Waste Heat Recovery and Utilization at United Silicon Iceland

Sara Lind Einarsdóttir

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20 ECTS thesis submitted in partial fulfillment of a
Baccalaureus Scientiarum degree in Energy- and Environmental
Engineering

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Abstract

The objective of this study is to consider waste heat recovery and utilization possibilities at a silicon metal plant being erected in Helguvík, Iceland. The main focus is put on steam production from the off-gas but other utilizations are also considered.

An energy analysis is conducted based on theoretical and estimated data for the furnace being built at United Silicon. The analysis shows that a considerable amount of the energy used in the process is lost as waste heat. Of an estimated 67,3MW supplied to the process, an estimated energy loss through the off-gas is around 34,3MW and only around 21,5MW can be found as chemical energy in the product.

Energy recovery equipment considered is heat recovery boilers for the off-gas. Recoverable energy was calculated to be around 27MW from the off-gas and three examples of possible industries are considered that could utilize steam produced from the waste energy. Estimated steam quantities that could be produced for the industries considered are calculated based on steam quality requirements of each industry.

The results show a decent amount of steam that can be produced for each process. Steam production from an energy recovery boiler could meet the thermal energy demand of a chlorine plant with the production capacity of 36.000 tons/year, a glycol plant with the production capacity of 30.000 tons/year and a urea fertilizer plant with a production capacity of up to 370.000 tons/year.

Other possibilities of heat recovery considered are from the cooling water. This waste energy has potential to be utilized for multiple low temperature purposes including greenhouses and fish farming. Another possibility for the cooling water is to use it to pre-heat the feed water to an energy recovery boiler to increase its efficiency.

Útdráttur

Markmið þessa verkefnis er að skoða varmaendurvinnslu og notkunarmöguleika frá kísilveri United Silicon sem er verið að reisa í Helguvík á Íslandi. Aðaláherslan er á gufuframleiðslu frá afgasinu en aðrir notkunarmöguleikar eru einnig skoðaðir.

Orkugreining er framkvæmd og byggist hún á fræðilegum og áætluðum gögnum fyrir ofninum sem verið er að reisa hjá United Silicon. Greiningin sýnir að töluvert magn orkunnar sem notuð er í framleiðslunni verður að varmatapi. Áætlað orkutap í afgasinu er um 34,3MW af þeim 67,3MW sem lagt er inn í framleiðsluna og aðeins um 21,5MW skilar sér sem efnaorka í framleiðsluafurðinni.

Varmaskiptar eru skoðaðir fyrir gufu framleiðslu frá afgasinu þar sem endurnýtanleg orka reiknast sem um 27MW frá afgasinu. Þrjú dæmi um mögulega iðnaði sem gætu nýtt varmaorkuna eru skoðuð og framleiðslugeta á gufu fyrir þá iðnaði áætluð út frá gæðaflokk gufunnar sem hver iðnaður krefst.

Niðurstöður sýna góða framleiðslugetu á gufu fyrir iðnaðina. Gufuframleiðsla frá orkutapinu gæti mætt eftirspurn á varmaorku fyrir klór verksmiðju með framleiðslugetu uppá 36.000 tonnum á ári, glýkól verksmiðju með framleiðslugetu uppá 30.000 tonnum á ári og urea áburðarverksmiðju með allt að 370.000 tonnum á ári í framleiðslugetu.

Aðrir nýtingarmöguleikar á varmatapinu eru frá kælivatninu. Þetta varmatap gæti verið nýtt í ýmsan iðnað sem þarfnast varmaorku með lágu hitastigi. Slíkir iðnaðir geta verið gróðurhús eða fiskeldi. Annar möguleiki væri að nota varmann í kælivatninu sem forhitara fyrir inntaksvatn í varmaskipti til þess að auka nýtni á honum.

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1 Introduction

In recent years Iceland has become a popular location for energy intensive industries because of its vast supply of clean, affordable energy. This allows Iceland to offer the most competitive electricity prices in Europe, resulting in a substantial advantage for industrial investors[1].

As the demand for energy rises with the increase in energy intensive industries in the country, it becomes more transparent that the resources are limited and need to be treated as such. In energy intensive industries, an immense amount of the energy used in the production processes is lost into the environment as waste heat. This waste heat, however, has much potential for further utilization.

One of the energy intensive industries starting operations in Iceland is a silicon metal plant that United Silicon is erecting. The plant is the first silicon metal plant in the country and is located in Helguvík, near Reykjanesbær[2].

During the production process of silicon metal, only around 32% of the energy used becomes chemical energy in the product. The remaining 68% of the energy is lost into the environment as waste heat [1]. The off-gas temperature from United Silicon is estimated to be around 450-500°C and the cooling water around 40°C. A substantial amount of energy can therefore be recovered from the process for further use.

The erection of the plant is divided into four phases, where one furnace is added during each phase. The production will start with one 32MW submergible electric arc furnace in phase one that is expected to produce around 22.000 tons/year of silicon. Production is scheduled to begin this summer of 2016 and it is estimated that around 60 employees will work at the facilities.

The objective of this study is to look at waste heat recovery from the silicon metal plant located in Helguvík, Iceland. The main focus is put on steam production from the off-gas but other utilizations are also considered. An energy analysis is conducted using theoretical and estimated data for the furnace to predict the recoverable energy. Industrial processes requiring thermal energy are also discussed and the potential steam production for such industries calculated. The study is conducted to determine the feasibility of energy recovery from United Silicon for the production of steam.

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[1] http://www.landsvirkjun.com/productsservices/energyproducts/data-centers/competitive-energy/
[2] https://www.fondel.com/en/fondel/press-en-news/fondel-participates-in-icelands-first-silicon-metal-plant

1

1.1 World Production and Price Trends of Silicon and Ferrosilicon

The production of silicon and ferrosilicon has been on the rise throughout the years as can be seen in figure 1-1. There, the combined production applies to silicon metal and ferrosilicon containing 50% and 75% silicon where the estimated world production is given in tons of silicon content [2].
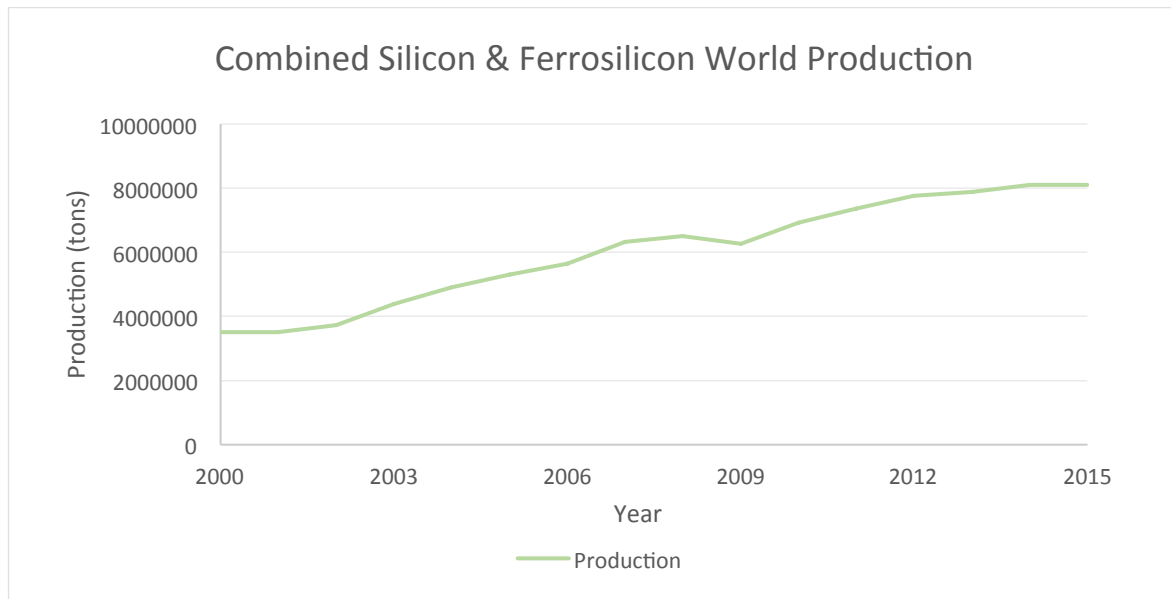
Figure 1-1: Combined world production of silicon and ferrosilicon
in metric tons silicon content [2]

In 2015 ferrosilicon accounted for 64% of the world production of silicon where the main producers were China, Russia, Norway and the United States, respectively [3]. There is one ferrosilicon plant located in Grundartangi, Iceland, that has been operational since 1979. The production capacity of this plant is 72.000 tons of ferrosilicon per year with a silicon content of 75%[3].

The main producers of silicon metal were China, the United States, Norway and France. Contributing around 68% of the estimated world production in 2015, China is the leading producer of silicon and ferrosilicon [3].

The price of silicon and ferrosilicon tends to fluctuate with demand changes in the ferrous foundry, chemical, steel and aluminum industry. Figure 1-2 shows the price fluctuations of silicon and ferrosilicon from 2004 to 2014 [4].

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[3] http://www.jarnblendi.is/um-elkem/sagan/
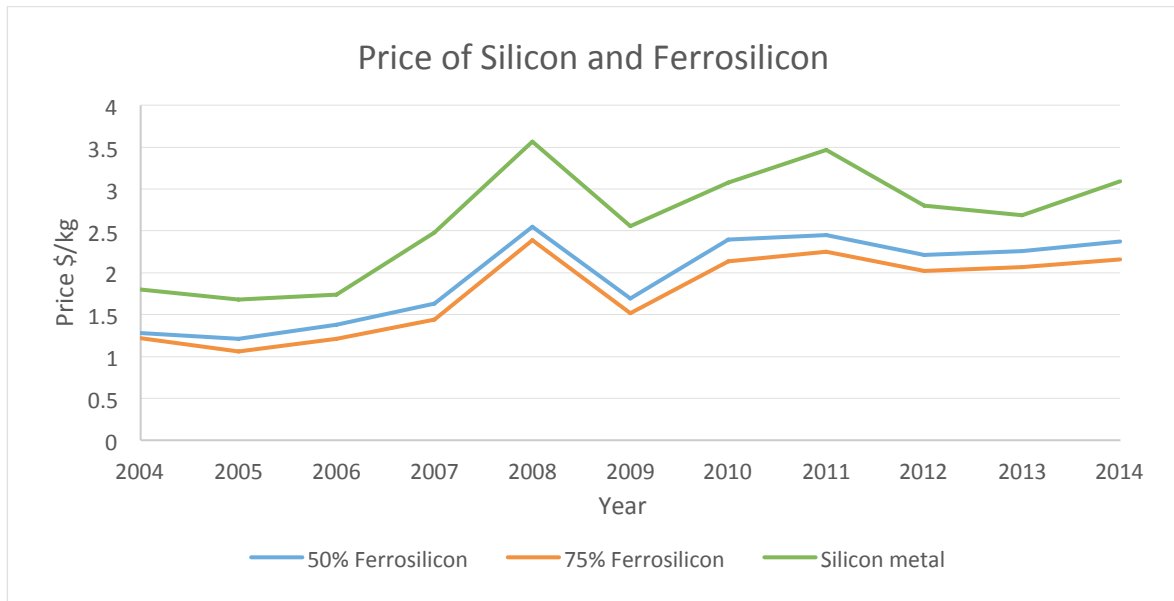
Figure 1-2: Average annual spot prices per kg of Silicon and Ferrosilicon [4]

In 2008, silicon prices were at an all-time average high but due to the global financial downturn that started in the third quarter of that year, silicon prices severely dropped in 2009. The prices fluctuated a lot in the following years as can be seen on the graph. However, since the beginning of 2015 they have been decreasing and the average silicon metal prices in February of this year were reported to be around 97,38 cents per pound or $2,14 per kg [4].

1.2 Use of Silicon Metal

The main uses of silicon metal are in alloying of other metals and as raw materials in the chemical industry. While ferrosilicon is usually used as an alloying element for steel, silicon metal is usually used as an alloying element for aluminum [1]. Reported consumption by end use of silicon metal in the United States in 2014 can be seen in figure 1-3 where the total consumption was 191.312 tons [4].

Consumption by end use of silicon metal in the U.S. in 2014

84.35%

14.76%

0.71%

0.15%

0.03%

■ Miscellaneous & Unspecified: Primarily silicones & other chemicals

■ Alloys: Primarily aluminium

■ Steel: Unspecified

■ Steel: Stainless & heat resisting

■ Superalloys
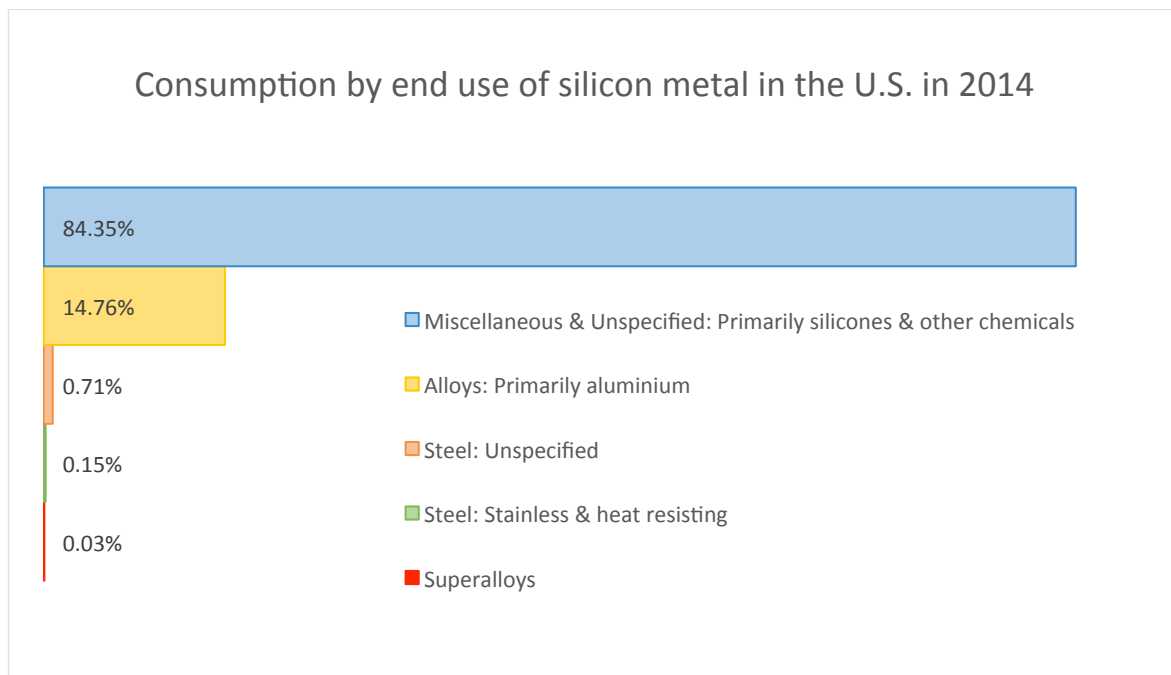
Figure 1-3: Reported consumption by end use for silicon metal in the U.S. in 2014 [4]

The largest application of silicon metal was in the production of chemicals such as silicones and silicates. Silicones are the primary products from the chemical industry and can be in the form of liquid oils, greases, rubbers and solid resins. Silicones are used as electric insulators, lubricants, protective coatings, hydraulic fluids and artificial body parts as they are chemically inert, water repellant and chemically stable and heat resistant up to 400°C [1].

Silicon metal can also be further purified to obtain pure silicon with a very low impurity range. Pure silicon is used as semiconductors in electronic devices and photovoltaic in solar cells.

2 Production Process of Silicon Metal

The production process of silicon metal consists of a number of steps and a silicon plant can be roughly divided into four fundamental groups [1]:

- Raw materials treatment and transportation system
- The furnace and the electrical supply system
- System for cleaning the waste gas and energy recovery
- Processing system for metal product

An illustration of the overall process at a typical silicon metal plant can be seen in figure 2-1.
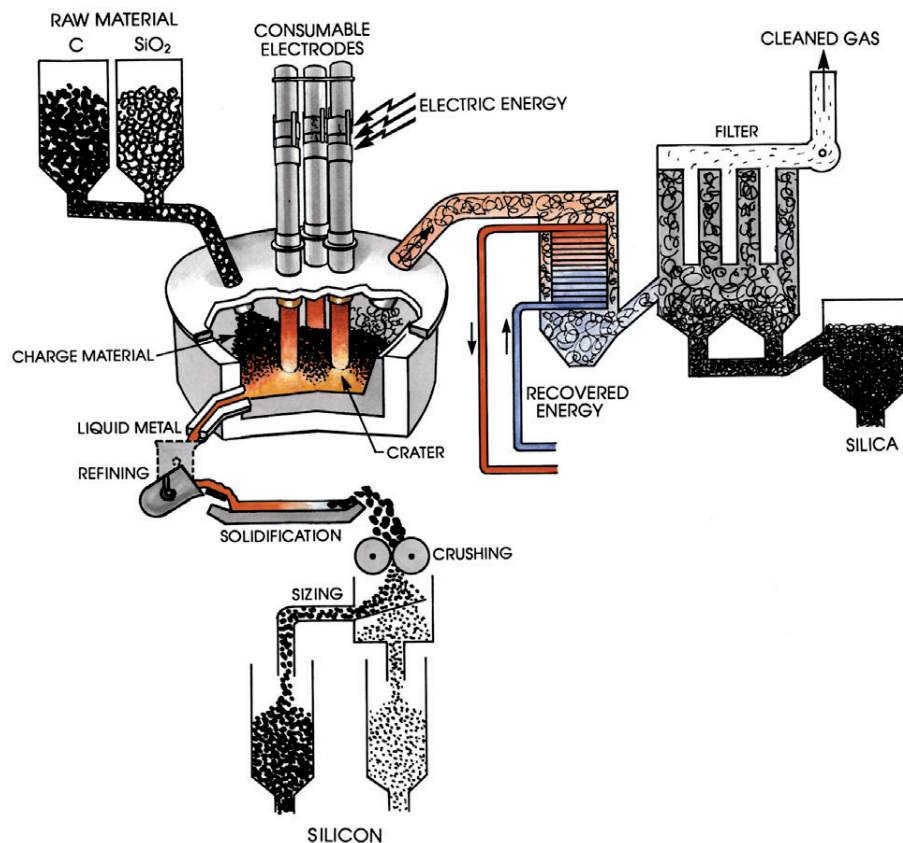
Figure 2-1: An overview of a typical silicon metal plant [1]

In the following chapters, the silicon metal production process is described in more detail.

2.1 Raw Materials

The raw materials used in the production of silicon metal consist of a silicon oxide source, reduction materials and a bulking agent like wood chips. Silicon oxide sources are either quartz or quartzite depending on the purity requirements of the silicon product. For the production of silicon metal, the purity requirements are high and therefore quartz is favored as a source of silicon oxide [1].

The reduction materials for the process are carbon materials like charcoal, coal and coke. These materials vary in reactivity with the silicon oxide and the quality of the reduction materials used in the process can affect the overall yield in the furnace.

The raw materials are shipped in bulk to the silicon metal plant either by road, rail or sea depending on its location [5]. United Silicon is located by a harbor and therefore ships will deliver the raw materials. After delivery they are stored in a storage facility where coarse materials are either stored in a bunker or open stockpile.

Raw materials are weighed and the correct blends of materials are placed into smaller storage bins. The material is transferred from the weighing system to the furnace by belt conveyors where feed bins containing the correct blends of materials are located above the furnace roof [5].

2.2 Furnace and Electrical Supply System

The electric arc furnace is the core of the silicon plant. For the production of silicon metal, an AC furnace is usually used with a diameter of around 10 meters [1]. Size is determined by the electricity consumption and the furnace at United Silicon will be 32MW.

The outer structure of the furnace is composed of a strong steel base and sidewalls that are welded together. To maintain a constant thickness and uniform heat in the hearth, the base of the structure is generally hollow so that it follows the refractory lining of the hearth [5]. The furnace at United Silicon can be seen in figure 2-2.

Figure 2-2: The furnace at United Silicon. (By permission of United Silicon hf.)

For better access to the entire perimeter of the furnace structure, it is placed on a rotating table that is able to rotate 360 degrees. The rotating table is compelled by a geared motor and rotates at the speed of around one to eight degrees per hour or 360 degrees in just over two days [5]. Figure 2-3 shows the rotating system for the furnace at United Silicon.

Figure 2-3: The rotating system for the furnace at United Silicon.
(By permission of United Silicon hf.)

The furnace roof and smoke hood are fixed to the building structure and do not rotate with the base and sidewalls. Furnaces for the production of silicon metal generally have a semi-closed structure where the fracture between the base and roof of the furnace allows the access of diluted air. During the smelting process, this diluted air mixes with CO; SiO_2 and SiO gas resulting in oxidization and the gas leaves the furnace through the smoke hood as CO_2 [5].

Feeding of raw materials is conducted at the top of the furnace where raw material blends are delivered to a specific area of the furnace by feed chutes. Other ports in the roof structure allow access for the electrodes to pass through and the off-gas. The construction of the roof consists of horizontal steel panels that are water-cooled and vertical smoke hood doors and panels. To protect the inside of the roof and smoke hood from combustion of the CO_2 gas, they are coated with a high temperature refractory castable [5].

The support system of the electrodes that pass through the furnace roof are also fixed to the building structure and do not rotate with the base and sidewalls. This allows the electrodes to evenly burn away silicon carbide produced in colder areas in the furnace as it rotates. Three electrodes deliver a three-phase current to the contents of the furnace, heating the charge to high temperatures that activate the reduction reaction [5].

The electrodes used for silicon metal production is usually a composite electrode where a new electrode is added to the top of the old electrode as it is consumed by the process [1]. An example of a composite electrode is the ELSA electrode that can be seen in figure 2-4 [6].
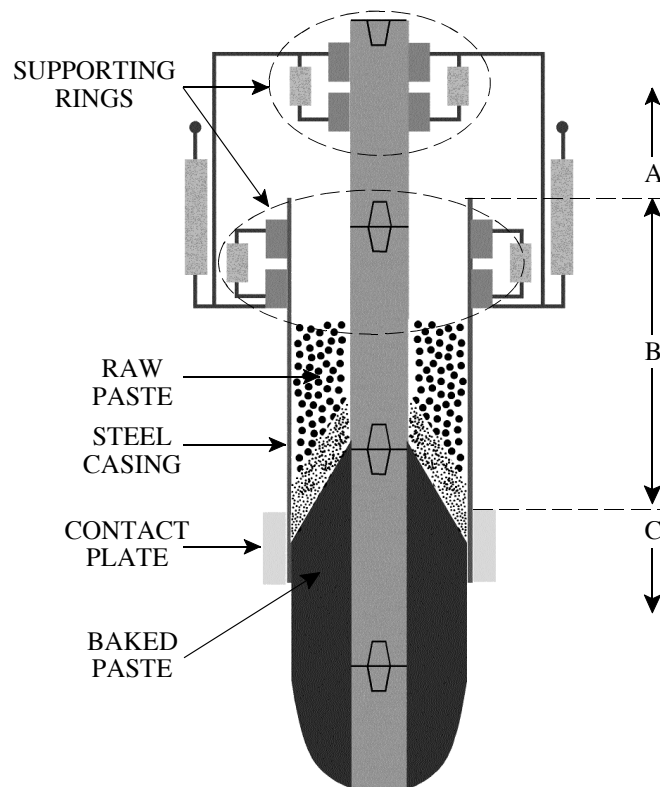
Figure 2-4: The ELSA electrode [6]

Electricity supply to the furnace is received as high voltage from the electric supply system. To meet the electricity requirements of the process, the voltage is transformed to a low voltage, high current electric source either by a three-phase step-down transformer or three single-phase step-down transformers. Non-magnetic stainless steel panels are located between the electrodes to prevent electromagnetic heating and insulation prevents stray currents from circulating on the roof of the furnace [5].

Tap holes are located on the sidewalls of the furnace and generally consist of carbon blocks. The furnace has multiple tap holes at consistent intervals that are opened with either a stinger or hydraulic drill and closed with a clay gun. The tapping process takes place approximately every two hours and can be batch operated or continuous [1]. At United Silicon the furnace has five tap holes and tapping will be continuous.

The molten silicon metal is tapped at a temperature of around 1600°C [7] into ladles that are attached to ladle carriages. The ladles are refractory lined and pre-heated before they are used in the tapping process. When the ladles have been filled, they are transported to a refining station for further processing.

2.3 Cleaning System for Waste Gas

As the gas leaves the furnace through the off-gas, it enters a cleaning system before being released into the environment. The gas leaves the furnace as CO_2 gas containing particles

of condensed silica fume (CSF). Before entering the bag filter plant, the gas is cooled in a radiant heat cooler [1]. If energy recovery is chosen, the energy recovery system is used to cool down the gas before entering the filter plant. At United Silicon the radiant heat cooler is equipped with a by-pass anticipated for an energy recovery system. The cooler can be seen in figure 2-5.

Figure 2-5: The radiant heat cooler at United Silicon. (By permission of United Silicon hf.)

In the bag filter plant the gas passes through a number of filter bags where particles are removed and cleaned gas is allowed to pass through. The gas is passed into the main induced draft fan and from there it is discharged into the clean gas stack [5].

The filters from the cleaning system are regularly cleaned where the dust is collected into bag filter hoppers and dislodged into the storage silo. The CSF dust is a by-product from the production process that can be used as a filler or addition to concrete, ceramics, refractory and rubber. For each ton of silicon metal produced, around 0,2-0,4 tons of CSF is produced [1].

2.4 Processing System for Metal Product

When the molten silicon metal has been tapped into ladles and moved to the refining station it is refined using oxygen. The purpose of refining the silicon metal is to lower the amount of impurities such as calcium and aluminum to meet the purity requirements for the silicon product.

The oxygen is introduced to the molten silicon through a nozzle at the bottom of the ladle. During the refining, samples are collected with a molten metal sampler to monitor the quality of the silicon. When the specific purity requirements have been met, the silicon is cast into suitable molds and cooled. Crushing and packing may be required in some cases after casting and cooling before transporting the final product to storage [1].

2.5 Chemistry of the Process

The industrial production of silicon metal is based on the carbothermal reaction where silicon dioxide is reduced by carbon. A simple chemical equation of the process can be written as [1]:

$$SiO_2(s) + 2C(s) \leftrightarrow Si(l) + 2CO(g) \tag{2.1}$$

Although equation 2.1 gives an idealized description of the overall chemical reaction, the actual chemical process is much more complex. A more detailed description of the reaction in the furnace can be written as [1]:

$$(1 + x)SiO_2 + (2 + x)C \leftrightarrow Si + xSiO + (2 + x)CO \tag{2.2}$$
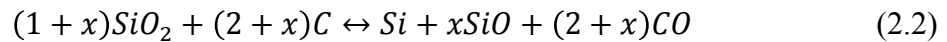
In equation 2.2 the notation x defines the silicon yield R, where [1]:

$$R = \frac{1}{1+x} \tag{2.3}$$

and therefore:

$$x = \frac{1-R}{R} \tag{2.4}$$

The furnace can be considered as two reaction zones, an outer pre-reaction zone and an inner main reaction zone. Each reaction zone always consists of several liquid or solid phases and one gas phase. The main silicon forming reactions take place in the inner zone where silicon dioxide reacts with silicon carbide to produce silicon, silicon oxide and carbon monoxide. Figure 2-6 shows a schematic of the process [1].
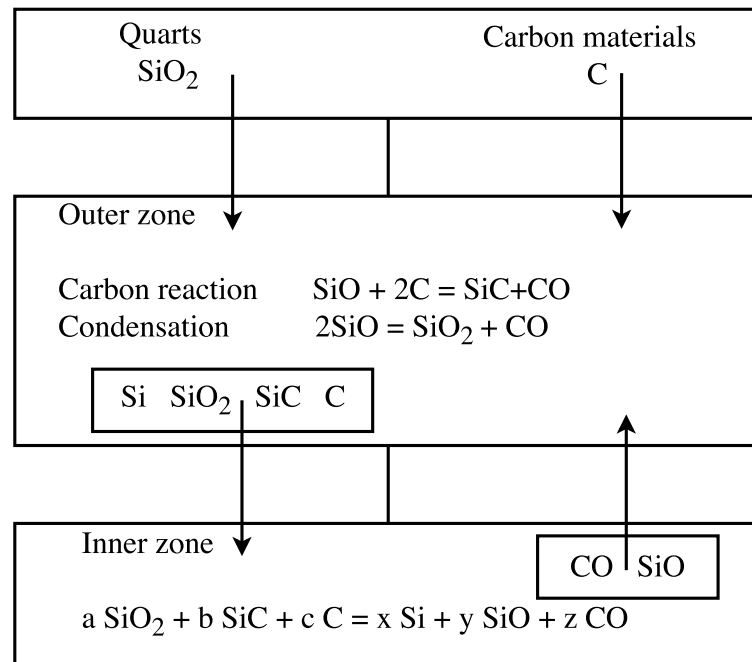
Figure 2-6: A schematic of the silicon process [1]

The silicon oxide and carbon monoxide gases produced in the inner zone proceed to the outer zone where most of the silicon is recovered. The recovered silicon is either in the form of silicon dioxide, liquid silicon or silicon carbide. Some silicon losses do occur with loss of silicon oxide gas to the off-gas [1].

3 Energy Analysis

To get an idea of the amount of waste energy from the furnace, an energy analysis is conducted using theoretical data as well as estimated data for the furnace being built. The energy analysis consists of a mass and energy balance for the furnace that is further discussed in the following chapters. The principle process flow can be seen in figure 3-1.

The principal process flow in production of silicon metal

Off-gas

Combustion

O_2, N_2

1400°C

Raw materials

Upper part of furnace

Heat exchange

25°C

1400°C

Si

Reduction

1600°C

Tapping

Solidification & cooling

Electric energy

Figure 3-1: The principal process flow in silicon metal production [1]

3.1 Energy into the Process

The energy going into the process consists of two main components, the electric energy and the chemical energy added with the raw materials [1]. Since the size of the furnace is determined by the electric power consumption, it is known that the electric energy added to the process is 32MW.

To obtain the amount of chemical energy added to the process, a material balance needs to be calculated. The predicted yearly production of silicon metal is around 22.000 tons and therefore the hourly production is assumed to be 2,5 tons with continuous production. The silicon yield from the furnace is assumed to be around 90%.

Different compositions of carbon materials give different amounts of energy to the process depending on the amount of fixed carbon and volatiles they contain. An example of carbon materials can be seen in table 3-1.

Table 3-1: Estimated carbon material compositions [1]

Type	Fixed Carbon (%)	Volatile (%)	Moisture (%)	Ash (%)	Energy content volatile* (kWh/kg)	Sulphur (%)
Coke	75	4	16	4	10,6	0,33
Coal	51	35	12	2	10,6	0,15
Charcoal	46	8	39	6	10,6	0,023
Woodchips	12	35	52	1	4,3	0,02

*Estimated values SINTEF

The carbon materials that will be used in this process will be coal, charcoal and woodchips. Examples of raw material mix orders can be seen in appendix A where 7 alternatives are given for the production of silicon metal with various product quality expectations. The carbon material distribution for this process is expected to consist of 10% charcoal, 40% coal and 50% woodchips. Table 3-2 shows an estimate of the amount of carbon materials used per hour for the production of 2,5 tons silicon metal.

Table 3-2: Estimated amount of carbon materials used per hour for the production of 2,5 tons silicon

Carbon Material	Quantity	Fixed Carbon	Volatiles
Coal	2,557 ton	1,304 ton	0,895 ton
Charcoal	0,639 ton	0,294 ton	0,051 ton
Woodchips	3,196 ton	0,384 ton	1,119 ton
Total:	6,392 ton	1,982 ton	2,065 ton

When the carbon material distribution has been established, the energy input from the fixed carbon and volatiles can be calculated. To calculate the energy input from the fixed carbon, equation 3.1 can be used [1].

$$Heat\ value\ of\ carbon = 393,505(x + 2)\frac{kJ}{mole}Si \qquad (3.1)$$

Where:

$$x = \frac{1-R}{R} \qquad (2.4)$$

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The silicon recovery from the process was assumed to be 90% which gives *R=0,9*. Solving for x using equation 2.4, we get *x=0,111*.

The heat value of carbon can then be calculated using equation 3.1, which gives a result of 830,689 kJ/mole Si. To convert the units from kJ/mole Si to MWh/MT Si, the following equation can be used [1]:

$$\frac{1000}{M_{Si} \cdot 3600} \cdot value \ in \ \frac{kJ}{mole} Si = value \ in \ \frac{MWh}{MT} Si \tag{3.2}$$

Here, M_{Si} is the atomic weight of silicon which is 28,09 g/mol and inserting the values into the equation gives:

$$\frac{1000}{28,09 \cdot 3600} \cdot 830,689 = 8,215 \frac{MWh}{MT} Si \tag{3.2}$$

Solving equation 3.2 gives 8,215MWh for one ton of silicon produced. The production is assumed to be 2,5 tons per hour and by multiplying the result we get 20,5375MWh, which is the energy into the process from fixed carbon.

The energy input from volatiles in the carbon materials can be estimated by using table 3-1. There, the energy content for volatiles are given in units of kWh/kg and can be multiplied by the amount of volatile material in each carbon source to obtain the energy amount. In table 3-2 the carbon materials were listed along with the amount used per hour and amount of fixed carbon and volatiles per hour for each material. Using these tables the energy content from volatiles can be calculated and are shown in table 3-3.

Table 3-3: Estimated energy content from volatiles per hour [1]

Carbon Material	Volatiles per hour (tons)	Energy Content (kWh/kg)	Energy Content per hour (kWh)
Coal	0,895	10,6	9487
Charcoal	0,051	10,6	540,6
Woodchips	1,119	4,3	4812
Total:	2,065		14840

The calculations show a total of 14,8MW energy input from volatiles in the carbon materials. An overview of all energy input into the process can be seen in table 3-4.

Table 3-4: Estimated energy input to the process [1]

Energy Type	Energy into the Process	Part
Electric Energy	32MW	48%
Chemical Energy Fixed Carbon	20,5MW	30%
Chemical Energy Volatiles	14,8MW	22%
Total:	67,3MW	100%

Calculations show that the overall energy input from the electric energy and the chemical energy is 67,3MW. This gives an estimate of the total energy input to the process when production at the plant begins.

3.2 Energy from the Process

The energy losses from the process occur in multiple locations on the furnace as well as electric energy losses from the transformers to the tip of the electrodes. Electric energy into the process is usually measured at the secondary transformers and around 16% of the electric energy is lost as a result of inductance and resistance before it reaches the tip of the electrodes [1].

Electric energy losses can be divided into different groups depending on the flow of the energy and where the energy is lost. In table 3-5 the energy losses from the electric system can be seen.

Table 3-5: Estimated energy losses from the electric system [1]

Electric Energy Loss in:	Losses (MW)	Percentage of Overall Electric Energy Input	Energy Lost As:
Transformers & Busbars	1,280	4%	Heat in cooling water
Smokehood, charging equipment etc.	0,960	3%	Heat in cooling water or steam in boiler
Electrode resistance	2,880	9%	Radiation to off-gas above charge & heating of raw materials
Total:	5,120	16%	

From an input of 32MW the losses in the electric system are around 5,1MW and the useful electric energy delivered to the process is therefore around 26,9MW or 84% of the total energy input.

Energy losses from silicon production vary between furnaces depending on their design and since operations have not started at United Silicon there have been no measurements on the furnace. In a theoretical furnace, energy losses due to heat loss from the furnace shell are estimated at around 5% of the electrical energy input. The main energy loss from the process is through the off-gas and only around 32% of the total energy input becomes chemical energy in the product [1]. Table 3-6 shows the estimated energy output from the production process.

Table 3-6: Estimated energy output from the process [1]

Energy Type	Energy from the Process	Part
Chemical Energy in Product	21,5MW	32%
Heat in Product	2,7MW	4%
Energy in Off-gas	34,3MW	51%
Energy in Cooling Water	5,4MW	8%
Radiation & Convection	3,4MW	5%
Total:	67,3MW	100%

A schematic of the energy balance can be seen in figure 3-2. Although this distribution of the energy balance is considered typical in silicon production, the framework may vary between furnaces.
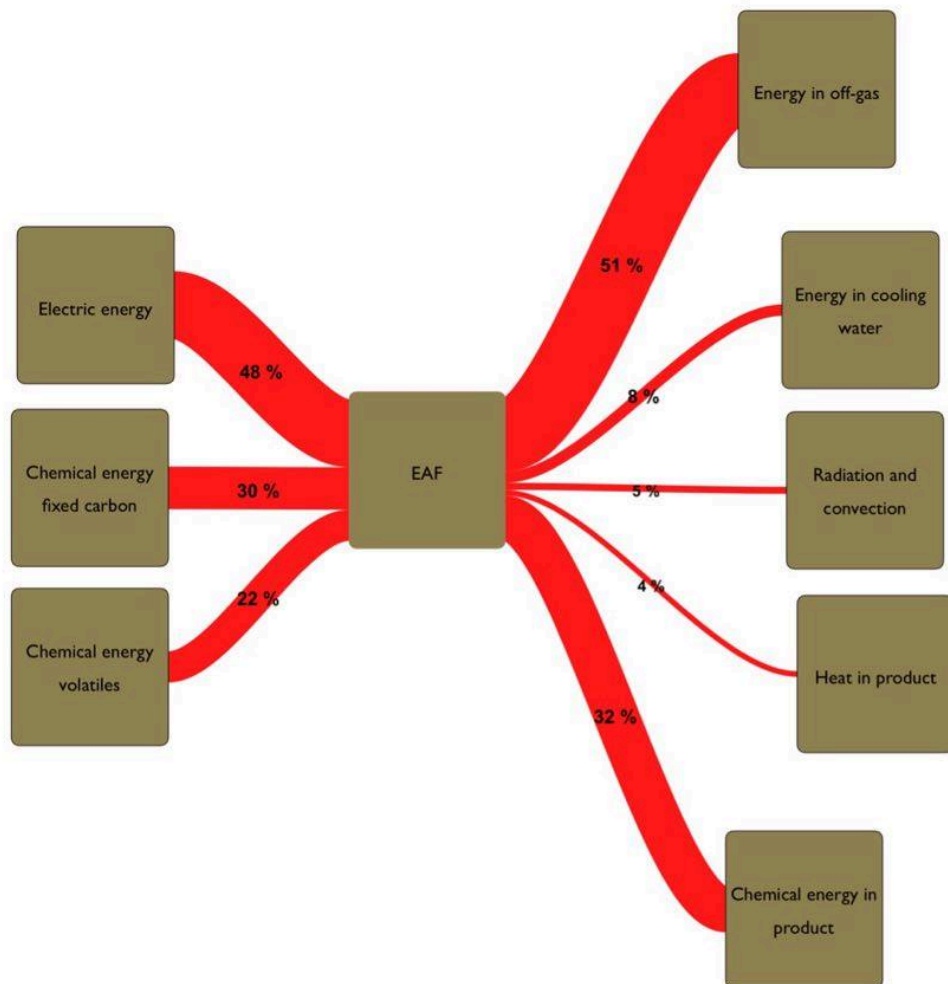

Figure 3-2: A schematic of the energy balance

4 Utilization

There are multiple possibilities in the utilization of the waste energy from the silicon production process. As seen in the previous calculations for the energy analysis, there is a vast amount of energy lost from the process as waste heat that ends up unused in the environment. The largest amount of energy is lost as heat to the off gas where around 34,3MW can be found but the easiest recoverable energy is in the cooling water.

With recovery methods, the waste energy can be a valuable by-product from the silicon plant. Possibilities for the utilization of waste energy could include steam production and electricity production from the off-gas and uses of the heat in the cooling water for numerous low temperature purposes. Due to affordable clean electricity in Iceland it is however not a feasible option for USi to produce electricity and therefore the focus is set on steam production.

4.1 Energy Recovery

The off-gas temperature from the furnace at USi is estimated to be around 450°C – 500°C after combustion and mixing with cool air and the off-gas flow is estimated to be around 250.000Nm^3/h. Since no measurements can be done at this time the density of the gas is assumed to be 1,3kg/Nm^3. This density was measure from a similar furnace at Elkem where ferrosilicon is produced [8]. Also, according to the same source, the off-gas is mainly composed of air and thus can be treated as such in calculations.

To recover the heat energy in the off gas a heat exchanger or boiler is used for the production of steam. For calculations on the heat load of the boiler the following equation can be used [9]:

$$\dot{Q}_{in} = \dot{m}_{gas} C_p \Delta T \tag{4.1}$$

Where $\dot{Q}_{in}$ is the heat load of the boiler, $\dot{m}_{gas}$ is the mass flow of the off-gas in kg/s, C_p is the gas specific heat (1,087 kJ/kg K at 477°C) and $\Delta T=T_1-T_2$ where T_1 and T_2 are the temperatures of the off-gas before and after the boiler.

The off-gas temperature can only be cooled down to a certain degree to avoid generation of sulfurous acid that can cause damage to the steel pipes due to corrosion. The acid dew point of the gas according to [1] is around 150°C but to be safe it is estimated that the gas would be cooled to approximately 200°C. An average of the estimated temperature for the off-gas is used in the calculations which is 475°C.

To calculate the heat load of the boiler, the mass flow of the off-gas must be in kg/s. Converting the estimated off-gas flow gives:

$$250.000\frac{Nm^3}{h} \cdot 1,3\frac{kg}{Nm^3} = 325.000\frac{kg}{h} = 90,28\frac{kg}{s} \tag{4.2}$$

Using equation 4.1 and the estimated data gathered then gives:

$$\dot{Q} = 90{,}28 \cdot 1{,}087(475 - 200) = 26.986{,}9 \text{ kJ/s} \tag{4.1}$$

The heat load of the boiler is therefore 26.987kW or around 27MW that can be used for the production of steam.

To determine the amount of steam produced from the boiler, the mass flow needs to be calculated. The amount of steam produced depends on the steam quality required and is contingent on the temperature and pressure. The mass flow of the steam from the boiler can be determined using the equation [9]:

$$\dot{m}_{steam} = \frac{\dot{Q}_{in}}{(h_2 - h_1)} \cdot \eta \tag{4.3}$$

Where $\dot{m}_{steam}$ is the mass flow of the steam from the boiler, $\dot{Q}_{in}$ is the heat load of the boiler, h_1 and h_2 are the enthalpies before and after the boiler and η is the efficiency of the boiler.

4.1.1 Energy Recovery Equipment

Waste heat recovery systems intended for steam generation are often referred to as heat recovery steam generators (HRSG) and can be of water tube or fire tube configurations. These types of boilers are commonly used for energy recovery from flu gas and are typically equipped with a gas bypass system to control the temperature of the gas exiting the system for further processing [10].

There are multiple aspects that need to be considered in the design of a waste heat boiler due to different working conditions depending on the process that the waste heat is recovered from. For recovery from a silicon plant, one of the most important considerations is the chemical composition of the flu gas. The off-gas from the silicon process contains both sulfur oxides, which is a corrosive gas that generates sulfuric acid if cooled below a certain temperature, and impurities that can cause intensive fouling problems.

The two different classifications of boilers refer to the fluid circulating inside the pipes of the system. In a water tube boiler, water flows inside the pipes while the flu gas is on the outside flowing across the pipes. In a fire tube boiler it is the opposite and the flu gas flows inside the pipes while the water is on the outside. Figure 4-1 shows the different configurations.
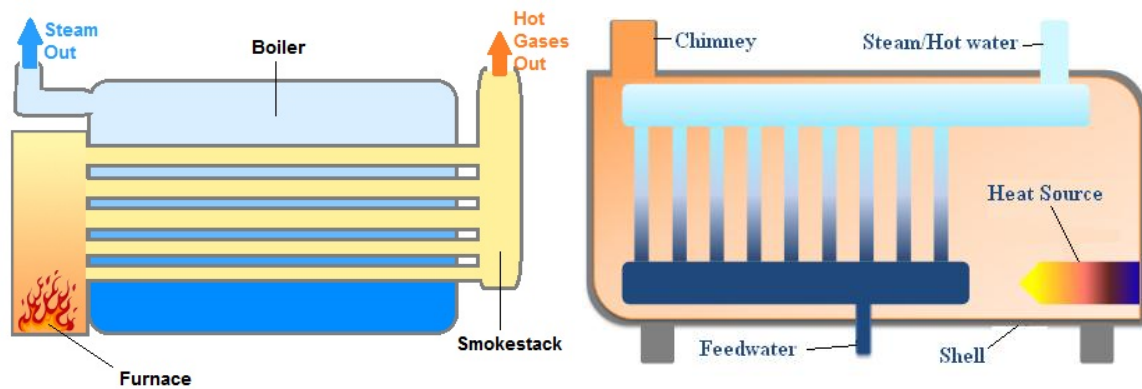
Figure 4-1: Fire tube[4] and water tube[5] boiler configurations

The fire tube configuration is limiting and does not allow for the production of high-pressure steam over 1,7MPa [8]. Since the flu gas flows inside the pipes, the heat transfer area is small compared to the water tube boiler, making them much larger in size and thus more costly. Another downside to the fire tube boiler is their large water delay in the shell making them slow in response to load changes and inconvenient if temperature swings occur. They can however handle high flu gas pressure [10].

Water tube boilers are smaller in size as they have a larger heat transfer area than the fire tube configuration. These boilers are suitable for the production of high-pressure steam with high temperatures and can handle flu gas with high flow rates. The water tube configuration usually consists of externally finned pipes that can be vertical or horizontal. Water in the pipes may have a natural or forced circulation and by having the water in the pipes, they do not have a large water delay like the fire tube configuration [11]. These boilers are the most frequently used when recovering energy from flu gas [8].

For energy recovery at United Silicon, the more feasible choice would be a water tube boiler as they offer production of higher quality steam. The design would need to meet certain requirements due to the off-gas composition. Some key design requirements can be seen in table 4-1.

Table 4-1: Some key design requirements for a waste heat boiler for the electric arc furnace

Required Features	Purpose
Cleaning System	To remove deposition of materials from heat transfer surfaces
Vertical water pipes	To reduce fouling (particles stick less to vertical pipes)
Adequate spacing between components	For inspection and cleaning

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[4] http://www.globalspec.com/learnmore/manufacturing_process_equipment/heat_transfer_equipment/steam_generators_boilers

[5] http://betterbricks.com/articles/boilers

Waste heat recovery boilers designed with approved standard technology for the electric arc furnace are available from Tenova. The system is called iRecovery[®] and is an evaporative cooling system equipped with some key features to insure the correct working conditions and a high yield of energy recovery [12].

The system is designed with a waste gas duct consisting of a tube-tube configuration where pressurized water at the boiling point circulates. Cooling of the gas is carried out through partial evaporation where around 5-12% of the circulating water is evaporated. This feature lowers the recirculation of water compared to standard cooling systems, thus reducing energy consumption of recirculation pumps and delivering a high-energy yield per mass unit [13].

Working pressures of the system range between 7 bar to 45 bar and can be adjusted according to steam pressure requirements. The steam-water mix is separated in a steam drum and the removed steam replaced with water that goes back into the circulation [12]. Figure 4-2 shows a simplified arrangement of the iRecovery system.
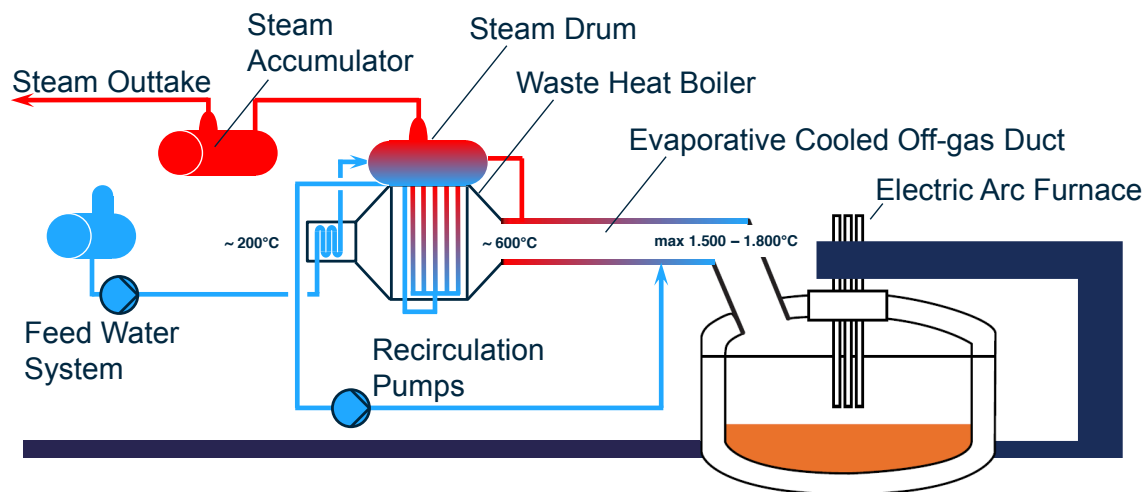
Figure 4-2: Simplified arrangement of the iRecovery system [13]

To remove material deposits from heat transfer surfaces, the system is equipped with a cleaning system consisting of a pneumatic rapping device that hits the header of each harp at adjusted force and frequencies. The material is collected into a hopper below where it is removed by a water-cooled chain conveyor [13].

Other features of the iRecovery system that bring additional advantages can be seen in table 4-2.

Table 4-2: Advantages of the iRecovery system [12]

iRecovery advantage	Issues dealt with
Elements maintain temperatures above sulfuric acid dew point	Eliminates corrosion problems
Temperature of elements are constant during all phases of operation	Thermal mechanical stress reduced
Closed loop circulation	Water consumption reduced
High heat transfer	Water flow volume reduced, smaller piping and pumps required and therefore maintenance cost reduced
Various excessive backup levels	Safety increased for different emergency situations

4.2 Industrial Processes Using Thermal Energy

There are multiple industrial processes that require steam for one or more steps in the overall process. These steam consuming steps may include digestion, evaporation hydrolysis, drying or distillation to name a few [14]. The location of such industrial plants is of much importance and varies between industries but a key factor is the distance to the steam source.

Since the Icelandic market is limited, large industries are more dependent on production of exportable commodities. As Helguvík is both close to a harbor and the international airport, it offers a good location for most industries relying on import of raw materials and exports of their products. There are a few properties available in Helguvík close to United Silicon that gives possibilities for steam consuming industries. An overview of the properties can be seen on Reykjanebær's website[6] where the closest available properties to United Silicon are around 400-500m away.

In the following subchapters, three examples of steam consuming industries that could possibly come to Helguvík are given along with a brief description of their production process. Calculations of an estimated amount of steam that United Silicon could produce for these industries are also considered.

4.2.1 Production of Chlorine

Chlorine is one of the main building blocks of the chemical industry and is produced through the electrolysis of salt brine. A co-product of chlorine is sodium hydroxide, also referred to as caustic soda, and with every ton of chlorine produced, around 1,1 ton of sodium hydroxide is produced. A by-product of the process is hydrogen and with every ton of chlorine produced, around 28kg of hydrogen is produced [15].

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[6] https://www.map.is/reykjanesbaer/

The largest consumption of chlorine is in the production of organic chemicals such as PVC and isocyanates. Sodium hydroxide applications include production of organic chemicals and inorganic chemicals such as pen tips, paints and ceramics. Figures 4-2 and 4-3 show the chlorine and sodium hydroxide applications for the EU and EFTA countries in 2012 [16].
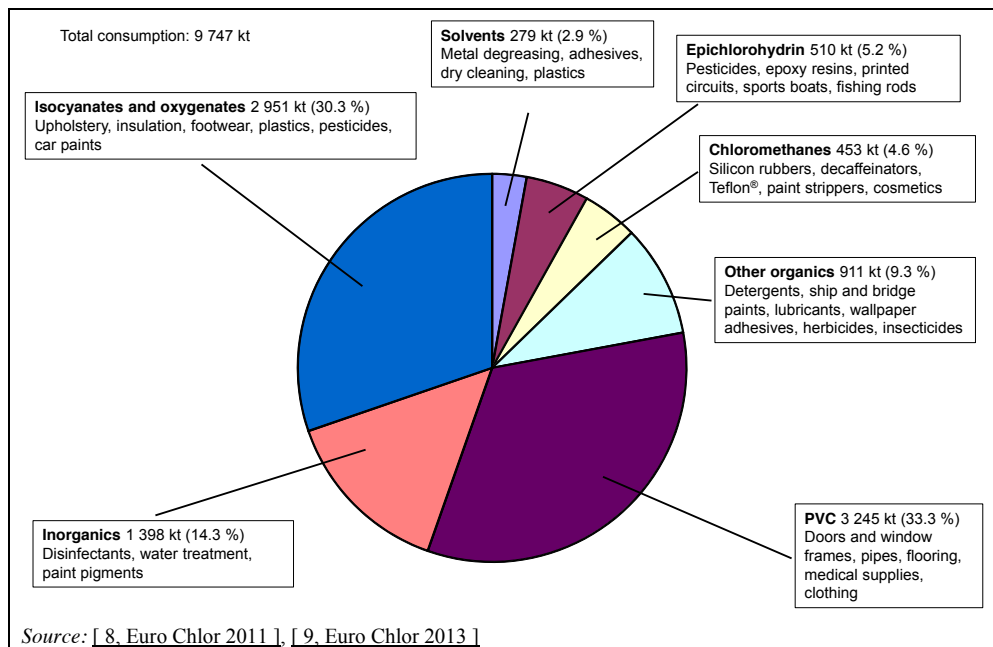

Figure 4-3: Chlorine applications in the EU and EFTA countries in 2012 [16]
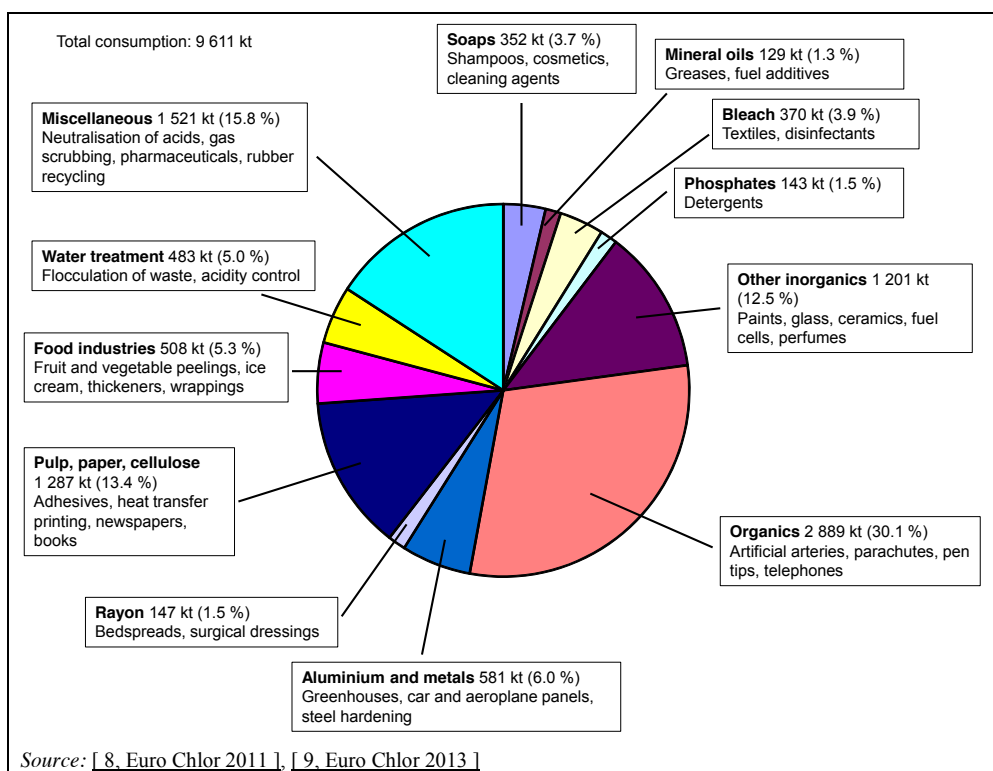

Figure 4-4: Sodium hydroxide applications in the EU and EFTA countries in 2012 [16]

There are three main methods used for the production of chlorine, the membrane technology, the mercury process and the diaphragm process [17]. Using the diaphragm process is the most steam consuming and therefore this method is assumed to be used if such an industry were to be set up in Helguvík to utilize steam from United Silicon.

The diaphragm technique was the first commercial process to be used in the production of chlorine and sodium hydroxide from salt brine. In a diaphragm cell, a diaphragm separates the chlorine at the anode from the hydrogen and sodium hydroxide at the cathode to prevent them from reacting and forming sodium hypochlorite. All reactions during the process take place within the cell [16].

Salt brine, used as raw material, is purified before entering the anode compartment of the cell. After entering the cell, it percolates through the diaphragm into the cathode compartment. High liquid level is maintained in the anode compartment with a controlled percolation rate establishing a carefully controlled, positive hydrostatic head. The liquor produced in the cell contains around 10-12wt-% NaOH and 15-17wt-% NaCl, where the NaOH solution is usually further purified by evaporation to obtain a more concentrated NaOH product [16]. A typical flow diagram of the process is shown in figure 4-5.
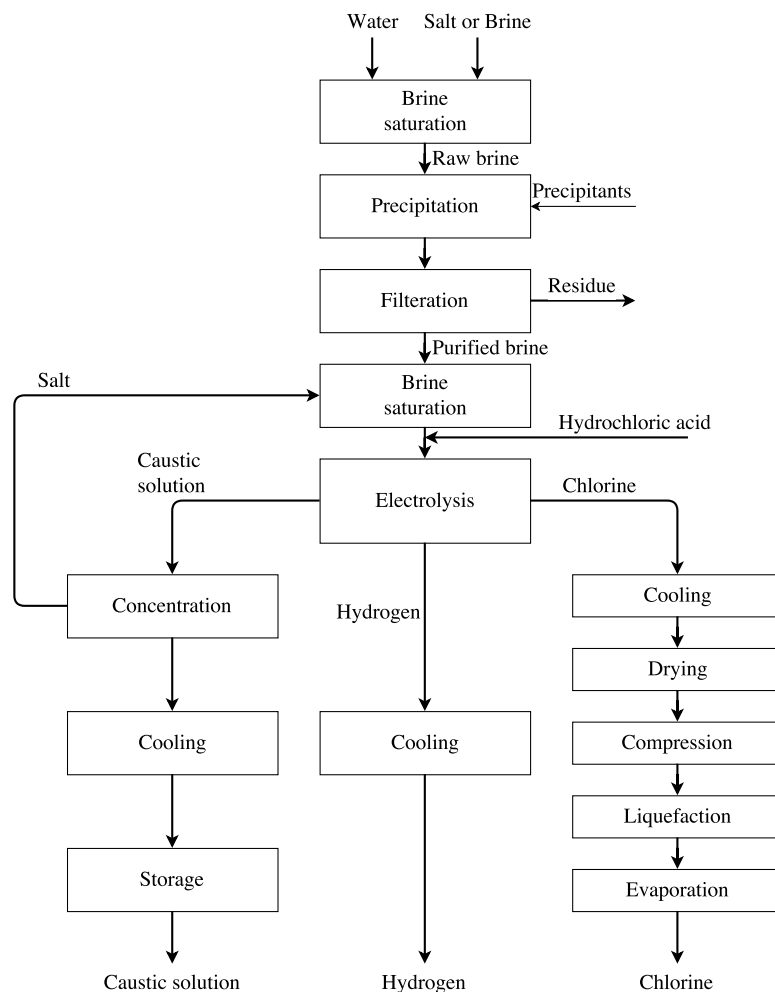
DIAPHRAGM CELL TECHNIQUE

Figure 4-5: A typical flow chart of the diaphragm process for chlor-alkali [16]

Raw materials used for the process are electricity, salt, sodium carbonate, sulfuric acid, steam and refrigeration [15]. The primary steam consumption is for evaporation of the sodium hydroxide to obtain a concentration of around 50 wt-%. Other uses of steam include preparation of the salt brine and chlorine evaporation. Table 4-3 shows an overview of the steam consumption of the process for chlor alkali plants in the EU and EFTA countries [16].

Table 4-3: Steam consumption of chlor-alkali plants in the EU and EFTA countries using the diaphragm method [16]

Process	Steam Consumption	Steam Temperature		Steam Pressure	
Preparation of salt brine	0,7-1,4 ton/ton salt			<5 bar	
Evaporation of sodium hydroxide	2,7-5,3 ton/ton Cl_2	Average: Median: Max:	245°C 285°C 300°C	Average: Median: Max:	15,3 bar 16 bar 25 bar
Evaporation of chlorine	0,1-0,8 ton/ton Cl_2	Average: Median:	208°C 190°C	Average: Median:	9,2 bar 8,8 bar

For a chlorine plant to be feasible it needs to have a production capacity of around 100-150 tons per day or 36.000-55.000 tons per year [15]. For the production of one ton of chlorine, it can be estimated that around 6 tons of steam is consumed where 20bar would be a reasonable pressure of the delivered steam to the plant. A chlorine plant with the production capacity of 100 ton per day would therefore consume around 600 ton of steam per day.

Using equation 4.3 the steam production from an energy recovery system at United Silicon can be estimated to determine if they could provide enough steam for this type of industry.

$$\dot{m}_{steam} = \frac{27000kW}{(2976,4-21,11)} \cdot 0,8 = 7,3 \frac{kg}{s} \tag{4.3}$$

For the production of steam with the temperature of 280°C and a pressure of 20 bar, assuming that the efficiency of the energy recovery system is 80% and the feed water into the system around 5°C, the steam production would be around 7,3 kg/s or around 630 ton per day. This would be enough to supply a chlorine plant with the production capacity of 100 ton per day.

4.2.2 Production of Glycol

Production of glycols in Helguvík has been planned by where Atlantic Green Chemicals (AGC) intended to produce ethylene and propylene glycols from glycerin [18]. Unable to acquire the property they initially requested, it is unknown whether the plant will be erected. There are however other properties available in Helguvík that could be suitable for this type of industry.

The production process is based on producing glycols from glycerin using steam and hydrogen and the technology is patented by the company Icelandic Process Development (IPD). Liquid products from the process consist of 87% propylene glycol, 11% ethylene

glycol and the remaining 3% are by-products of ethanol, n-propanol and methanol. In addition to the liquid products, a by-product of methane gas is also produced [19].

The process starts with pre-handling of the raw materials where glycerol, water and hydrogen are mixed before entering the reactor. In addition to the raw materials, alkali hydroxide is added in small quantities as a catalyst. After leaving the reactor, the gas and liquid products are separated for further processing [19]. A flow diagram of the process can be seen in figure 4-6.
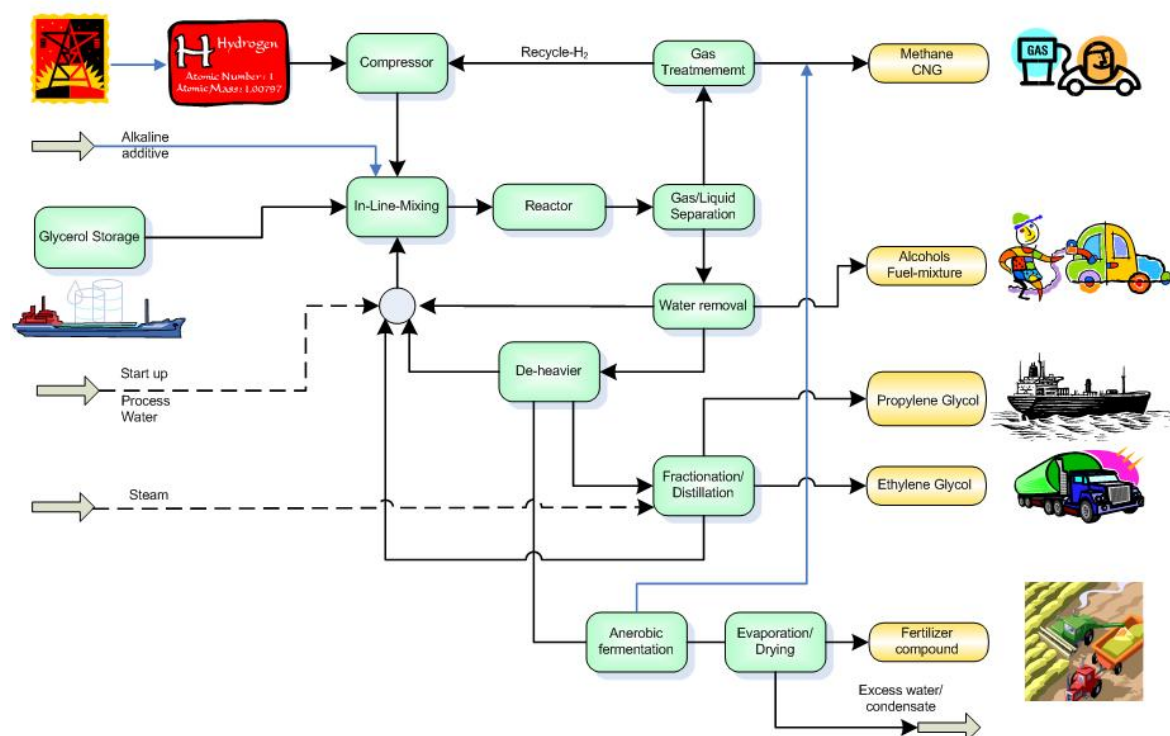
Figure 4-6: Flow diagram of the glycol production process [18]

Steam consumption for this process is around 4 tons for each ton of product produced at a pressure of 12 bar. Table 4-4 shows the estimated steam consumption per hour for different production capacities.

Table 4-4: Estimated steam consumption per hour for glycol plants [19]

Production Capacity of Plant	Steam Consumption
30000 ton/year	14 ton/hr
60000 ton/year	56 ton/hr
125000 ton/year	97 ton/hr

Using equation 4.3 the estimated amount of steam produced for this process at United Silicon can be calculated. Feed water for the energy recovery system is assumed to be 5°C

and the efficiency of the boiler 80% where the produced steam pressure is 12 bar at a temperature of around 188°C.

$$\dot{m}_{steam} = \frac{27000kW}{(2782,73-21,11)} \times 0,8 = 7,8kg/s \qquad (4.3)$$

An estimated production capacity of steam for this process would thus be around 7,8kg/s or 28 tons/hr. For a glycol plant with a production capacity of 30.000 tons/year this would be more than enough but the supplies would not keep up with the demand of a much larger plant.

4.2.3 Production of Fertilizers

World demand for easy to transport, high-analysis fertilizer has been steadily increasing in the past years and is expected to reach 200 million ton in 2019-2020 [20]. The most consumed nutrient for crop is nitrogen where urea is the most popular nitrogen fertilizer accounting for around 56% of the nitrogen world market. The main phosphate nutrient consumed as a fertilizer is ammonium phosphate while consumption of other phosphate fertilizers is relatively low in comparison[7].

In Iceland there are 14 companies listed that produce fertilizers where the main production is organic fertilizers and only 1 company produces an inorganic fertilizer. In 2015, 50.572 tons of fertilizer was imported into the country of which 11.649 tons was nitrogen, 1.719 tons phosphorus and 2.561 tons potassium [21].

A fertilizer plant in Iceland could be a feasible option, where a nitrogen fertilizer would be the best option of production based on import information for Iceland and world demand. The major straight fertilizer with 46% nitrogen content is urea[8]. Since it is the most popular nitrogen fertilizer, it is assumed that urea would be produced if a plant would be erected.

The raw materials used for the production of urea are liquid ammonia and carbon dioxide. A frequently used method for the production process is the ammonia stripping or Snamprogetti process. The production process can be divided into the following main operations [22].

- Urea synthesis and high-pressure recovery
- Urea purifications and low-pressure recovery
- Urea concentration
- Urea prilling
- Waste water treatment

Figure 4-7 shows a flow diagram of the urea production process using the snamprogetti method.

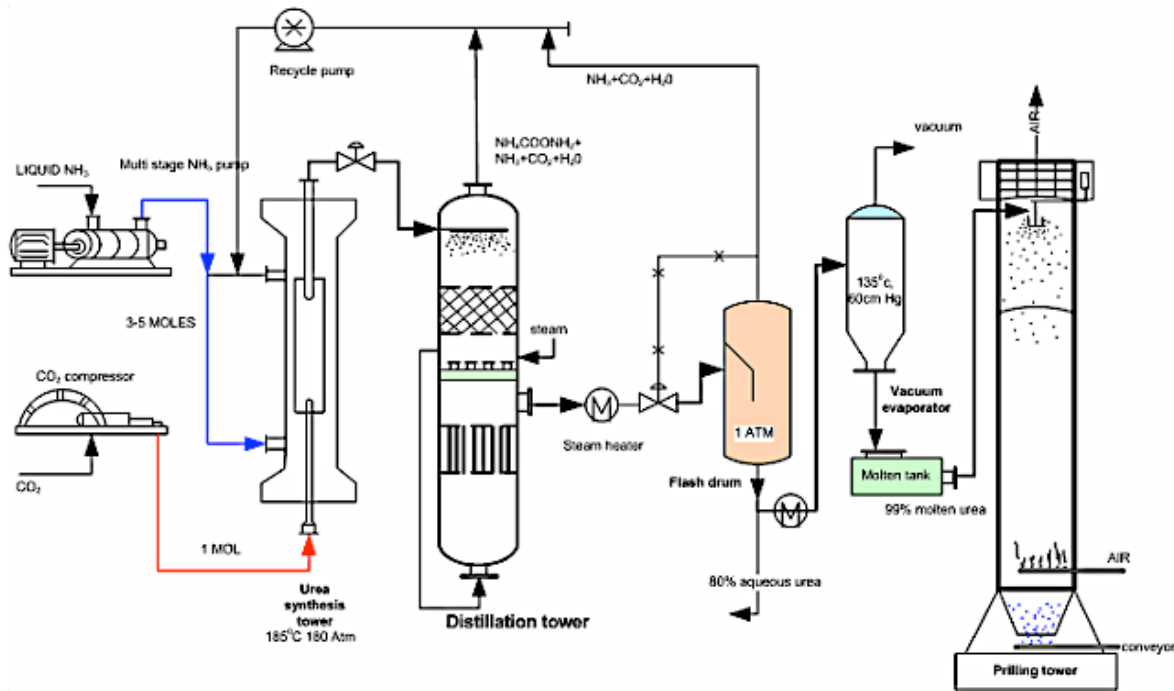
[7] http://www.fertilizer.org/
[8] http://www.fertilizer.org/

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Figure 4-7: Flow diagram of urea production process[9]

Steam consumption of the process varies depending on the steam quality used and whether prilling or granulation is the finishing process in the production. Table 4-5 shows the various steam consumptions for the different end processes and steam qualities[10].

Table 4-5: Steam consumption per ton urea produced

Steam Quality	Prilling	Granulation
110 bar, 510°C	840kg	810kg
23 bar, 220°C	620kg	620kg

In table 4-5 high-pressure steam is used when a CO_2 compressor is driven by a steam turbine and medium-pressure is used when a CO_2 compressor is driven by an electric motor.

The estimated amount of steam that could be produced for these processes at United Silicon can be calculated using equation 4.3. For steam quality of 110 bar and 510°C, assuming feed water is 5°C and 80% efficiency of the boiler, the quantity of steam produced is:

$$\dot{m}_{steam} = \frac{27000 kw}{(3387{,}67 - 21{,}11)} \cdot 0{,}8 = 6{,}4 kg/s \tag{4.3}$$

For steam quality of 23 bar and 220°C, using the same assumptions as before, the quantity of the steam produced is:

[9] http://dramarnathgiri.blogspot.is/2015/08/flow-diagram-of-urea-production-process.html?view=magazine
[10] http://www.saipem.com/static/documents/spm_UREAri_L02_14_01_10.pdf

$$\dot{m}_{steam} = \frac{27000kw}{(2795,32-21,11)} \times 0,8 = 7,8kg/s \qquad (4.3)$$

Therefore, a demand of around 23 tons/hr of high-pressure steam or 28 tons/hr of medium-pressure steam could be met. Table 4-6 shows estimated production capacities for the different steam qualities and end methods that United Silicon could supply steam for.

Table 4-6: Estimated production capacities of urea per hour that United Silicon could supply steam for

Steam Quality	Prilling	Granulation
110 bar, 510°C	27,4 ton/hr	28,4 ton/hr
23 bar, 220°C	45,3 ton/hr	45,3 ton/hr

The largest production capacity would be obtained using the lower pressure steam for both the prilling and granulation end process. If such a plant were assumed to be operational for 8.300 hours a year, the estimated production capacity would be around 376.000 tons a year. Using the higher-pressure steam, a plant could have an estimated production capacity of 227.500 tons a year if the prilling process were used or 235.500 tons if the granulation process were used, assuming the same operational hours as before.

Based on the imported nitrogen fertilizer to Iceland in 2015, the countries demand for the product is around 12.000 tons. Large amounts of the production would thus need to be exported making Helguvík a convenient location for this type of industry. A fertilizer plant would also need to be supplied with electrical energy, as their process is very energy intensive.

4.3 Other Utilization

Other possibilities of utilizing waste energy from United Silicon would be to utilize the waste heat from the cooling water. After cooling, the temperature of the cooling water leaving the process is around 40°C. This source of energy could be used for multiple low temperature purposes such as greenhouses or fish farming.

For greenhouses, the temperature intake is determined by the requirements of the crops being grown. Water supplied to greenhouses vary in temperatures between 40-100°C and is distributed in pipes that can be placed under the soil, on the soil or on benches [23]. Utilizing the cooling water from United Silicon could be feasible for certain greenhouses requiring a low temperature intake of around 40°C.

Fish farming in Iceland has been increasing rapidly since 2002 and there are around 70 working farms around the country. Around 15-20 fish farms are using geothermal water for heating where the intake temperature is around 20-50°C. Typically, the geothermal water is used to heat up fresh water from about 5-12°C in heat exchangers to reach the optimum temperature for the fish [24].

Utilization of the cooling water from United Silicon for fish farming could be very promising. The temperature is very suitable and the location could offer either in-land fish farming or sea cage farming. It is likely that the water could be used directly into the farming by mixing with seawater since it is fresh ground water.

Another option for utilization of the cooling water would be to combine it with the steam production. The cooling system could be used as a pre heater for the waste heat boiler and therefore the temperature of the feed water into the boiler would increase from around 5°C to around 40°C. These assumptions are based on an estimated feed water intake of 5°C for a boiler. This would increase the steam production making it more efficient.

5 Conclusion

United Silicon is erecting a silicon metal plant in Helguvík where they will be producing metallurgical grade silicon with a by-product of condensed silica fume. During the production process, an immense amount of energy is lost as waste heat that offers potential for the third product.

The main objective of this project was to consider waste heat recovery from United Silicon and possible utilizations. Theoretical and estimated data was used to conduct an energy analysis for the furnace to get an idea of the amount of energy lost from the process. The analysis shows that the total energy into the process is around 67,3MW and around half of the input energy is lost in the off-gas, or around 34,3MW with an estimated temperature of 450°C-500°C.

Energy recovery from the off-gas was mainly considered where the emphasis was put on steam generation. Due to low electricity prices in Iceland and higher efficiency when producing steam rather than electricity, this option was considered more feasible.

Energy recovery systems were considered where the two types of boiler configurations typically used for energy recovery were compared. The water tube boiler was considered to be more suitable as it offers steam production of higher quality than a fire tube boiler. A boiler configuration designed with approved technology for energy recovery from the electric arc furnace is available from Tenova.

The heat load of a boiler was calculated to be around 27MW where the production capacity of steam is dependent on the steam quality required. Utilization possibilities were considered for three industries requiring thermal energy for their processes. Calculations show that the estimated amount of steam produced would be able to supply thermal energy for a 36.000 ton/year chlorine plant, a 30.000 ton/year glycol plant and a urea fertilizer plant with production capacity up to 370.000 ton/year depending on end processes used.

This shows that the supply of steam produced from energy recovery at United Silicon could meet the demand of decently sized industrial plants requiring thermal energy for their process.

Other utilization possibilities from United Silicon include use of the waste energy from the cooling water. The energy loss in the cooling water was calculated to be around 5,4MW where the temperature is estimated to be around 40°C. Possible utilizations include low temperature purposes like fish farming and greenhouses. It could however be more feasible to use this energy source as a pre-heater of feed water for a boiler recovering energy from the off-gas.

Recoverable energy was based on one 32MW furnace but when the erection of the silicon plant is complete there will be four working furnaces. Therefore, when the plant is fully erected and all furnaces operational the production capacity of steam can be fourfold.

The furnace roof is not insulated and therefore there is potential to increase the temperature of the off-gas. With insulation the temperature could be increased to around 550°C-600°C resulting in more recoverable energy.

For energy recovery at United Silicon to be feasible, customers for the steam produced would have to be found. If industries requiring decent amounts of thermal energy would set up in Helguvík, energy recovery from United Silicon would be a feasible option as it offers great potential.

5.1 Further Studies

Before setting up an energy recovery system at United Silicon, an economic analysis would need to be conducted to make the final determination on the feasibility. The price of steam was not considered in this study as well as the price of the energy recovery equipment. These would all have to be considered if an energy recovery system is to be set up to determine the payback period.

Other studies that could be considered are more precise estimations on the waste heat recovery from the process. When the production has started, measurements could be taken from the furnace to obtain more accurate data for the calculations. This would give a more accurate result on the amount of recoverable energy and production capacity of steam.

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Appendix A

MIX ORDERS	Alt. 1 kg/t	Alt. 2 kg/t	Alt. 3 kg/t	Alt. 4 kg/t	Alt. 5 kg/t	Alt. 6 kg/t	Alt. 7 kg/t
Quarz	2,479	2,473	2,585	2,474	2,473	2,530	2,531
Charcoal (I)	931	–	456	466	186	369	184
Charcoal (II)	–	1,160	–	581	930	460	805
Low ash coal	–	–	435	–	–	–	–
Petrol coke	–	–	190	–	–	193	97
Wood chips	751	750	1,150	735	735	939	940
TOTAL WEIGHT	4,161	4,383	4,816	4,256	4,324	4,491	4,557

EXPECTED PRODUCT QUALITY

Target								
Si 99.0 min	99.35 – 99.13	99.14 – 99.02	99.18 – 99.01	99.25 – 99.08	99.18 – 99.04	99.26 – 99.09	99.20 – 99.06
Fe 0.21 max	0.13 – 0.25	0.13 – 0.19	0.27 – 0.35	0.13 – 0.22	0.13 – 0.20	0.17 – 0.25	0.15 – 0.22
Al 0.15 max	0.11 – 0.16	0.11 – 0.16	0.24 – 0.3	0.11 – 0.16	0.11 – 0.16	0.12 – 0.17	0.12 – 0.17
Ca 0.14 max	0.06 – 0.10	0.06 – 0.08	0.08 – 0.11	0.06 – 0.09	0.06 – 0.09	0.07 – 0.10	0.06 – 0.09