needed to reduce mill-scale, all the Fe was calculated as Fe_2O_3.

Mill-Scale

All the data for mill-scale was available in furnace data (Kennedy, 2019a). Two of the batches were missing composition data, an average from the other batches was used in this case. From the furnace data, Fe was reported as an element, and not as oxides or compounds. Therefore, all the Fe was calculated as Fe_2O_3.

3.2.2. Output

The chemical analysis for the slag, microsilica and cleaned gas is available in Appendix A: Output Analyses.

Slag

Data as composition and weight was available for the tapped metal on a daily basis. Slag was included in the weight; therefore, it was necessary to separate the slag from the metal mass. By assuming the slag contained no iron it was possible to find an average slag percentage in a year. Further this was used to find a composition of the slag, which later was compared to the average slag percentage used by Elkem at 2,5 %.

Microsilica

For the microsilica composition data and the total weight shipped in 2019 was available. MS production from furnace 5 was estimated to be 60 % of the total shipping weight. This number was used to find an average daily production of MS, which was then used to find a weekly production by using the operative 333 days. The losses from the emergency stack is calculated in the same way, by using a total weight assay from 2019.

Diffuse Emissions

The diffuse emissions are mostly losses of smoke from the tap hole as microsilica and losses of raw material from handling and transport. For the raw material an average percentage of the composition was used, while the composition of microsilica was from the previous mention MS data.

Cleaned Gas

The cleaned gas was calculated in two different ways. By using a calculation received from Elkem from 2019 (Tangstad, 2019), it was possible to find the amount of CO_2-emissions. This analysis will be referred to as CO_2-calculation in this thesis, see Appendix A: Output Analyses. These numbers were only used for comparison. The numbers used in the MFA were found by assuming all the carbon surplus, after balancing all the flows from input and output, goes to CO_2-equivalents. Other components in the cleaned gas (e.g. CH_4) is not studied closely, but a gas surveys conducted by SINTEF at Bjølvefossen in 2019 (Ksiazek et al., 2019) is used to get an indication of the CH_4- emissions.

Potential Carbon Flows

The Al content has an impact on the solubility of carbon in FeSi-metal. Calculations were made to estimate the changes in CO_2-emissions as a function of Al% in metal. From Figure 4 the solubility of carbon was determined for FeSi65 for both 0% Al and 0,8% Al. Further, 20 ppm was subtracted to adjust for the difference in Si percentage in the metal. The solubility was then used to identify the variations in CO_2-emissions for the two Al contents.

3.3. The Data Structure

Mapping all the flows in and out of a system will require calculations of flows with partly poorly reported data. Figure 11 portrays the structure of the currents in and out of the system. The flows are numbered and color-coded to clarify the data input.

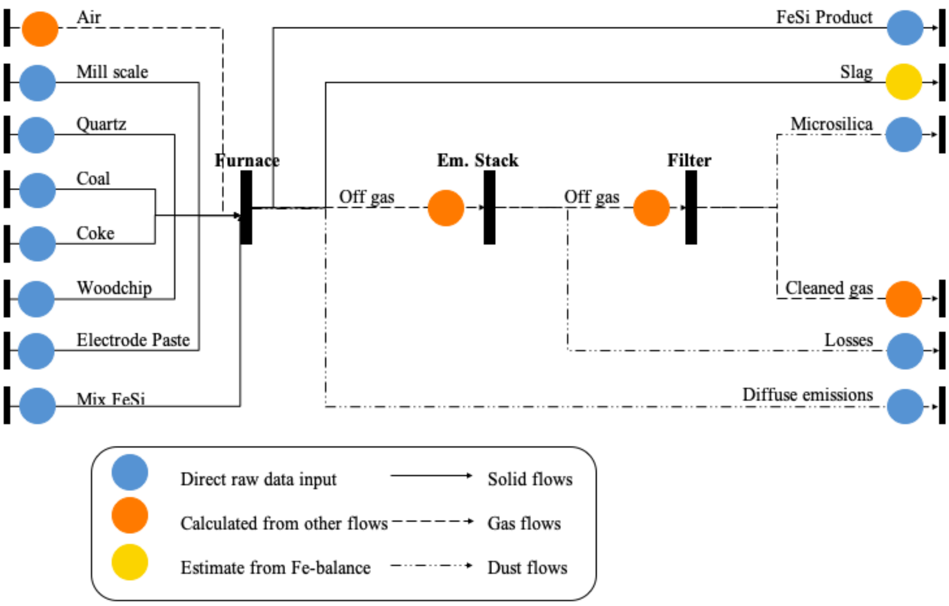

Figure 11 Flow structure; the color-codes is used to differentiate between the various ways the mass values are obtained for the separate flows, and the arrows represent the state of the flow.

3.3.1. Assumptions

Some assumptions were made to make the MFA; the assumptions listed below apply for the whole project.

- There is no Fe or SiC content in the slag, and therefore the slag composition can be calculated with the assumption that all Fe units report to metal with an analysed composition.
- If the difference between input and output is negative (more out of the furnace than in), it is assumed there is an error in raw material analysis (inadequate composition data), particularly for minor and trace elements.
- If the difference between input and output is positive (more in than out of the furnace), individual assumptions are formulated to balance the flow.
- There are no stock accumulation in the processes.
- Coarse dust extracted through the radiclone is omitted in the MFA *.
- From the mill-scale input, all reported Fe is calculated as Fe_2O_3.

* The total amount of coarse dust in a year was estimated to be approximately 3800 kg a year (Lutro, 2020). Because of the minor losses, this flow was not included in the MFA.

3.3.2. Errors

There will always be errors present when analysing large amounts of data. Some of the most significant are listed below.

Systematic Errors:

- Lack of composition analysis in raw materials for minor and trace elements like Na and Mg, compared to more precise analyses on output. This results in a negative balance for some of the minor and trace elements
- When the analysis is estimated from other batches to get an average composition where this is missing
- Mill-scale in the quartz silo (‘rensk’); error on the input weight. Estimated around 1,5 tonnes per day.
- When a balance per week is calculated, there will be offsets because of the delay in the material flow in the furnace.

Random Errors:

- Inexact calculations
- Analytical errors
- Timing of the first and last tap will affect the balance when converting the data to a weekly basis. An estimate of 2 taps on a weekly basis is used as an uncertainty.

3.4. Experimental Work

The original plan was to execute two separate experiments: testing the slag composition and analysing the carbon materials e.g. woodchips and coal. Both of the experiments were initiated, but were not carried out completely, due to various complications.

3.4.1. Slag Samples

The slag samples were sent from Bjølvefossen to NTNU for a composition analysis. The plan was to prepare the samples by cutting them into small pieces and cast them into epoxy before looking at the composition in scanning electron microscope. By using a hammer, it was possible to get a few pieces without having to cut. During the casting, a crushing sound was detected caused by high pressure, and this was a sign of porosity in the slag. By using a saw, it was possible to get pieces of slag with more metal and therefore denser samples which would not pulverize. During the cutting, a garlic-like smell was noticed, which might be an indication of phosphine. The samples were isolated in plastic bags and sent for testing. The experiment was no longer possible to perform due to time pressure.

3.4.2. Samples of Carbon-Bearing Raw Materials

The purpose of this experiment was to find moisture variations in the woodchips used in the FeSi production.

Woodchips

When visiting the ferrosilicon plant Bjølvefossen, multiple samples of coal and woodchips were collected. The woodchip samples were collected from the woodchip storage which supplies both furnaces automatically. A 10L bucket was filled to the top by a shovel. The bucket was then shaken by hand to get an even surface without any pressure applied on the woodchips. Further, the sample was weighed before it was put back in the woodchip storage. For three days, sampling happened every hour from 09:00 to 17:00, while one sample was collected in the afternoon.

Coal

Samples was collected from the bottom of the coal silo that leads to furnace 5. For safety reasons, the control room was informed before taking the samples. The samples were placed in plastic bags and marked with time, date and silo number. For three days, samples were collected every other hour from 09:00 to 17:00, while one sample was taken in the afternoon.

Moisture Analysis

One sample from each; the woodchips storage and the coal silo were prepared for moisture analysis by spreading them on a tray and weighed. The tray was placed in an oven at 105 ºC for 14 hours. Further, the samples were weighed again to determine the moisture.

4. Results

The results will be represented in four parts: the raw materials (section 4.1), output analysis (section 4.2), Sankey diagrams (section 4.3) and uncertainties (section 4.4).

4.1. Raw Materials Analysis and Variations

The raw materials entering the furnace will always contain impurities. The chemical analysis will have variations depending on the material, supplier, time of year and batch. This chapter will show the variations in carbon materials, mill-scale and quartz within the batches used in 2019.

4.1.1. Mill-Scale

Figure 12 show differences in element content for different batches of iron scrap. Elkem Bjølvefossen has various suppliers and is referred to by the letters A-E in this thesis.

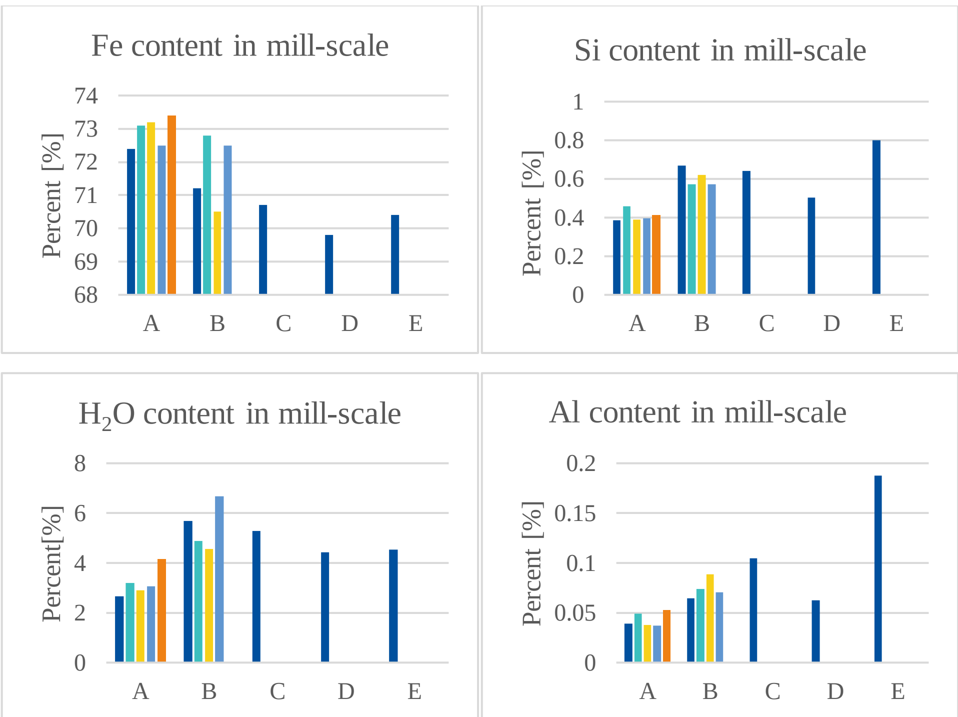

Figure 12 Differences in element content for mill-scale; the varying colours represent batches, and letter A-E represent suppliers [%].

4.1.2. Quartz

The box plot in Figure 13 show the variation in SiO_2 and Fe_2O_3 for the two types of quartz used at Elkem Bjølvefossen in 2019.

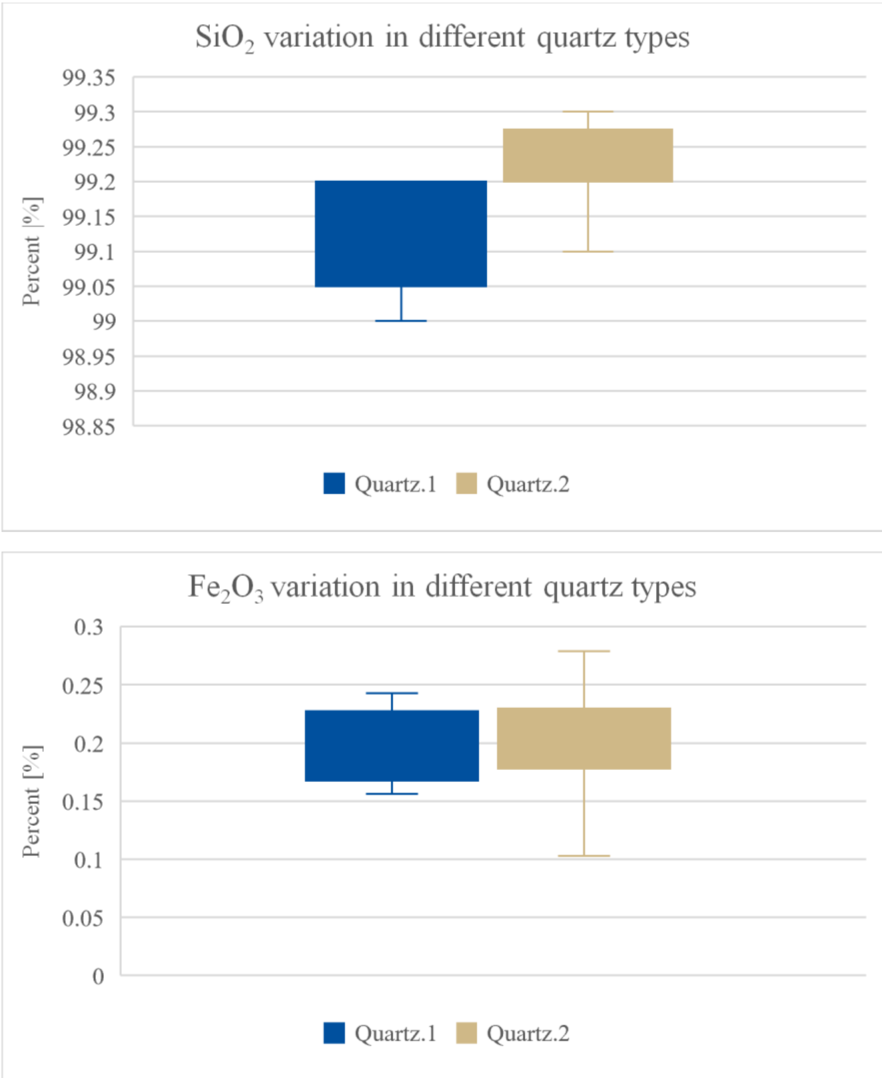

Figure 13 Variations in SiO_2 and Fe_2O_3 for quartz.1 and quartz.2. The solid box represents the interquartile range and the whiskers represent the minimum and maximum value [%].

4.1.3. Carbon-Bearing Raw Materials

Figure 14 visualizes the different distribution of moisture, volatiles and fix C in coal, coke and woodchips. The distribution is calculated from the total input from 2019.

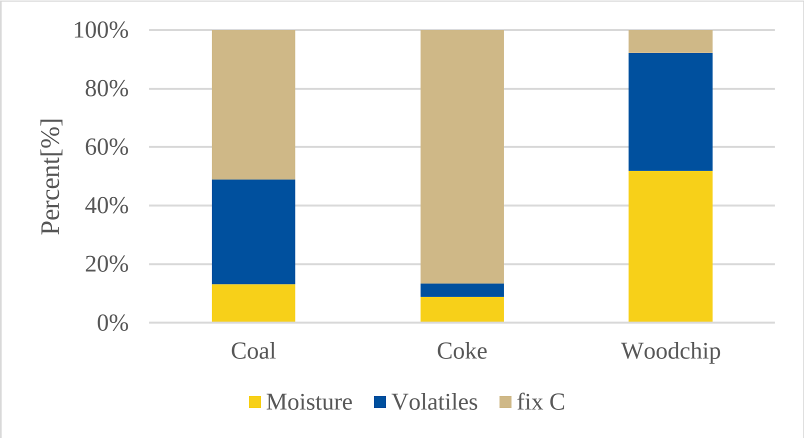

Figure 14 Distribution of moisture, volatiles and fix C in different carbon material [%]

These parameters will also vary between different batches. Figure 17 presents the variation in fix C, volatile, moisture and ash in different batches of coal used in furnace 5 in 2019. Every shipment has a batch number for identification, and #000 represent the last three digits of this number.

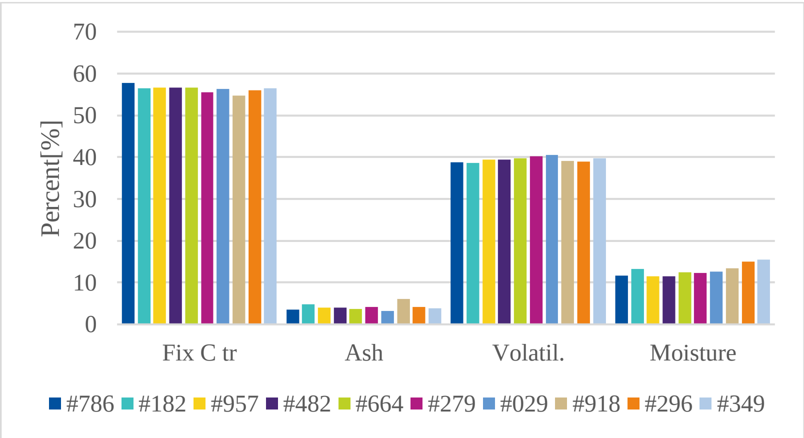

Figure 15 Variations in different batches of coal [%].

Table 8 is an overview of the amount of fix C and volatile needed in kilograms to reduce the quartz and mill-scale according to equation 1, 3 and 4. From the balance it is clear that it is not enough fix C available from the raw materials to reduce both the quartz and the mill-scale.

Table 8 Required fix C and volatile for reduction of quartz and mill-scale[kg]

	Required for reduction of		Available from raw materials	Balance
	Quartz	Mill-scale		
Fix C	16475	3402	18975	-902
Volatile		3402	10954	7552

4.2. Outputs Analysis

Figure 16 illustrates the total calculated mass flows for a year for the major elements. Note that another process, Emergency Stack, is added compared to the theoretical illustration of the major element flows (Figure 9). This is because the theoretical system has no losses. The numbers for diffuse emissions and emergency stack are too low to appear in this figure. The numbers represent fractions from the production of 1 tonne FeSi52.

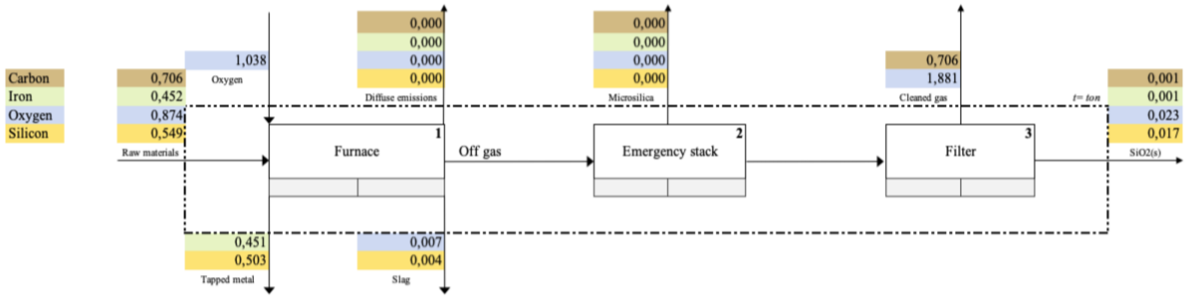

Figure 16 Major element flow, fraction from the production of 1 tonne FeSi

From the iron balance the slag percentage was found to be an average of 1,82% per year, by assuming that the slag contains no FeO. This was used to find the composition of the slag shown in Table 9. The SiO_2 was found by taking 100% of the total slag weight minus the rest of the oxides; Al_2O_3, CaO, MnO, K_2O and P_2O_5.

Table 9 Slag composition calculated from Fe-balance

Slag	**1,82%**
SiO_2	43,88%
Al_2O_3	35,06%
CaO	8,72%
MnO	9,82%
K_2O	2,17%
P_2O_5	0,35%

4.2.1. Distribution of the Elements

Figure 17 show the element yield to various outputs such as FeSi product, MS, cleaned gas, slag, and other losses (diffuse emissions and losses from the emergency stack). The input source is the raw materials. For oxygen, the air is calculated as an input source in addition to the oxygen contained in the raw materials.

The Fe-element is balanced by the slag, and is used as base for other elements such as Ca, Al and Mn. This is why the Fe has 100% yield all 52 weeks. The yield varies for Ca, Al and Mn, which can be explained by the deviation on a weekly basis for these elements.

For C and O, the total yield is 100% as of the calculated flows. Figure 17*f* shows the distribution of the elements to the different output sources, where the average yield of 2019 is applied.

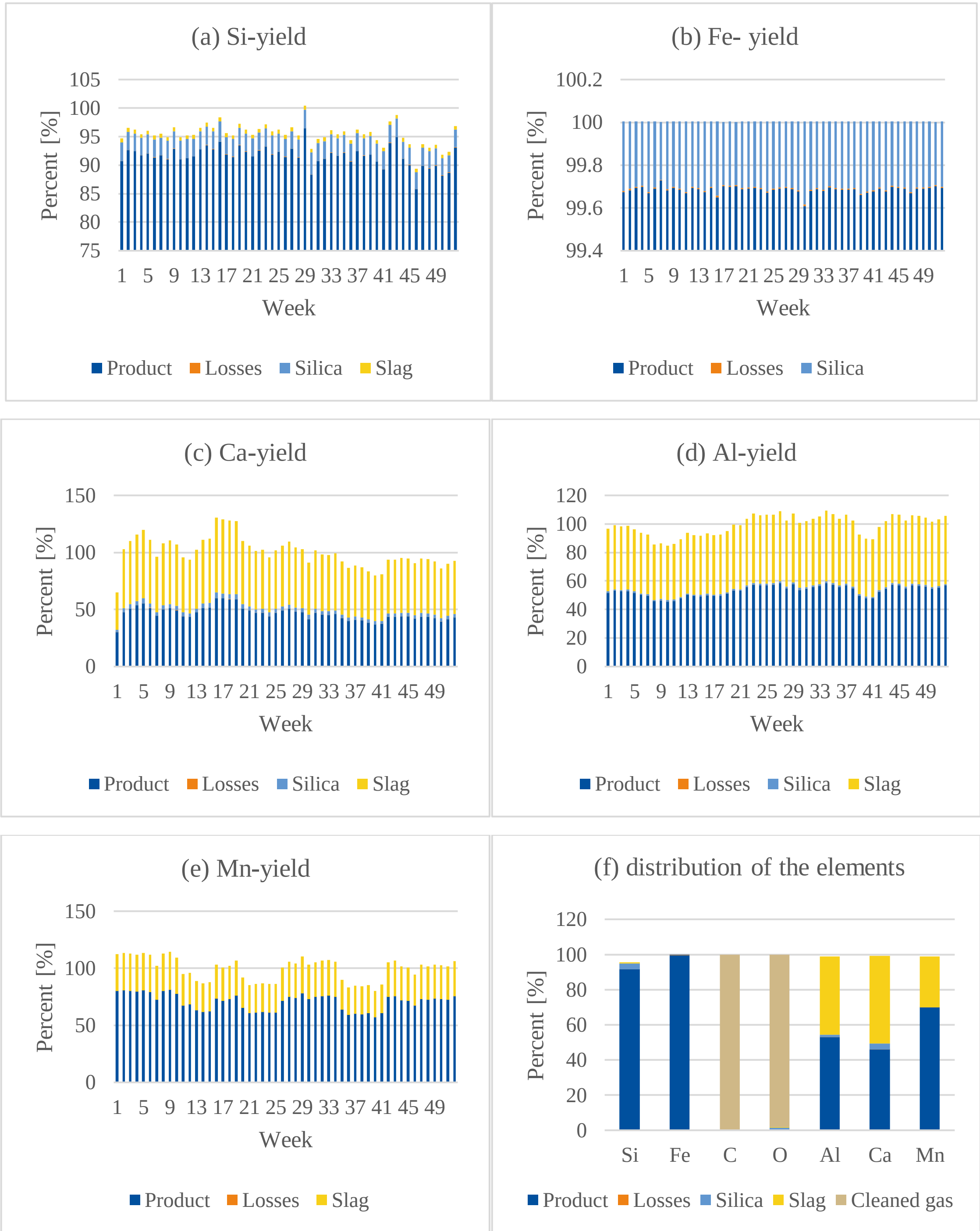

Figure 17 Element yield to various output sources on a weekly basis. (a): silicon yield, (b): iron yield, (c): calcium yield, (d): aluminium yield, (e): manganese yield, (f): yearly average distribution to output sources [%].

Element C and O have respectively 99,9% and 98,0% distribution to the cleaned gas, also showed in Figure 17*f*.

4.2.2. Losses

Figure 18, Figure 19 and Figure 20 visualize the total loss of respectively major, minor and trace elements in 2019. The blue lines represent losses from the emergency stack. These losses have the same composition as MS, which is why Si and O have such high loss value in Figure 18 compared to Fe and C. MS analyses did not include Mn, and has therefore no value for emergency stack in Figure 19. The beige lines represent losses from diffuse emissions

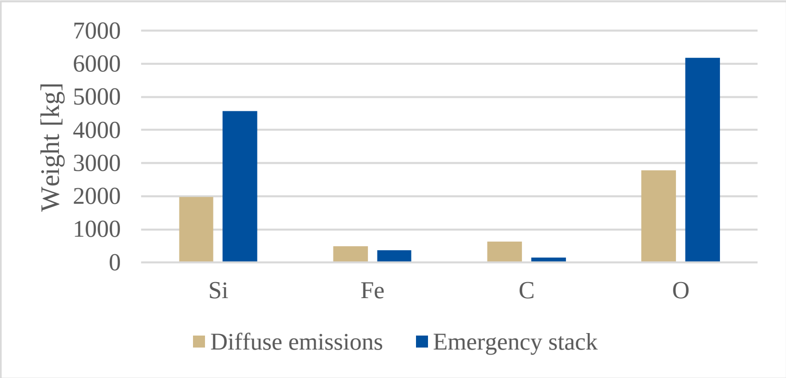

Figure 18 Total losses of major elements 2019 [kg]

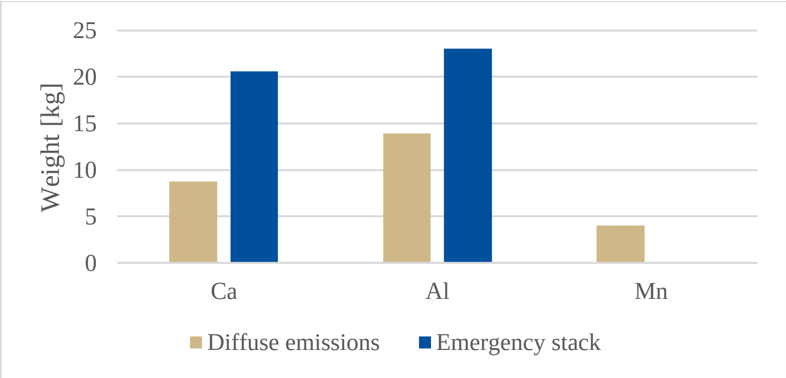

Figure 19 Total losses of minor elements 2019 [kg]

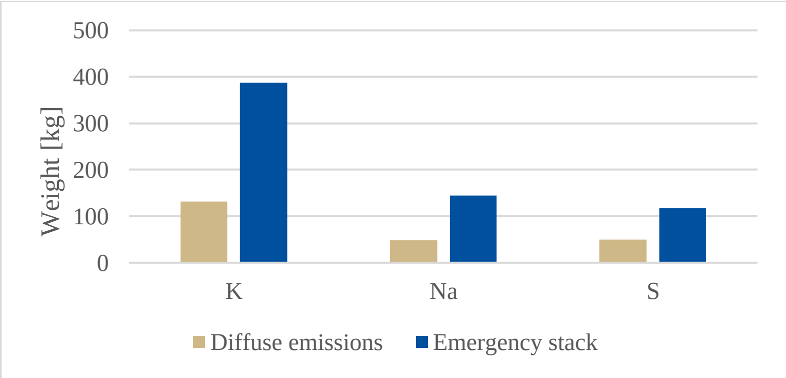

Figure 20 Total losses of trace elements 2019 [kg]

4.2.3. CO_2-Emissions

Figure 21 shows the comparison of the two different analysis of CO_2-emissions. The blue lines represent the numbers found by using the CO_2-calculation from **Error! Reference source not found.** in appendix A, while the beige lines represent the numbers found by mass balance. The difference is small and hard to distinguish from one another.

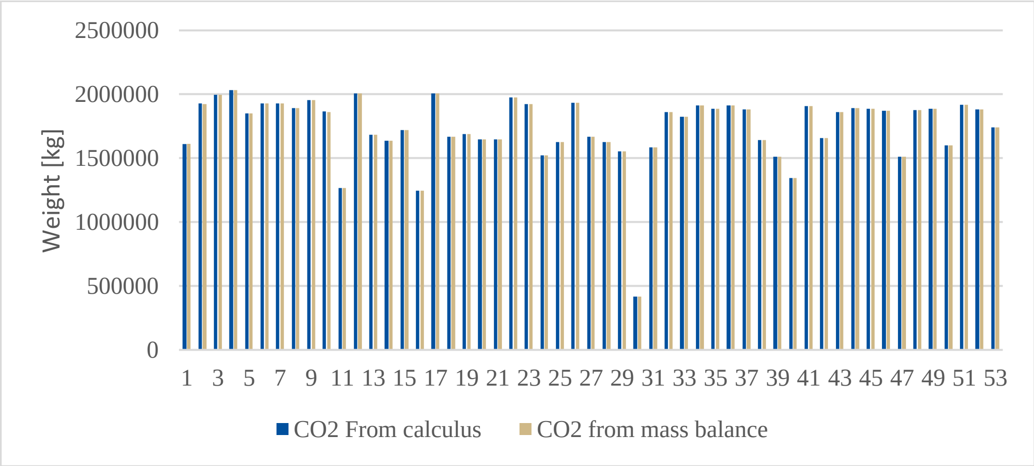

Figure 21 CO_2-emissions from CO_2-calculation, compared to CO_2-emissions calculated from mass balance [kg]

Figure 22 shows the carbon content in FeSi product and cleaned gas for different Al contents in the metal. 0,002% C separate the two cases. With no carbon in the product, there will be 0,09% more C in the cleaned gas compared with 0,8% Al.

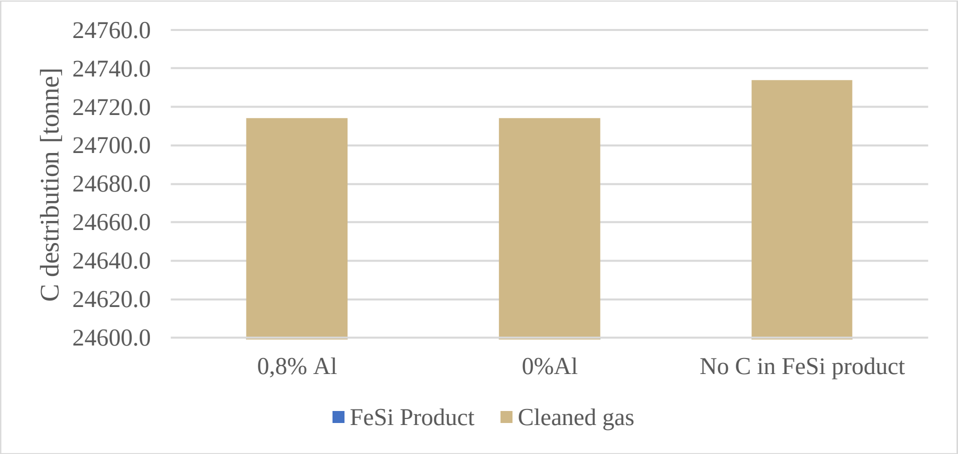

Figure 22 C in FeSi product and cleaned gas output for Al content of 0% and 0,8% in FeSi metal, compared with no C in FeSi product [tonne].

4.3. Sankey Diagrams

The Sankey diagrams presented in Figure 23 – 29 show the flows from different processes in the defined system, where the furnace and the gas treatment (emergency stack and filter) are the main processes. The flow input to the furnace includes the raw material inventories and the additional air from the atmosphere for the oxygen balance. The process "others" in the Sankey diagrams combine the input from the electrode paste and mixed-FeSi source. The total mass, tonnes, for each element is used as basis for the Sankey diagrams. Also, the analyses for the quartz and carbon-bearing materials are performed on a dry basis, while the H_2O in mill-scale are included in the calculations.

The cleaned gas, slag and losses (from the emergency stack and diffuse emissions) are “waste” from the plant, while both microsilica and FeSi are valuable export products.

4.3.1. Major Elements

For the major elements, Si, Fe, C and O, individual Sankey diagrams are represented in Figure 23-26.

For the Si-Sankey in Figure 23, 877 tonnes are uncounted for and named "unknown" in the diagram. From the Si-Sankey, one can read that the main flow follows the path "quartz-furnace-FeSi product," while smaller flows lead to the microsilica product, slag, and losses.

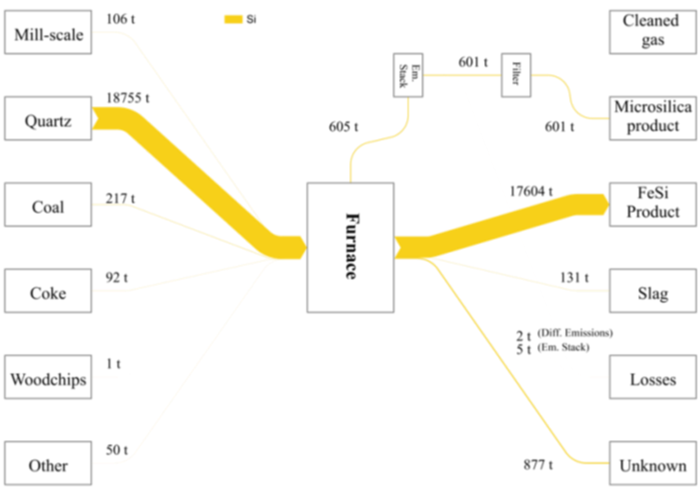

Figure 23 Sankey diagram showing the Si-layer. The “other” flow in input include paste and Mixed-FeSi [tonne]

The Fe-Sankey in Figure 24 is balanced by the assumption that there is no Fe in slag, as mentioned earlier. The main flow follows the path "mill-scale-furnace-product," while small quantities end up in microsilica or as losses.

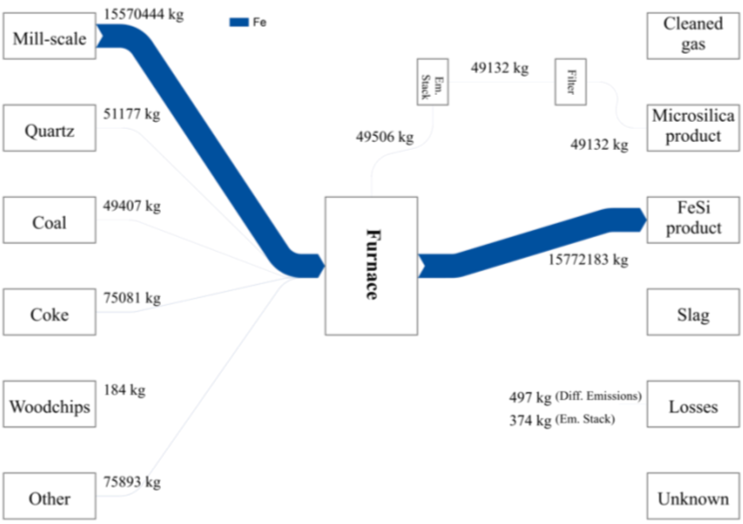

Figure 24 Sankey diagram showing the Fe-layer. The "other" flow in input include paste and Mixed-FeSi [tonne]

The C-Sankey is based on total carbon and is balanced to the cleaned gas as CO_2, shown in Figure 25. The essential carbon sources are coal, coke and woodchips, while small amounts come from the paste and mill-scale. Most of the carbon goes through the gas treatment, while small amounts end up as products and losses.

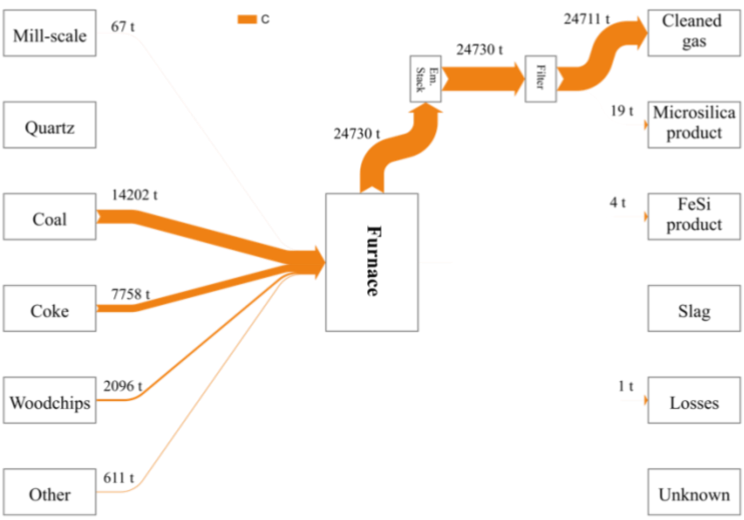

Figure 25 Sankey diagram showing the C-layer. The "other" flow in input include paste and Mixed-FeSi [tonne]

The oxygen is bound to the raw materials as oxides, and there will be flows from all the input sources. In Figure 26, one can see that a significant flow of oxygen comes from the atmosphere to balance the sizeable cleaned gas-output. Small flows go to the products and losses as oxides.

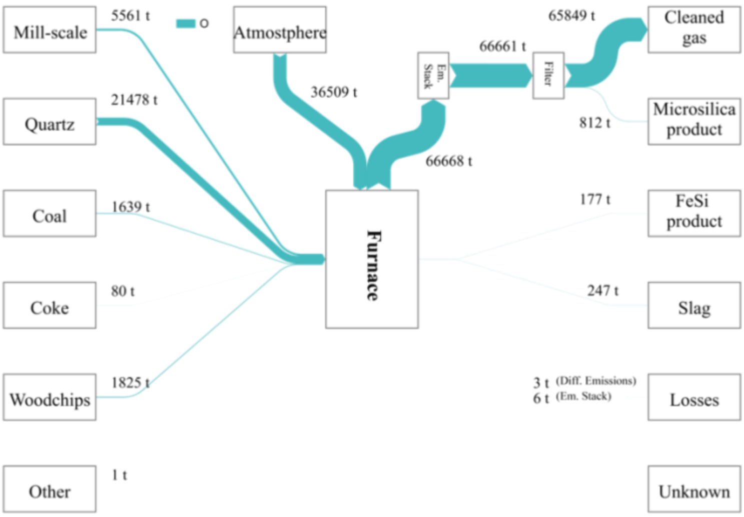

Figure 26 Sankey diagram showing the O-layer. The "other" flow in input include paste and Mixed-FeSi [tonne]

Figure 27 combine the Sankey diagrams from Figure 23 to Figure 26 and gives an overview of the major element flows for Elkem Bjølvefossen in 2019.

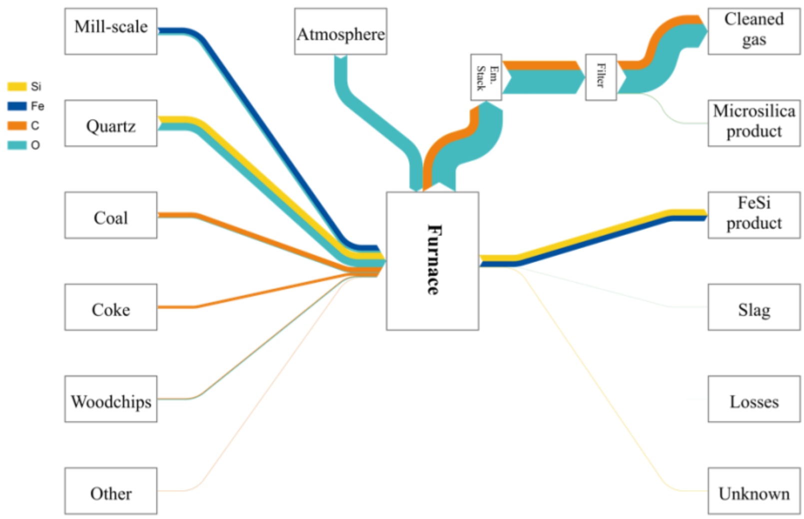

Figure 27 Sankey diagram showing the major elements layer. The "other" flow in input include paste and Mixed-FeSi [tonne]

4.3.2. Minor Elements

The minor elements Al, Ca, Mn and H, are represented in the Sankey diagram shown in Figure 28. Al, Mn and Ca are balanced by calculating the slag composition by difference, while H is balanced from the cleaned gas.

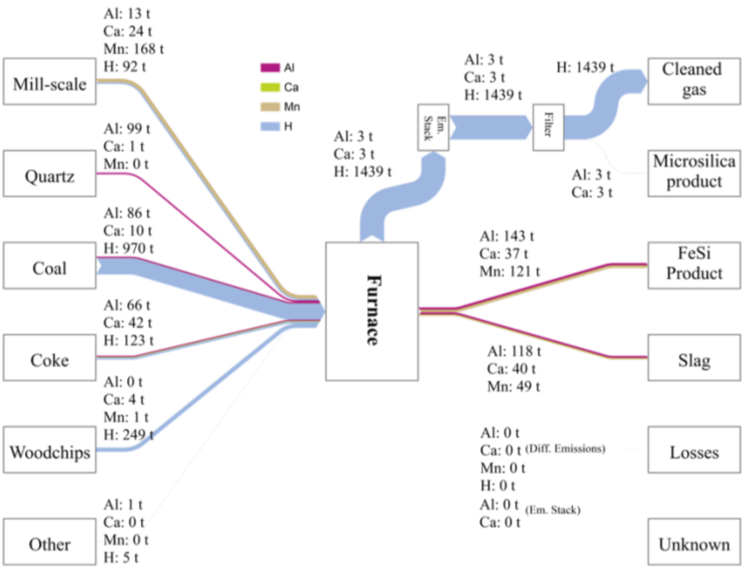

Figure 28 Sankey diagram showing the minor elements layer. The "other" flow in input include paste and Mixed-FeSi [tonne]

4.3.3. Trace Elements

The trace elements are, in this case, K, P, Ti, Na, Mg, S, Cl and N. In Figure 29 these elements are represented in a Sankey diagram. Na, Mg and Cl are missing respectively 18943 kg, 16665 kg and 1425kg on the input side, and this is shown in the Sankey diagram as "unknown". K and P are balanced from the slag, Ti are balanced from the product, and S and N are balanced from the cleaned gas.

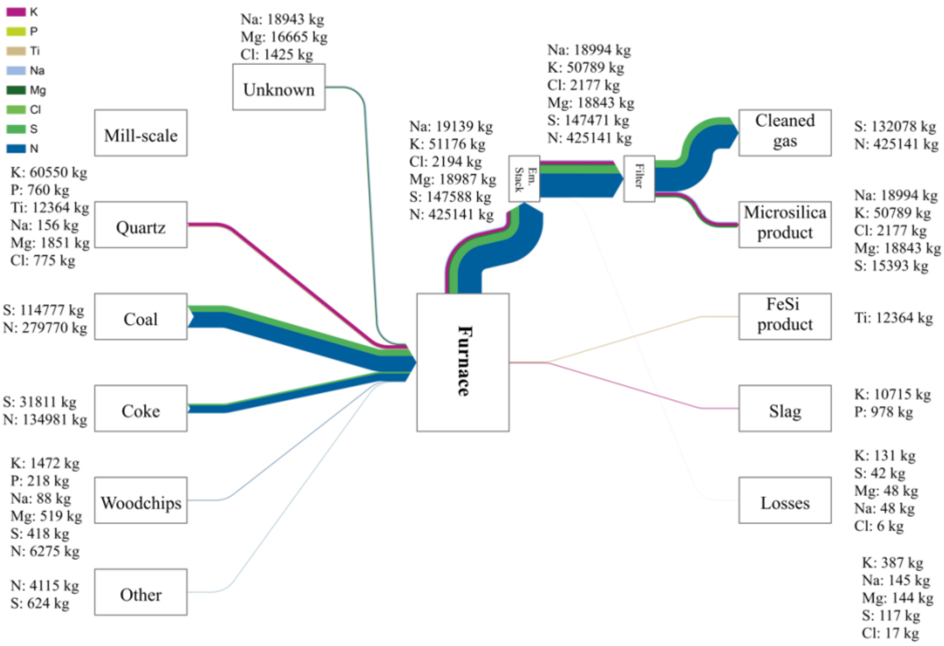

Figure 29 Sankey diagram showing the trace elements layer. The "other" flow in input include paste and Mixed-FeSi [kg]

4.4. Uncertainties

Figure 30 shows the percentage distribution of the std.dev and mass flow for the major and minor elements. The base is an average week of 2019, and the std.dev determine the uncertainties from week to week. The total std.dev for the raw material input and the total output is respectively 13% and 9%.

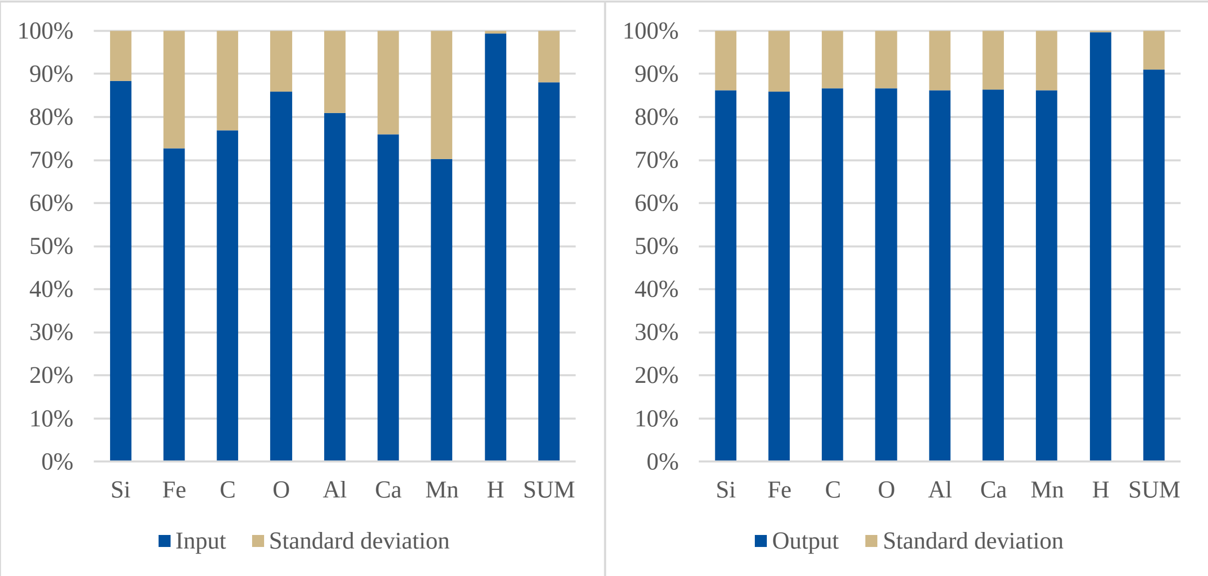

Figure 30 Standard deviation for the major and minor elements on an average week. (a) Show the std.dev on input, while (b) show the std.dev on output [%].

Table 10 Show the difference for the major and minor elements if the mill-scale in the quartz silo was considered. One can see that there would be 364 tonnes more Fe and 230 tonnes less Si in the raw material input for 2019.

Table 10 Deviation from 'rensk'; mill-scale in the quartz silo

	Deviation	
Element	*Total 2019 [t]*	*Average week [kg]*
Fe	364	6992
Si	-230	-4414
Ca	0	7
Al	-1	-19
Mn	4	74
H	2	34
O	-138	-2656

4.5. Moisture Analysis

Result from the moisture analysis that was taken in Bjølvefossen is available in Table 11 Moisture Analysis of Woodchip and Coal from Elkem Bjølvefossen. The tests were taken 10.03.2020 and only include woodchip and Coal. From the two samples, the moisture was found to be 52,3% in woodchip and 14,4% in Coal.

Table 11 Moisture Analysis of Woodchip and Coal from Elkem Bjølvefossen.

	Wet [g]	**Dry [g]**	**Moisture [g]**	**Moisture [%]**
Woodchips	1964,9	936,9	1028	52,3
Coal	2295,5	1964,7	330,8	14,4

5. Discussion

This chapter will discuss how the material balance for the processes is executed, the major, minor and trace elements in the process, CO_2-emissions, slag composition, and to what degree the results can be trusted. Several assumptions (listed in section 3.3.1) are made to do a material balance for the furnace and gas treatment processes. The mass balance is seen in a MFA perspective at element-level, where the elements are examined on a yearly basis, but also weekly where this is of interest.

5.1. Major Elements

The Major elements in this thesis are considered to be Si, Fe, C and O. All the major elements, except Si, are balanced from an output flow as shown in Figure 11.

5.1.1. Iron

The iron balance is, as mentioned, executed with the assumption that the slag is free of Fe. In the industrial FeSi process, this is not strictly true. This assumption is a necessity to get an iron balance and a base for the balance of Al, Ca, Mn, K and P. The slag will contain Fe_2O_3* in the range of 0,3% to 2,8%. With this considered, the Fe yield to the product will decrease with approximately 0,008%-0,08% compared to results represented Figure 17b. The following deviation is minimal from this assumption, and will give the best approach, as shown in the Sankey diagram in Figure 24.

The Fe balance is the groundwork for the minor and trace elements found in the slag; this means that the uncertainties from the Fe-balance will impact the uncertainties in these elements.

* Reported as Fe_2O_3, but actually present as FeO.

5.1.2. Silicon

The Si data was well documented, both the input and output flows. There is no Si-flows calculated from other flows, but it is calculated directly from the furnace data (A). By comparing the theoretical material flow in Figure 9 and the calculated material flow in Figure 16, one can see that all the major elements are realistically similar, except from Si. These results indicate that 0,025 tonnes Si is unaccounted for per tonne FeSi product produced. This deviation is also shown in Figure 23, where a flow called “unknown” describes 877 tonnes of Si that is unclear where ends up. If the ‘rensk’ is included in the balance, there would still be 647 tonnes of Si unaccounted for. A difference was expected, but not to such an extent. Because of incorrect analysis on microsilica, the Si output was a bit lower than it should be, 40 tonnes in a year to be exact. This alone is not a big impact, but several minor occurrences like this, could lead to large amounts of Si. Weighing errors from input, moisture in the quartz and MS analyses, are examples of errors that could cause the deviation.

5.1.3. Carbon

The total carbon is balanced by assuming that the surplus output from the furnace, passes through the filter. By doing this, the total carbon balance checks out, but which chemical compound the carbon is in, is difficult to determine. It was expected that considerably amounts exit the furnaces as CO_2, but to get an estimate of the CO_2-emissions from 2019, CO_2-calculation (Table A3) was used. Figure 21 show that there is an insignificant difference between the calculations from CO_2-calculation and calculations from the mass balance for the full year of 2019. To be exact, the difference was a negative 5,4 tonnes for 2019, with a weekly average std.dev of 17,5 kg. This is calculated with the average of 0,8% Al in the metal. This means that Elkem Bjølvefossen had less CO_2-emissions in 2019 compared to the expected amount from the CO_2-calculation. Because of the negative difference, it was not able to estimate carbon emissions in other compounds than CO_2 from these numbers.

The solubility of carbon in FeSi-metal shown in Figure 4 will give a reasonable estimate of how much carbon that is in the FeSi product. The percentage of Al% in the metal will affect the solubility of carbon in the FeSi metal, and therefore affect the CO_2-emissions. The FeSi product from furnace 5 at Elkem Bjølvefossen contained an average of 0,8% Al, and this has been compared to 0% Al in the metal and no carbon in metal. Figure 22 displays the two circumstances for 2019, and determines the increase of carbon emissions to be 0,002%. This slight increase will not affect the CO_2-emissions or the ferrosilicon plant significantly. With no carbon in the metal, the C in cleaned gas will increase with 0,09%.

Table 8 describes the amount of fix C and volatile needed in kilograms to reduce the quartz and mill-scale according to equation 1, 3 and 4. From the balance it is clear that it is not enough fix C available from the raw materials to reduce both the quartz and the mill-scale. Some of the FeOx is reduced by CO gas or hydrogen gas, and H_2O may then react with C to make CO and H_2. Any CO_2 may also react with C to produce CO. The amount of reduction done by any given gas is unsure, but it is typical to assume that there is 6 –12% short of carbon, and that this same magnitude must be accomplished by the volatiles (Kennedy, 2020) . Also, a detailed balance must include the reduction of Na, K, Ca and Mg. Almost all Na, K, and Mg in the microsilica was first reduced to $Na_{(g)}$, $K_{(g)}$ and $Mg_{(g)}$ for so to be re-oxidized in the off-gas system (Kennedy, 2020).

5.1.4. Oxygen

The oxygen enters the furnace with the raw materials as oxides and from the atmosphere. The air is drawn in at the top of the furnace and burns hydrocarbons, H_2, CO and SiO gas. Therefore, the oxygen is balanced from the atmosphere input as illustrated in the Sankey diagram in Figure 26. There are uncertainties connected to this input, and exactly how much oxygen that burns with the gas, which will have an impact on the heat balance and NO_x generation.

5.2. Minor Elements

The Minor elements in this thesis are considered to be Al, Ca, Mn and H. All the minor elements are balanced from an output flow as shown in Figure 11. The slag composition and hydrogen balance will be discussed in this chapter.

5.2.1. Slag

The average slag percentage was found as 1,82% from the Fe-balance, which is significantly lower than the slag percentage used by Elkem at 2,5%. In theory the slag composition would be around 38,7% for Al_2O_3, which is reasonably similar to the calculated composition at 35,06%. However, for the CaO, the theoretical value is around 26% (Schei et al., 1998, s.87), while the calculated number is 8,72%. To get a CaO percentage closer to the theoretical value, it is calculated that 50% more Ca is a necessity from the input. This missing input might be caused by systematically error, such as poorly reported data from the raw material. For the SiO_2, the theoretical composition is about 31,5%, while the calculated value is at 43,88%. The SiO_2 composition is dependent on the other components in the slag, and will vary at the same rate they possibly do. In this case the slight difference in the theoretical and calculated value can be a result of the missing information about CaO. If the CaO percentage was higher, the SiO_2 would be lower, and both of them more equal to the theoretical values.

5.2.2. Hydrogen Balance

Hydrogen enters the furnace through carbon-bearing raw materials as volatile compounds and also in mill-scale in minor amounts. The hydrogen will vaporise in the furnace due to the high temperatures, and therefore hydrogen is balanced by the cleaned gas output. It is uncertain which chemical compound hydrogen departures as, and this would potentially affect the carbon balance. Gas surveys conducted by SINTEF at Bjølvefossen in 2019 have found significant amounts of H_2 gas (~10.0%) and CH_4 (~3,0%) inside the charge prior to combustion (Ksiazek et al., 2019). If 3% of the CO_2 equivalents consists of CH_4, the total emissions would increase considerably, and also affect the carbon balance calculated.

5.3. Trace Elements

The trace elements in this thesis are considered to be K, P, Ti, Na, Mg, Cl, S and N. Some of the trace elements such as K and P are balanced by the slag output, which is previously discussed (section 5.2). The trace elemental flows are presented in the Sankey diagram in Figure 29.

Titanium

The titanium enters the furnace as a trace element in quartz. From the Ellingham diagram in Figure 5, one can predict that the Ti enters the FeSi metal output because of the similarities to Si. Therefore, the Ti is balanced to the product, as shown in the Sankey diagram in Figure 29.

Sodium, magnesium and chlorine

Na, Mg and Cl are missing respectively 18943 kg, 16665 kg and 1425 kg on the input side as shown in Figure 29. This suggest absent composition data from the raw materials. These elements are typically challenging to analyse accurately, and it is not abnormal for it to be under-reported.

Potassium and phosphorous

The K and P is balanced from the slag, from Table 9 the slag contains 2,17% K_2O and 0,35% P_2O_5. According to the analysis done by Elkem in 2008 available in Table 5, the slag contained 0,05 - 0,07% K_2O. It is important to remember that the analysis from 2008 was for FeSi75, which could be an explanation of the noticeably difference. The analysis from Table 5 did also not contain any P_2O_5, but from the incident at the lab where traces of phosphine was detected, it is fair to assume that the sample did in fact contain phosphor. The P detected is presumably concentrated into metal droplets e.g. Fe_3P and AlP. In this thesis, the excess P is balanced by the slag, but P contained in quartz essentially reports to metal. It would be interesting to get some new analysis of the slag composition, both for FeSi75 and FeSi52.

Sulphur and nitrogen

From Table 4 it is possible to predict that most of the S and N will exit the system as cleaned gas, and is therefore balanced as such. The output analyses (Appendix A: Output Analyses) only report SO_3 in MS and not in the metal. From the Sankey diagram in Figure 29 the amount of S in the cleaned gas is 132 tonnes, while the Norwegian Environment Agency report 498 tonnes of SO_2 in 2019 (Miljødirektoratet, 2019). The SO_2 is cleaned in the off-gas system, and will not enter the atmosphere. Airborne emissions from Si/ FeSi production by Kero, Grådahl and Tranell (Kero et al., 2017) is a study about these gases, which takes a closer look at this part of the production. For future work, it would be interesting to study what determines the SO_3 content of MS and how this change with alkali elements, and also what off-gas process conditions that favour the reaction of SO_2 to SO_3.

5.4. Experimental Work

From the experimental work it was detected a minor trace of phosphine, sulphur dioxide and cyanide in the slag samples. These samples were from 2008 and FeSi75 production. From Table 9 there is expected some phosphorous*, but the analyses sent from Elkem indicated it did not contain any P. This might be because of the metal phase present in the slag. Also, processing and storage of the slag over an extended period could be a crucial factor for these types of reactions during experimental work. For future work it would be interesting to get some new analysis of the slag for different types of FeSi. Due to Covid-19 and closed laboratories, it was not possible to perform moisture analysis on the carbon materials. This would also be interesting to look at for future work. One sample of each was however tested for moisture at Bjølvefossen where the moisture for woodchips and coal was found to be 52,3% and 14,4%, respectively. These numbers were satisfyingly similar to both the theoretical value from Figure 2 and the numbers from the analyses sent from Elkem (Figure 14).

5.5. Uncertainties

The mass balance is uncertain due to systematically errors like incorrect analysis, estimated analysis, delay in material flow and mill-scale in the quartz silo (‘rensk’).

5.5.1. Major Errors

The mill-scale in the quartz silo can qualify as a major error because of the consequence for the mass balance. Table 10 Deviation from ‘rensk’; mill-scale in the quartz silo, show the deviation if the ‘rensk’ is considered. A total of 364 tonnes more Fe, and a total of 230 tonnes less Si on the input side, would affect the mass balance, the yield and the slag. The amount of 1,5 tonnes per day is a rather rough estimate, and this is why the ‘rensk’ is not considered for the central mass balance calculations. Elkem has no reliable method of measuring the ‘rensk’ on the ferrosilicon plant, but this would be an interesting thing to take a closer look at in the future.

* All surplus P report to the slag in this thesis.

Most of the raw material input is analysed batch by batch, and one can assume that these are accurate. The quartz input applies an average analysis where the variations in SiO_2 and Fe_2O_3 content is shown in Figure 13. The variations are minimal for the batches used in 2019, but there will still be a deviation in the total mass balance. For woodchips, an average analysis of spruce is used for the entire year of 2019. There is an absence of information about variations regarding the weather and other factors impacting the moisture content of the raw materials. Also, the mass balance of Na, Mg and Cl indicates that there is inadequate analysis of the ashes in carbon-bearing materials. The errors regarding variations in the raw materials will approximately be in the order of ± 2% for coal and coke, ± 10% for woodchips and ± 0,5% for quartz. Mill-scale has a somewhat variable oil content, and oil free mill-scale might pick up moisture to a greater extent (Kennedy, 2020).

5.5.2. Minor Errors

Figure 30 show the standard deviation for the major and minor elements in and out of the furnace. The std.dev is determined from the 52 weeks in 2019, and indicates the variations from week to week. The std.dev of 13% and 9% for respectively input- and output flows are somewhat misleading because of the analysis types used. The input flows mainly have time relevant chemical analysis, while the output flows use average analysis for microsilica, losses to the emergency stack and diffuse emissions.

The yield to the several outputs for the major and minor elements is shown in Figure 17. For Si, Ca, Al and Mn, the yield varies on a weekly basis; this is because of the average slag percentage used, and the variations indicate the deviation from week to week.
The weekly deviation is in addition to the reasons mentioned earlier, also a result of the delay in the furnace mass flow. In this thesis, the stocks in the processes are not taken into consideration.

In some cases, Si is calculated by difference, given the difficulty in getting Si to report accurately. This means that Si in MS and slag is calculated backwards, and will include errors accordingly.

6. Conclusion

A material flow analysis for furnace 5 at Elkem Bjølvefossen has been carried out based on raw material and product data from 2019. The basis for distribution of major, minor and trace elements is the assumption of 100% Fe yield.

6.1. Major Elements

The CO_2-emissions were calculated in two different ways; from a CO_2-calculation provided by Elkem and from the mass balance in the MFA. A difference of 5,4 tonnes in the entire year of 2019, with a weekly average std.dev of 17,5 kg, was found. This is calculated with the average of 0,8% Al in the metal. By using an average of 0% Al in the metal, the CO_2-emissions will increase with 0,002%.

- Insignificant difference between CO_2- emissions calculated from mass balance and CO_2-calculation provided by Elkem. Indicates that the calculations are accurate.
- Insignificant increase of CO_2-emissions with different Al content in metal.

From the Si-balance, 877 tonnes are unaccounted for, which can have several explanations. Examples of errors that could cause the deviation are listed below.

- Rensk (~ 230 tonnes Si)
- Incorrect analysis on microsilica (~ 40 tonnes Si)
- Weighing errors
- Moisture in the quartz and MS analyses

6.2. Minor- and Trace Elements

The average slag percentage was found as 1,82% from the Fe-balance. From the calculations, the composition of K_2O and P_2O_5, were found to be respectively 2,17% and 0,35%. Despite the analysis sent from Elkem showed no P in the slag, it was detected traces of phosphine as well as cyanide. This indicates droplets of metal in the slag, but also processing and storage of the slag over an extended period could be a crucial factor of these findings. K_2O was estimated to be 0,05-0,07% according the Elkem analysis. Further conclusions found from the slag is listed below.

- Al content in slag; reasonably accurate compared to theoretical value.
- Ca content in slag; low compared to theoretical value, indicates inadequately reported data from the raw materials
- SiO_2 in slag is calculated by difference, which might be off because of the Ca-deviation.

6.3. Future Work

For future work it would be interesting to

- Look at the slag and its composition, including the metal content and P concentration in metal droplets.
- Perform a moisture analysis on the carbon materials
- Perform a more comprehensive sensitivity analysis and a data reconciliation to improve the accuracy of the results. Specifically, take a closer look at the 'rensk' and the impact it actually has on the material balance.
- A study on what determines the SO_3 content of MS and how this change with alkali elements
- Look at the Mn content in microsilica.

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Slag analysis from FeSi75 production executed in 2008 (Lutro, 2008).

Table A1 Slag-analysis form FeSi75 production provided from Elkem, executed in 2008.

% SiO_2	% Al_2O_3	% MgO	% CaO	% Fe_2O_3	% Na_2O	% K_2O
60,05	6,26	16,19	28,65	2,76	0,046	0,057
55,29	4,82	12,75	31,54	1,23	0,209	0,045
48,59	6,08	12,10	26,61	2,04	0,087	0,051
52,44	6,20	13,33	27,01	1,60	0,079	0,053
54,40	6,16	12,29	24,78	0,56	0,073	0,057
58,50	6,23	11,57	26,74	0,60	0,128	0,071
56,09	6,15	11,61	25,88	1,05	0,104	0,058
57,55	6,17	10,06	24,62	0,27	0,123	0,061
53,47	6,21	15,39	22,55	0,46	0,113	0,058
55,01	6,24	16,79	22,65	0,45	0,123	0,055
53,05	6,22	18,30	22,65	0,49	0,104	0,057
54,18	6,23	19,67	21,57	0,48	0,112	0,058
54,82	6,21	17,84	21,44	0,52	0,110	0,058
54,49	6,20	15,48	20,15	0,25	0,096	0,059
56,84	6,24	16,31	20,36	0,68	0,104	0,061
55,79	6,24	15,65	19,97	0,83	0,082	0,061

Table A2 is a representation of the average composition of the tapped metal (Kennedy, 2019a).

Table A2 Elements found in the tapped metal

[%]	Tapped metal
Si	52,102
Ca	0,148
Al	0,771
Fe	45,886
Mn	0,446

Table A3 present the CO_2-calculations provided by Elkem (Tangstad, 2019).

Table A3 CO2-calculation of carbon and associated CO2 emissions by feed/output type

Kalkyle CO_2	*Item name*	*MT C*	*CO2*
Innstraum	Koks	10,199.2	37,369.9
Innstraum	Kull	28,242.9	103,481.8
Innstraum	Kalkstein	3.7	13.6
Innstraum	Elektrodemasse	1,077.4	3,947.7
Innstraum	Propan	79.3	290.3
Utstraum	Microsilica	5.1	18.7
Innstraum	Jernkjelde	363.7	1,332.5
Utstraum	FeSi	10.9	39.8
Innstraum	Acetylen	9.43	34.5
Innstraum	Silisiumdioksyd	5.9	21.5
Innstraum	Leire - stengemasse	40.6	148.6
Innstraum	El.masse reperasjon	3.5	12.6
Fråtrekk innstraum	Treflis jomfrueleg	3,835.2	14,052.2
Sum innstraumar			146,618.9
Andel CO_2 frå biomasse		9.584 %	

Table A4 show an analyse of microsilica from 2019 (Lutro, 2019).

Table A4 Microsilica analysis

Microsilica [%]			
SiO2	83,416	**Si**	38,988
Na2O	1,662	**Na**	1,233
K2O	3,970	**K**	3,296
C	1,244	**Mg**	1,223
MgO	2,027	**Ca**	0,176
CaO	0,246	**Al**	0,196
Al2O3	0,371	**Fe**	3,188
Fe2O3	4,559	**S**	0,999
SO3	2,496	**O**	52,705
Cl	0,141	**H**	0,048209
H_2O	0,433878		

Chemical analysis of mill-scale, quartz and carbon-bearing materials. Mill-scale analysis is presented in Table B1 and Table B2 (Kennedy, 2019a). The elements usually appear as oxides. The different batches are separated by batch numbers sown as #000 in the tables.

Table B1 Chemical analysis for the different batches used in 2019: Mill-scale A

%	#736	#035	#192[a]	#724	#097	#522	#085g
Si	0,385	0,457	0,408	0,388	0,397	0,413	0,408
Fe	72,400	73,100	72,920	73,200	72,500	73,400	72,920
O	26,070	25,205	25,426	25,215	25,840	24,798	25,426
H	0,299	0,358	0,357	0,323	0,341	0,466	0,357
Al	0,039	0,049	0,043	0,038	0,037	0,052	0,043
Ca	0,065	0,067	0,077	0,075	0,084	0,096	0,077
Mn	0,742	0,763	0,768	0,760	0,801	0,775	0,768

Table B2 Chemical analysis for the different batches used in 2019: Mill-scale B, C, D and E

	B				C	D	E
%	#579	#814	#209	#855	#283	#072	#073
Si	0,668	0,571	0,620	0,573	0,641	0,504	0,799
Fe	71,200	72,800	70,500	72,500	70,700	69,800	70,400
O	26,414	24,949	27,186	24,970	27,407	28,362	26,294
H	0,636	0,547	0,511	0,747	0,591	0,495	0,508
Al	0,064	0,074	0,089	0,070	0,105	0,063	0,187
Ca	0,116	0,109	0,128	0,151	0,126	0,293	1,325
Mn	0,903	0,950	0,966	0,988	0,429	0,484	0,486

[a] An average of the other batches.

Qartz.1-2 and 3 represent different quartz types with various size. These quartz analyses are an average of 5 representative quartz batches (Kennedy, 2019b).

Table B3 Chemical analysis of quartz

%	Quartz.1	Quartz.2	Quartz.3
Si	46,327	46,384	0,463
Fe	0,139	0,125	0,001
O	53,170	52,989	0,532
Al	0,254	0,228	0,003
Ca	0,001	0,001	0,000
Ti	0,015	0,048	0,000
Mg	0,005	0,005	0,000
K	0,080	0,216	0,002
Mn	0,001	0,001	
P	0,002	0,002	0,000
Cl	0,002	0,002	
Na			0,000

Table B4 present the analysis of coal. The coal is analysed at batch level, where two of the batches is estimated from the others. Also, some of the elements were missing in the furnace data provided by Elkem (Kennedy, 2019a) and different sources is used as an estimate (SGS, 2018).

Table B4 Chemical analysis of the different batches of coal

%	#786	#182	#957[a]	#482[h]	#664	#279	#029	#918	#296	#349
Fixed C	57,70	56,50	56,59	56,59	56,70	55,60	56,30	54,70	56,00	56,40
Volatile	38,76	38,58	39,35	39,35	39,72	40,23	40,51	39,12	38,89	39,81
Ash	3,55	4,87	4,06	4,06	3,61	4,16	3,21	6,13	4,12	3,79
Moisture	11,59	13,18	11,56	11,56	12,46	12,32	12,56	13,35	14,99	15,46
Si	1,04	1,47	1,47	1,47	0,97	1,10	0,82	1,59	1,07	1,01
Fe	0,18	0,26	0,26	0,26	0,21	0,27	0,20	0,57	0,32	0,29
C[b]	79,19	79,19	79,19	79,19	79,19	79,19	79,19	79,19	79,19	79,19
O[i]	9,14	9,14	9,14	9,14	9,14	9,14	9,14	9,14	9,14	9,14
H[i]	5,41	5,41	5,41	5,41	5,41	5,41	5,41	5,41	5,41	5,41
Al	0,42	0,51	0,51	0,51	0,42	0,50	0,41	0,64	0,45	0,48
Ca	0,03	0,04	0,04	0,04	0,06	0,07	0,05	0,09	0,06	0,07
Mn										
N[i]	1,56	1,56	1,56	1,56	1,56	1,56	1,56	1,56	1,56	1,56
S[i]	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64	0,64
SiO_2	62,84	64,67	64,67	64,67	57,24	56,56	54,36	55,35	55,58	56,81
Fe_2O_3	7,43	7,60	7,60	7,60	8,41	9,29	8,72	13,40	11,16	10,88
CaO	1,01	1,19	1,19	1,19	2,26	2,29	2,31	2,07	2,20	2,46
Al_2O_3	22,11	19,70	19,70	19,70	22,15	22,66	24,12	19,63	20,48	24,03

[a] Estimated from batch #182
[b] Separate analysis (SGS, 2018).

Table B5 present the chemical analyses for coke, electrode paste (Campello-García et al.) and woodchips (Phyllis2, 2020). For paste and woodchips, average analyses are applied in the MFA.

Table B5 Chemical analysis for coke, paste and woodchips

	Coke		Paste	Woodchips
%	#443	#555		
Fixed C	88,20	89,20	85,50	16,22
Volatile	4,22	4,85		83,78
Ash	7,57	5,92	3,30	2,27
Moisture	7,65	8,46		51,90
Si	1,05	1,07		0,03
Fe	1,53	0,57	5,00	0,00
C[a]	90,24	90,24	95,00	50,10
O[j]	0,93	0,93	0,23	43,63
H[j]	1,43	1,43	0,77	5,95
Al	0,98	0,67		0,01
Ca	0,45	0,50		0,09
Mn				0,01
N[j]	1,57	1,57	0,64	0,15
S[j]	0,37	0,37	0,10	0,01
Ti				
Mg				0,01
K				0,04
P				0,01
Cl				
Na				0,00
SiO_2	29,66	38,74		
Fe_2O_3	28,93	13,84		
CaO	8,33	11,86		
Al_2O_3	24,52	21,32		

[a] Separate analysis for coke (Kennedy, 2020)

Secure job-analysis was done before the experimental work at Elkem. This is something Elkem does before every new job to make sure it is safe to perform the task.

Sikker Jobbanalyse - SJA

Elkem A Bluestar Company

Arbeidsoppgave/leveranse: Prøvetaging av kull i utmater til veievogn

AO-nummer og firmanavn

Beskrivelse av arbeidet:
Lokasjon: Veiedørk

Krever arbeidet:
(Fjern kryss for de sjekklistene som ikke skal inkluderes)

- [x] Varmt arbeid
- [ ] Mobilt utstyr
- Arbeid i
- [x] Energiisolering
- [x] Entring i trange rom

Trinn	Aktivitetsbeskrivelse (stegvis)	Faremoment – mulig konsekvens	Risikoreduserende tiltak	Ansvarlig
1	Ta prøve med bøtte fra kullsilo 23	klemfare, påkjørsel	veievogn må gjøres energiløs (lysgitter brytes og	RS
			Kontrollrom må ha beskjed ved prøvetaging	
Utstyr	**Utstyr som skal brukes på jobben**	**Faremoment – mulig konsekvens**	**Risikoreduserende tiltak**	**Ansvarlig**

Sjekkpunkt	Ivaretatt	Ikke aktuelt
Dokumentasjon og erfaringsdata		
Er ansvarsforhold og organiseringa klarlagt?	ok	
Er orden og reinhald i samsvar med standard?	ok	
Er arbeidsoperasjonen kjent og arbeidet grundig nok planlagt?	ok	
Er det utarbeida dekkande prosedyrar / instruksar / standard?	SJA	
Kompetanse		
Er personellet tilstrekkeleg kvalifisert og med nok erfaring ?	ok	
Er det andre som burde deltatt i SJA-utarbeidelsen	ok	
Personlig sikkerhet		
Er personellet ikledd arbeidstøy iht standard? InosaId21804	ok	
Er det nødvendig å bruke spesielle hanskar, drakter eller anna personlig verneutstyr?	nei	
Er det nødvendig med tettsittande vernebriller?	nei	
Støymåling i området gjort kjent? Behov for hørselvern?	nei	
Er det god nok ventilasjon?	ok	
Er der nødvendig med gassmåling? Bærbar målar nødvendig?	nei	
Er fluktveier klarlagt og kontrollerte? Møteplass?	ok	
Er det trygg og sikker tilkomst og ferdsel i området?	ok	
Er det vanskelege kommunikasjonsforhold?	varsler kontrollrom ved	
Er det tatt omsyn til andre aktivitetar i området?	ok	
Er det fare for at bevegelig utstyr kan koma inn i arbeidsområdet?	ja, veievogn, energiisoleres	
Er det nødvendig å sikra området med sperring og skilting?	nei	
Er det risiko for brannskade?	nei	
Er det arbeid i fleire høgdenivå?	nei	
Er det kjent hvor nærmeste førstehjelpsustyr og nøddusjer er?	ja	
Hvilken maske skal brukes støv-, gass- eller friskluftsmaske?	støv	
Er det behov for ekstra belysning i området?	nei	
Tiltak for å unngå varmestråling?	nei	
Tiltak for å unngå klem og kuttskader?	tilltak for å unngå påkjørsel,	
Vil det være behov for at du og kollega løfter sammen/samløft? Tiltak for unngå klem og kuttskader?	nei	
Tiltak for å unngå feilbelastning eller tunge løft?	nei	
Er det i bruk helsefarlege stoff / gass / væske som krev varsling?	nei	

Ytre Miljø		
Er det fare for uønska utslepp til grunn / vatn / sjø / luft?	nei	
Er det avfall som skal kjeldesorterast og leverast til mottak?	nei	
Behov for oljeoppsamling?	nei	
Medfører arbeidet ytre støy? Bør naboer informeres om eventuelt høyt støynivå?	nei	
Varmt arbeid InosaId26900		
Er det nødvendig å sperre av områder for gnistregn?	nei	
Er det risiko for brann og / eller eksplosjon p.g.a. arbeidet?	nei	
Er det nødvendig med brannvakt eller anna vernevakt?	nei	
Tiltak for å skjerme andre mot stråling?	nei	
Behov for varmt arbeidstillatelse?	nei	
Er det nødvendig å dekke til utstyr?	nei	
Energiisolering InosaId17743		
Er det nødvendig med Merking Låsing Prøving? Sjå Inosa id 17743.	sikkerhetsbryter betjenes og	
Er det fare for elektrisk støyt?	nei	
Entring i trange rom InosaId23436		
Er det nødvendig å ha rømningsmaske med luftflaske tilgjengeleg?	nei	
Behov for kommunikasjonsutstyr?	mibiltelefon	
Produktkvalitet		
Fare for forurensing av ferdigvare, mellomprodukt eller råvarer?	nei	

Sikker Jobbanalyse - SJA

Elkem A Bluestar Company	**Arbeidsoppgave/leveranse: Prøvetaging av flis**	**AO-nummer og firmanavn**

Beskrivelse av arbeidet:
Lokasjon: Flisbinge

Krever arbeidet:
(Fjern kryss for de sjekklistene som ikke skal inkluderes)

- [x] Varmt arbeid
- [ ] Mobilt utstyr
- [ ] Arbeid i
- [x] Energiisolering
- [x] Entring i trange rom

Trinn	Aktivitetsbeskrivelse (stegvis)	Faremoment – mulig konsekvens	Risikoreduserende tiltak	Ansvarlig
1	Ta prøve med spade i flisbinge	Klemfare, fallfare	Stå bak rekkverk ved utmatingsrenne ved	RS
			Kontrollrom må ha beskjed ved prøvetaging	
Utstyr	**Utstyr som skal brukes på jobben**	**Faremoment – mulig konsekvens**	**Risikoreduserende tiltak**	**Ansvarlig**

Sjekkpunkt	Ivaretatt	Ikke aktuelt
Dokumentasjon og erfaringsdata		
Er ansvarsforhold og organiseringa klarlagt?	ok	
Er orden og reinhald i samsvar med standard?	ok	
Er arbeidsoperasjonen kjent og arbeidet grundig nok planlagt?	ok	
Er det utarbeida dekkande prosedyrar / instruksar / standard?	SJA	
Kompetanse		
Er personellet tilstrekkeleg kvalifisert og med nok erfaring ?	ok	
Er det andre som burde deltatt i SJA-utarbeidelsen	ok	
Personlig sikkerhet		
Er personellet ikledd arbeidstøy iht standard? Inosaid2 1804	ok	
Er det nødvendig å bruke spesielle hanskar, drakter eller anna personlig	nei	
Er det nødvendig med tettsittande vernebriller?	nei	
Støymåling i området gjort kjent? Behov for hørselvern?	nei	
Er det god nok ventilasjon?	ok	
Er der nødvendig med gassmåling? Bærbar målar nødvendig?	nei	
Er fluktveier klarlagt og kontrollerte? Møteplass?	ok	
Er det trygg og sikker tilkomst og ferdsel i området?	ok	
Er det vanskelege kommunikasjonsforhold?	varsler kontrollrom ved	
Er det tatt omsyn til andre aktivitetar i området?	ok	
Er det fare for at bevegelig utstyr kan koma inn i arbeidsområdet?	ja, horisontale hydraulikksylindere, derfor to	
Er det nødvendig å sikra området med sperring og skilting?	nei	
Er det risiko for brannskade?	nei	
Er det arbeid i fleire høgdenivå?	nei	
Er det kjent hvor nærmeste førstehjelpsustyr og nøddusjer er?	ja	
Hvilken maske skal brukes støv-, gass- eller friskluftsmaske?	støv	
Er det behov for ekstra belysning i området?	nei	
Tiltak for å unngå varmestråling?	nei	
Tiltak for å unngå klem og kuttskader?	klem, hyraulikksylindere	
Vil det være behov for at du og kollega løfter sammen/samløft? Tiltak for unngå klem og kuttskader?	nei	
Tiltak for å unngå feilbelastning eller tunge løft?	nei	
Er det i bruk helsefarlege stoff / gass / væske som krev varsling?	nei	

Ytre Miljø		
Er det fare for uønska utslepp til grunn / vatn / sjø / luft?	nei	
Er det avfall som skal kjeldesorterast og leverast til mottak?	nei	
Behov for oljeoppsamling?	nei	
Medfører arbeidet ytre støy? Bør naboer informeres om eventuelt høyt støynivå?	nei	
Varmt arbeid Inosaid26900		
Er det nødvendig å sperre av områder for gnistregn?	nei	
Er det risiko for brann og / eller eksplosjon p.g.a. arbeidet?	nei	
Er det nødvendig med brannvakt eller anna vernevakt?	nei	
Tiltak for å skjerme andre mot stråling?	nei	
Behov for varmt arbeidstillatelse?	nei	
Er det nødvendig å dekke til utstyr?	nei	
Energiisolering Inosaid17743		
Er det nødvendig med Merking Låsing Prøving? Sjå Inosa id 17743.	nei	
Er det fare for elektrisk støyt?	nei	
Entring i trange rom Inosaid23436		
Er det nødvendig å ha rømningsmaske med luftflaske tilgjengeleg?	nei	
Behov for kommunikasjonsutstyr?	mibiltelefon	
Produktkvalitet		
Fare for forurensing av ferdigvare, mellomprodukt eller råvarer?	nei	

https://studntnu.sharepoint.com/sites/o365_BachelorElkem/Delte dokumenter/PA perm/Forprosjekt/Risk Assessment Norsk - Redigerbar.xlsx 02.06.2020 Side 1 av 3

NTNU	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av	Side	Erstatter
HMS		Rektor		01.12.2006

Enhet: **IMA** **Dato:** 13.05.2020

Linjeleder: **Tor Grande**

Deltakere ved kartleggingen (m/ funksjon):

(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Kort beskrivelse av hovedaktivitet/hovedprosess: Bacheloroppgave Heidi Grande og Fride Müller. Materialstrømanalyse ved Elkem

Er oppgaven rent teoretisk? *(JA/NEI)* NEI

"JA" betyr at veileder innestår for at ***oppgaven ikke innholder noen aktiviteter som krever risikovurdering****. I dette tilfellet er det ikke nødvendig å fylle ut resten av skje*

Skal du motta prøver fra industri? *(JA/NEI)* *JA*

"JA" betyr separat risikovurdering av prøvene individuelt

Er det trygt å utføre arbeidet utenfor normal arbeidstid (8-17)? (JA/NEI) JA

Signaturer: *Ansvarlig veileder:* Korinsky *Studen* Fride Müller Heidi Grande

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Kutting av prøver med sirkelsag	F.M og H.G		beskyttelseskap		biller, hanser og frakk
2	støping	F.M og H.G		avtrekk		briller, hansker og frakk
3	polering	F.M og H.G				briller, hansker og frakk
4	SEM	F.M og H.G				hansker
5	Smittevern	F.M og H.G		Ekstraordinære rutiner for bruk av LAB		Holde 1 meter avstand, håndhygiene og andre hygienetiltak
6						

https://studntnu.sharepoint.com/sites/o365_BachelorElkem/Delte dokumenter/PA perm/Forprosjekt/Risk Assessment Norsk - Redigerbar.xlsx 02.06.2020 Side 1 av 3

NTNU	Kartlegging av risikofylt aktivitet	Utarbeidet av	Nummer	Dato
		HMS-avd.	HMSRV2601	22.03.2011
		Godkjent av	Side	Erstatter
HMS		Rektor		01.12.2006

Enhet: **IMA** **Dato:** 13.05.2020

Linjeleder: **Tor Grande**

Deltakere ved kartleggingen (m/ funksjon):

(Ansv. veileder, student, evt. medveiledere, evt. andre m. kompetanse)

Kort beskrivelse av hovedaktivitet/hovedprosess: Bacheloroppgave Heidi Grande og Fride Müller. Materialstrømanalyse ved Elkem

Er oppgaven rent teoretisk? *(JA/NEI)* NEI

"JA" betyr at veileder innestår for at ***oppgaven ikke innholder noen aktiviteter som krever risikovurdering****. I dette tilfellet er det ikke nødvendig å fylle ut resten av skje*

Skal du motta prøver fra industri? *(JA/NEI)* *JA*

"JA" betyr separat risikovurdering av prøvene individuelt

Er det trygt å utføre arbeidet utenfor normal arbeidstid (8-17)? (JA/NEI) JA

Signaturer: *Ansvarlig veileder:* Korinsky *Studen* Fride Müller Heidi Grande

ID nr.	Aktivitet/prosess	Ansvarlig	Eksisterende dokumentasjon	Eksisterende sikringstiltak	Lov, forskrift o.l.	Kommentar
1	Kutting av prøver med sirkelsag	F.M og H.G		beskyttelseskap		biller, hanser og frakk
2	støping	F.M og H.G		avtrekk		briller, hansker og frakk
3	polering	F.M og H.G				briller, hansker og frakk
4	SEM	F.M og H.G				hansker
5	Smittevern	F.M og H.G		Ekstraordinære rutiner for bruk av LAB		Holde 1 meter avstand, håndhygiene og andre hygienetiltak
6						

Material Flow Analysis of FeSi Furnace at Elkem Bjølvefossen

Fride Müller and Heidi Andersen Grande
Norwegian University of Science and Technology, Department of Materials Science and Engineering

Elkem is one of the world's foremost supplier of silicon-based materials, and have plants all over the world. Elkem Bjølvefossen is located in a small town called Ålvik and is of the division Elkem Foundry. Bjølvefossen specialise in production of ferrosilicon (FeSi) and magnesium-FeSi master alloys (Elkem ASA). The raw materials needed to produce these alloys are a silicon source (quartz), a carbon source (coal, coke and woodchips) and an iron source (mill-scale). Through the raw materials, impurities will be introduced to the furnace, and affect the process in various ways. It is crucial to have a good understanding of the flows and behaviour of the impurities (Schei et al., 1998). Material Flow Analysis (MFA) is a method to estimate all the flows in and out of a system, and by using Sankey diagrams, the quantities and different paths for the flows is visualized in a structured way. By understanding the material flows in the system, one can operate the processes more efficiently, prevent losses, and better report emissions.

Silicon production

FeSi is produced industrially in arc furnaces by reduction of SiO_2 and Fe_xO_y with carbon. The furnace holds a temperature of about 1300ºC-2000ºC and the liquid metal is tapped from the bottom of the furnace. From this process, microsilica is also produced from the off-gas, which is sold as a by-product (Schei et al., 1998)

The data structure

Most of the raw material data was analyses done by Elkem. The main material flow was the raw materials input and the tapped metal output. Flows like the gas treatment, microsilica product, off-gases, and other minor flows (slag and dust) also occurred. The raw material composition data was calculated

from oxides to pure elements (Figure C1) represents the flows and how their data are obtained.

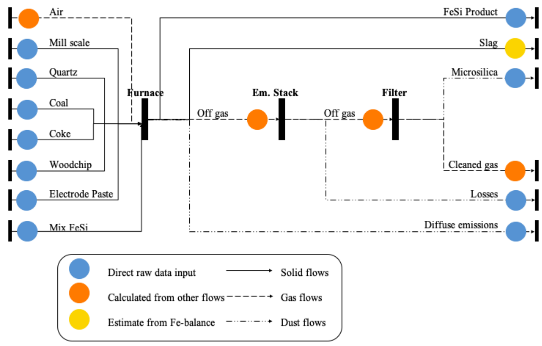

Figure.C1 Flow structure; the color-codes differentiate between the various ways the mass values are obtained for the separate flows, and the arrows represent the state of the flow.

Balancing the slag

From the iron balance the slag percentage was found to be an average of 1,82% per year, by assuming that the slag contains no FeO. This was used to find the composition of the slag shown in Table.C1.

Table.C1 Slag percent and -composition

Slag	1,82%
SiO_2	43,88%
Al_2O_3	35,06%
CaO	8,72%
MnO	9,82%
K_2O	2,17%
P_2O_5	0,35%

Sankey Diagrams

Major Elements

In Figure.C2 a typical Sankey Diagram is shown. The size of the arrows represents the weight in tonnes, while the colours separates the elements. Notice the output called “unknown”, this represents a surplus of Si which is unaccounted for. Weighing errors from input, moisture in the quartz and MS analyses, are examples of errors that could cause the deviation, among other things.

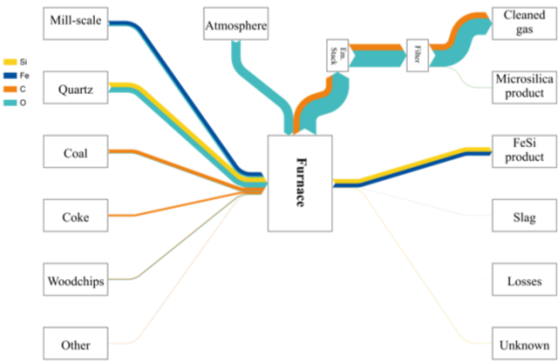

Figure.C2 Sankey diagram of the major elements in FeSi production

Minor Elements

The minor elements Al, Ca, Mn and H, are represented in the Sankey diagram shown in Figure.C3. H is balanced from the cleaned gas, while the others are balanced from the slag composition.

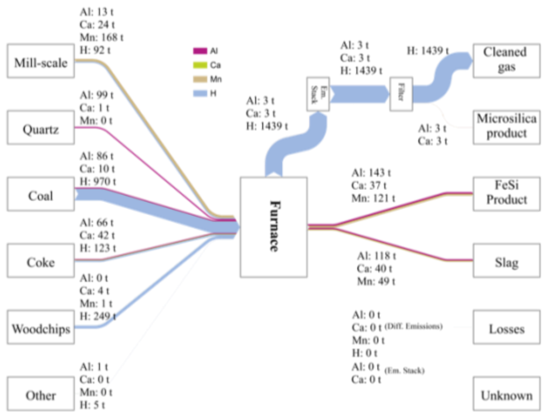

Figure.C3 Sankey diagram of the minor elements in FeSi production

Trace Elements

The trace elements (K, P, Ti, Na, Mg, S, Cl and N) are represented in Figure 4. Na, Mg and Cl are missing respectively 18943 kg, 16665 kg and 1425kg on the input side (“unknown” flow), This suggest absent composition data from the raw materials. These elements are typically challenging to analyse accurately, and it is not abnormal for it to be under-reported.

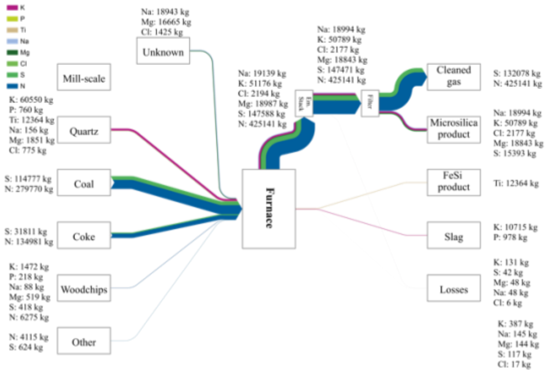

Figure.C4 Sankey diagram of the trace elements in FeSi production

References

ASA, E. *About Elkem* [Online]. Available: https://www.elkem.com/about-elkem [Accessed 24. Jan 2020].

SCHEI, A., TUSET, J.K., & TVEIT, H.. 1998. *Production of High Silicon Alloys* Trondheim, Tapir Academic Press