ENERGY BALANCE OF A 45 MW (FERRO-) SILICON SUBMERGED ARC FURNACE

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ABSTRACT

As a part of the FUME research programme that is being done by the Norwegian Ferroalloy Research Association (FFF), the SINTEF Group and NTNU (Norwegian University of Science and Technology), an energy balance for a 45 MW (ferro-) silicon submerged arc furnace have been made. The energy content and dynamics in and out of the process have been measured. New and improved equipment for flow and temperature measurement of cooling water has been utilized to increase the accuracy of the calculations of energy losses to the furnace equipment. The results from the energy balance visualize the energy potential in the different material flows. In addition, the paper presents how surplus energy from the Elkem Salten plant is being used.

1 INTRODUCTION

According to the "International Energy Outlook" for 2009 by the EIA [1] the total marketed energy consumption in the world will grow by 44 % from 2006 to 2030. This growth is predicted to occur first in non-OECD countries. Even though there is an expected increase in the use of renewable energy, coal and natural gas are still assumed to fuel nearly two thirds of the world's electric generation in 2030.

This increase in the demand for energy will stimulate research on and the realization of energy production based on renewable energy, but the utilization of the existing potential in high and low quality energy will become an important part of future energy production.

The global resources of fossil fuels are limited and therefore production of clean or CO2-free energy will have important financial benefits for users. In addition, there are the environmental consequences if the new energy production replaces energy produced from coal or natural gas.

Looking at the ferroalloy industry there are two main potential sources for energy recovery, an off-gas with a high temperature that is suitable for electric energy production and the considerable amounts of cooling water that represent potential thermal energy
A study done in 2002 [2] summed the consumption of electric energy in the Norwegian ferroalloy industry (including silicon metal) at approximately 7700 GWh/year, excluding energy in reduction materials. From this the potential for energy recovery is calculated to be in the area of 1310 GWh/year, or approximately 17 % of the total electric energy consumption.
The study states that realizing this potential in recycled energy would decrease CO_2 emissions by about 460 000 tonnes/year if it replaced natural gas or 1 010 000 tonnes if it replaced coal as the energy source.

2 THE (FE)SI PROCESS

A simple sketch of the (ferro) silicon process is given in Figure 1. The sketch shows a (ferro) silicon furnace surrounded by raw material silos, electric connection, off-gas removal system and equipment for energy recovery, tapping, casting and crushing.

The furnace consists of steel casing walls, covered on the inside by a refractory material capable of withstanding both high temperatures and chemical attacks. The bottom of the furnace is usually made of carbon lining.
The furnace is filled with raw materials which act as a source for Si and C. The raw materials are added to the furnace at the top, fed directly to the furnace surface by charging tubes, often placed symmetrically around the electrodes.

The process itself is cyclic. The raw materials are consumed in the bottom of the furnace where silicon production occurs, creating an open space around the electrode tips, called a crater. The already charged raw materials will drop into the crater after a while and this creates a sink in the furnace top, which now has to be refilled with new raw materials. This cycle runs unattended most of the time. At infrequent intervals, the furnace operator has to manipulate the furnace surface to either achieve a better sink or to stop process gas escaping from "blowholes" through the burden.

Above the furnace a hood collects all the off-gases from the process. The process within the crater of the charge creates mainly two gases, SiO and CO, which both burn with O_2 from air at the top of the furnace creating amorphous SiO_2 (also called fume silica) and CO_2.
The off-gas is now filtered through bag house filters and the condensed fume silica is collected.
The remaining gas components such as CO_2, SO_2 and NOx, are released to the air.

Since the off-gas escapes from the furnace at a high temperature it is ideal for energy recovery by using a combined heat and power system. This consists of a steam cycle for electric energy recovery and a water cycle for latent heat recovery. The temperature of the off-gas from the furnace is controlled by the amount of excess air that is mixed with the process gas.

The silicon process is a high energy process, requiring temperature above 1800 °C. These temperatures are obtained by large amounts of electric energy, fed to the furnace through 3 electrodes deeply submerged in the charge mix. The arc that burns on the tip of each electrode will create a crater where the Si-producing reaction occurs. From this crater a flow of SiO and CO-gas goes upwards through the raw material mix, where most of the SiO-gas will either react with C to form SiC or condense to Si + SiO_2, the latter reaction releasing heat which acts as a preheating of the new raw materials. Some of the SiO-gas will reach the furnace top, reacting with the O_2 in the air to amorphous SiO_2, going to the bag house filters. The CO-gas flows to the surface of the furnace and reacts with O_2 to CO_2.

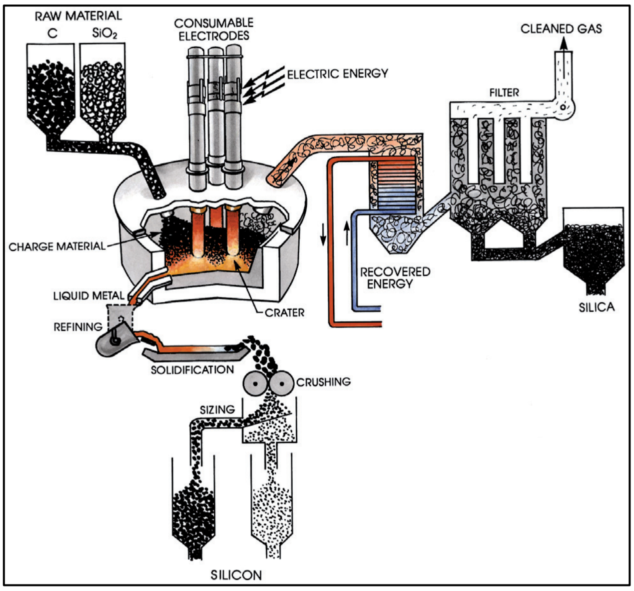

Figure 1: Principle sketch of the (Fe)Si process. From "Production of Silicon Alloy", Schei et al. (1998) [3].

Tapping of the furnace is done through tap holes located at the bottom of the furnace and tapping is done through one hole at a time. The furnace can have several tap holes. As some furnaces rotate,

the operators are given the opportunity to switch between tap holes, leaving the unused for maintenance.
The metal is often tapped into ladles where it may undergo some form of refining before casting. After casting and cooling, the metal is transported to crushing, screening and packing before it is shipped out to customers.

3 CASE STUDY – ELKEM SALTEN PLANT

Location

Elkem Salten is located in the Sørfold municipality in the north of Norway, roughly 100 km north of the Arctic Circle and 80 km east of the city of Bodø.

History

Construction of the plant began in the mid-1960s and the first electric smelting furnace came into operation in 1967. Three years later a second furnace was added, and in 1972 the third and largest furnace began producing ferrosilicon. In the last few decades the plant has developed from being a pure FeSi75% producer to now being specialized in higher silicon alloy production.
Elkem Salten has three furnaces with a total installed furnace capacity of approximately 120 MW. All three furnaces are Elkem design furnaces with Søderberg electrode technology. The main products from the plant are high silicon alloys and silica fume products (Microsilica®).

Energy balance

In April 2009, SINTEF, Norsk Elektro Optikk, MOLAB and plant resources conducted a measurement campaign on one of Elkem Salten's furnaces. This included a mass balance for materials and off-gas, as well as data collection from the cooling water system to give a basis for a complete energy balance of the furnace.

Improvements in measuring energy captured in cooling water

The investigation after an accident at one of Elkem's plants in 2006 [4] concluded that one of the root causes of the accident was cooling water leaking into the furnace over a period of time, in the end causing a violent explosion. This led to the action that all furnaces in the Elkem Silicon division had to install a surveillance system on the cooling water flow, focusing on getting a total overview for equipment located closest to the furnace centre.
The system installed at Elkem Salten is an inline measurement of flow and temperature with equipment from Endress & Hauser [5]. It presents water flow (in litres per second) and temperature for the electrode equipment, some centre-water courses on the smoke hood and charging tubes, as well as courses in the chimney located close to the furnace surface.

Energy balance for the furnace

To present the energy balance for the furnace we have drawn Sankey diagrams. The diagram for the furnace as it operates today is shown in Figure 2. The details are given refer to a furnace with 10 MW electric load. The off-gases are cooled by letting in extra air at the furnace top and then sending this to the bag house filters.

We note that the energy content in raw materials slightly exceeds the electric energy input. We also see that the amount of energy captured in the cooling water system is approximately 28 % of the electric input. With no energy recovery system installed, all the energy in the off-gas is released to air by letting in cold outside air at the furnace top and the energy contained in the cooling water is only partly used for district heating.

To investigate the potential for an energy recovery system at this furnace we use numbers reported in [6] and calculate the new energy flows.
The Sankey diagram for the same furnace with an energy recovery system is shown in Figure 3. Once again we show the data referred to as for a 10 MW furnace.

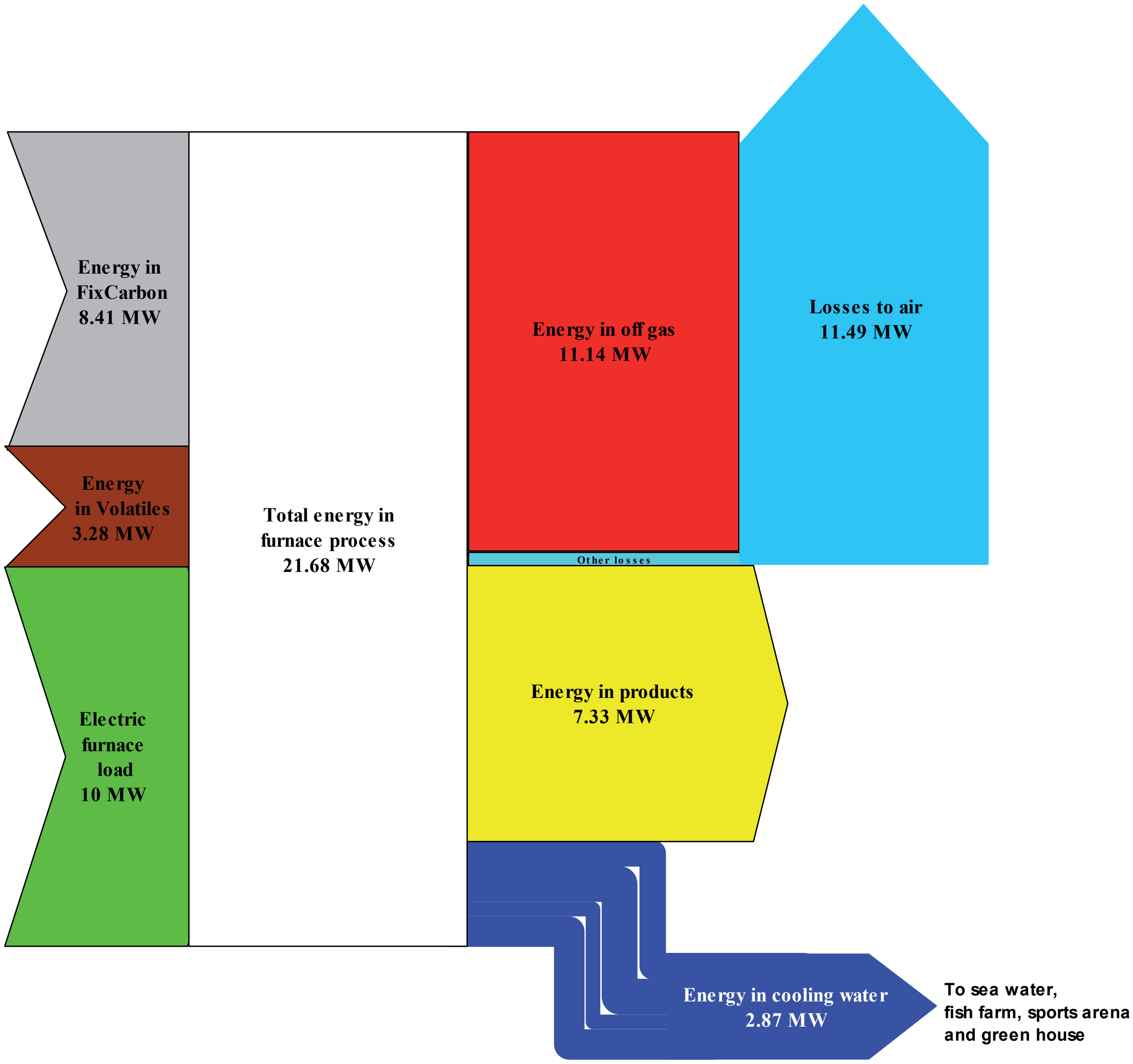

Figure 2: Sankey diagram for the Salten furnace

The Sankey diagram in Figure 3 returns the recovered energy back to the furnace, but an option could of course be to deliver this energy to external users. As we see from the diagram approximately 20 % of the furnace electric load could be recovered, but installing an energy recovery system also adds an additional source for thermal energy, the cooling water from the turbine and generator. This new thermal energy source together with the already described furnace cooling water adds up to 91.3 % of the electric furnace load input.

To increase the energy recovery the most important parameters are:

- the energy in the off-gas is proportional to the furnace load - and increased furnace size may have a relative lower loss of energy pr unit size
- the other most important parameter is the amount of volatiles in the raw materials - increased usage of coal and wood-chips gives higher energy in the off-gas compared to the use of coke and charcoal as the carbon source
- high off gas temperature will lower the energy in the off-gas after boiler and allow higher steam temperature and pressure that improves the efficiency of the boiler and turbine system
- good access to cold cooling water will allow lower condensator pressure that also is important to the energy recovery

However, the recovery of electric energy will require a partial redesign of the furnace exhaust gas handling system which includes a flue gas heat exchanger, evaporator and superheater, steam turbine, generator and cooling system. The financial implications of this will not be discussed here. An alternative system where primarily hot water is produced could also be of interest, assuming there are available customers for the hot water. For both systems more work is needed to verify a technological and financial evaluation and to investigate the potential in the use of energy.

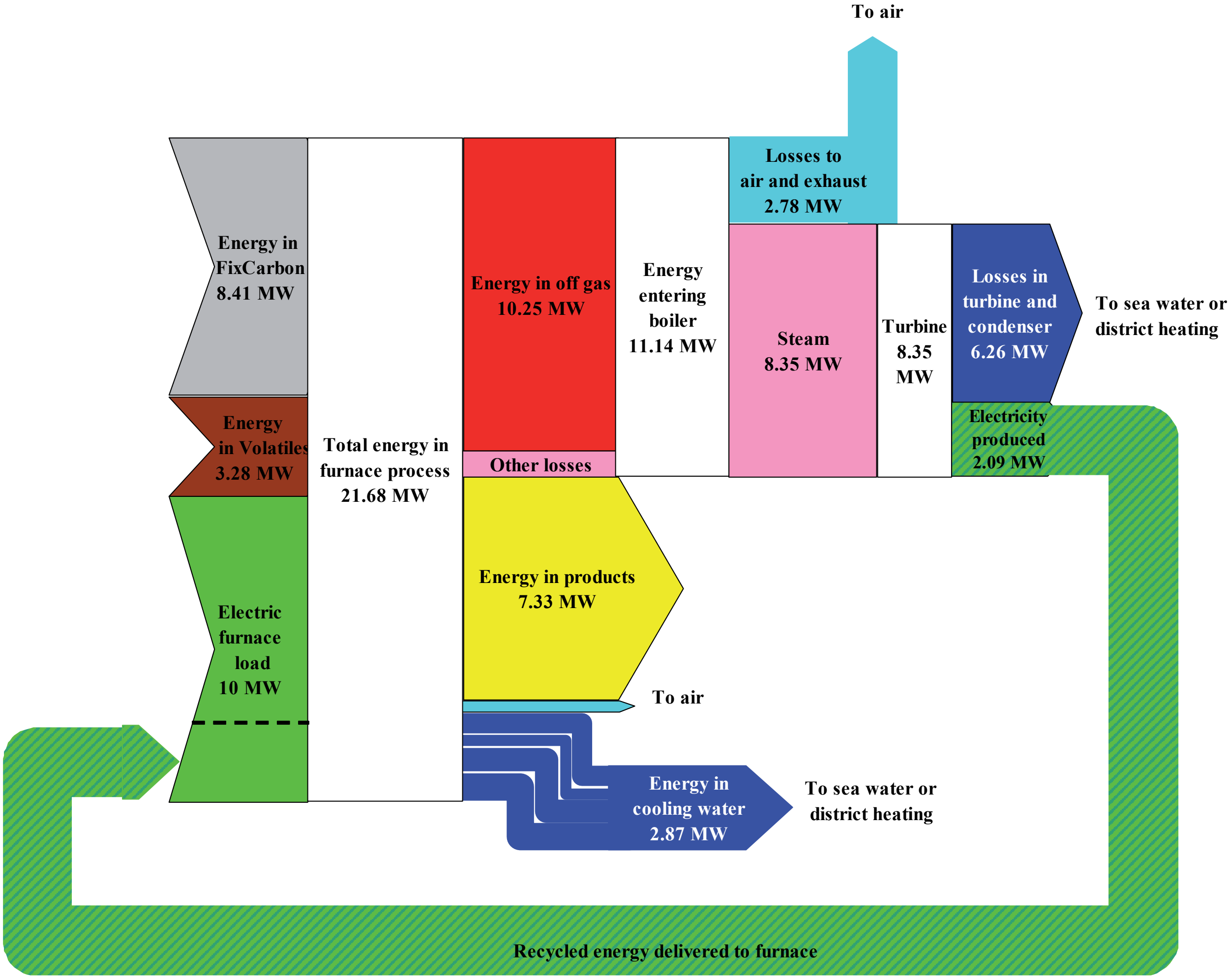

Figure 3: Sankey diagram for furnace with energy recovery installed

Energy changes and variation in the system

Due to the fluctuating nature of the furnace process there will be considerable variation in the energy flows when we look at the data on a shorter time frame. To try to illustrate this variation we have calculated the energy balance for the furnace over a period of 48 hours, letting the average of 8 hour data represent that period. For convenience we have related all numbers to the electric furnace load, letting the electric furnace load represent 100 %.

The variation in input and output energy is given in Figures 4 and 5.

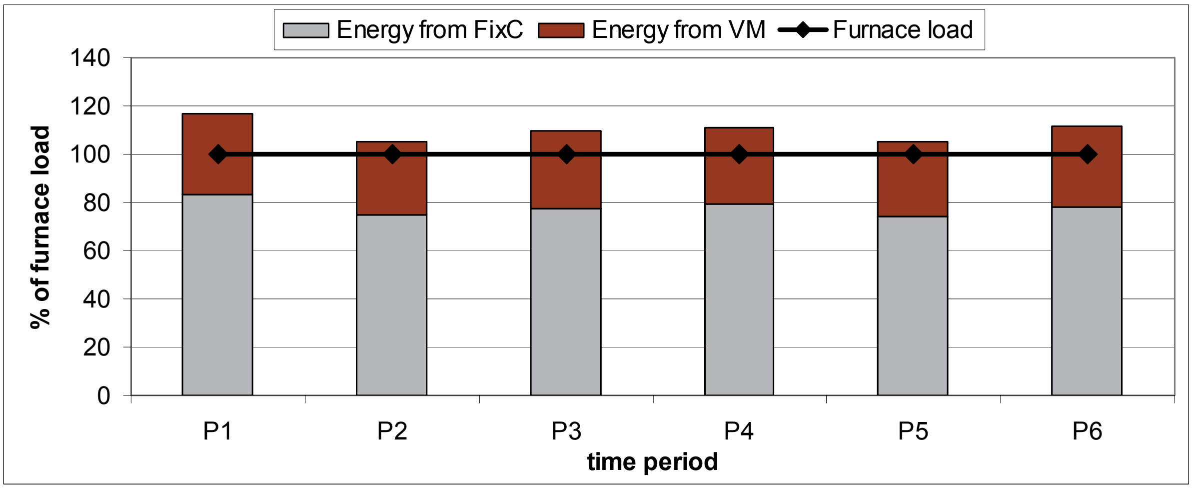

Figure 4: Input flows of energy to the furnace

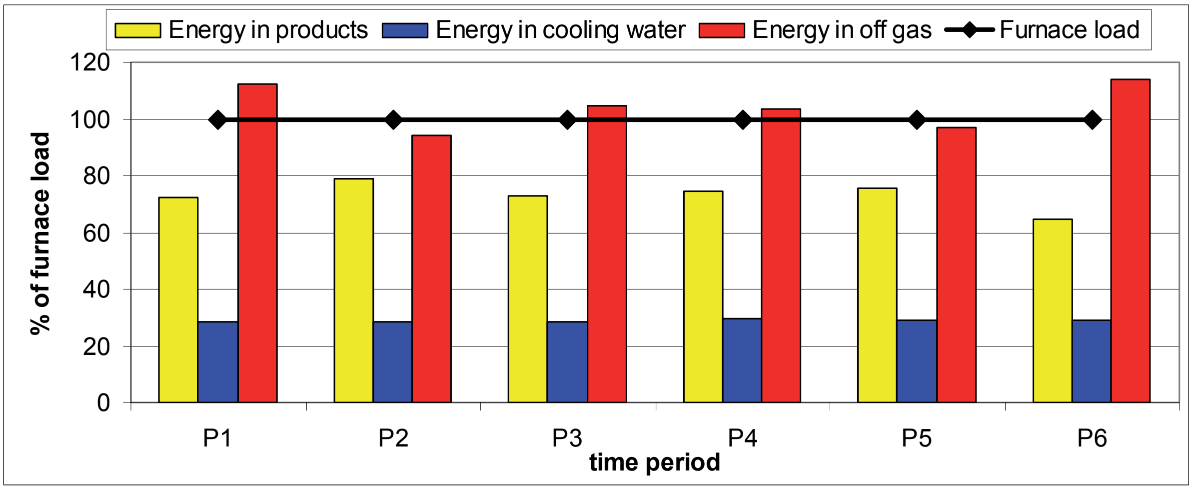

Figure 5: Output flows of energy from the furnace

The variation in electric furnace load over the given time periods is +/- 1 % of 45 MW.

Based on the input of electric load we see that a considerable amount of the variation is explained by variation in charging the furnace and in the tapping process.
Not removing metal from the furnace will in a relative short time give an unwanted partial oxidation-reaction between silicon and quarts, resulting in an increase in SiO-gas production. This gas heats the charge burden and the off-gas products, increasing the energy content of the off-gas.

4 USE OF LOW QUALITY ENERGY FROM ELKEM SALTEN

A new study presented by ENOVA [7] in 2009 concludes that the thermal energy potential in the Norwegian ferroalloy industry is 4795 GWh per year, divided into 74 % in off-gas, 3 % in steam and 23% in hot water.

Being a large plant Elkem Salten has a significant amount of hot cooling water available. As a result of this there are currently three facilities, a football field, a greenhouse complex and a fishfarm taking advantage of this situation, all closely located to the plant as shown in Figure 6.

Figure 6: Map over plant area. From www.gulesider.no, Norwegian Mapping Authority

Rose production in greenhouses – Sisoflor

A master's study entitled *"Utilization of energy in cooling water from process industry - vegetables or flowers in greenhouse"* [8] done at HBO in Bodø in 1990 gave an idea that energy from the cooling water could be the basis of rose production in greenhouses. Contact was made with a horticulture chain and the company Sisoflor was established.

Water from the greenhouse is heat exchanged against cooling water from two furnaces. The water coming into the greenhouse is used twice, first heating up the soil that the roses grow in directly and then heat exchanged once more inside the greenhouse to heat up fresh water for the fertilizer system. A principle sketch of the system is given in Figure 7.

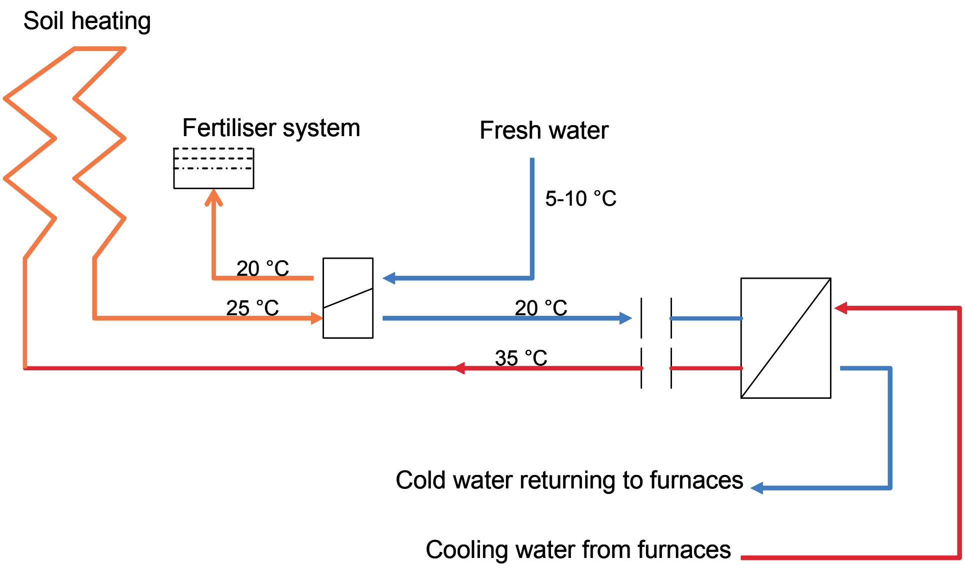

Figure 7: Principle sketch of the water system in the greenhouse

The first operation, heating up the soil increases the soil temperature by 2 °C, while the in greenhouse the heat exchanger heats up the fresh water from 5-10 °C to 20 °C.

The energy outtake in the two operations is calculated to be

- Heating of soil: 70 kW
- Heating of fresh water: 78 kW

  In total: 148 kW

Since the difference in summer and winter temperatures this far north is rather large the overall energy outtake is calculated with a 65 % degree of utilization, giving a total energy in the area of 840 MWh/year [9].

Additional use of process heat
The source of the heat exchanger is as mentioned mainly cooling water from two furnaces, but in addition to this the greenhouse engineer has installed an extra source of hot water. This is done by twirling copper pipes around one off the off-gas channels and insulating the coil from the surroundings. Placing this coil close to the furnace has enabled heating of a part the returning water from the heat exchanger to 75 - 80 °C. This water is then fed into a tank and pumped back to the heat exchanger with a temperature of approximately 70 °C. Calculations done by the greenhouse engineer estimate the energy outtake to be in the area of 200 kW [9]. The principle sketch is shown in Figure 8.

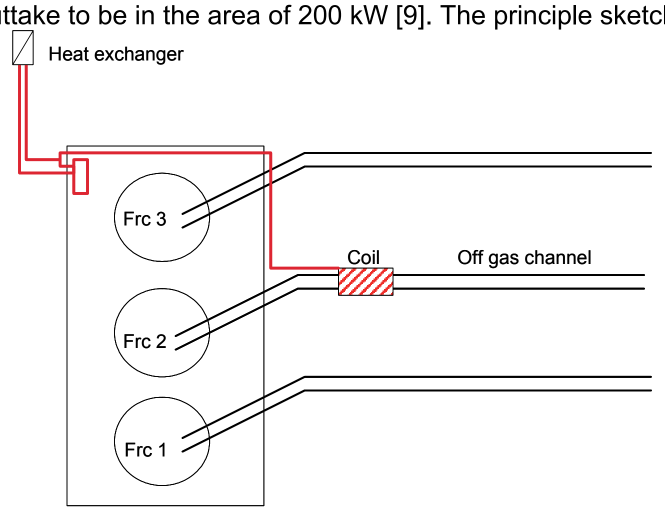

Figure 8: Principle sketch of additional use of process heat

Low energy to football field – Lakselva Stadion
As a result of a very active sports committee at the plant in the end of 1980s, the plant management in cooperation with the local authorities decided to build a new football field close to the plant and integrate a water-based heating system for the field and the wardrobe facilities. The result was a 65 m x 100 m field, with over 30 000 metres of pipes laid 15 cm underneath the surface, giving an all-year sports arena available for local sport clubs and other.

The water heating for the football field is in a closed circuit which is passed through the same heat exchanger as the greenhouse uses, giving an energy outtake in the area 5.5 million kWh/year [10].

Fishfarm Sisomar
The fish farm was established in 1986 and is a land-based facility, having all the hatcheries and tanks on land. The idea behind the farm was that cold fresh water from a nearby lake could be heat exchanged against the plant cooling water, giving a stabile fresh water temperature to the farm, regardless of season. This enables the farm to control and increase the growth of salmon.
Since the lake is fed with water from a glacier the fresh water temperature to the heat exchangers is varying from 1-2 °C in the winter to 10-12 °C in the summer. The inlet temperature from the heat exchangers to the fish farm is approximately 18 °C.
The fresh water is heat exchanged against part of the cooling water from all three furnaces, in three separate heat exchangers, and then pumped back to the fishfarm. The principle sketch is shown in Figure 9.

Each hour 300 m^3 of fresh water is pumped through the system, giving an energy outtake of 2.78 MW in the summer and 5.55 MW in the winter months [11].

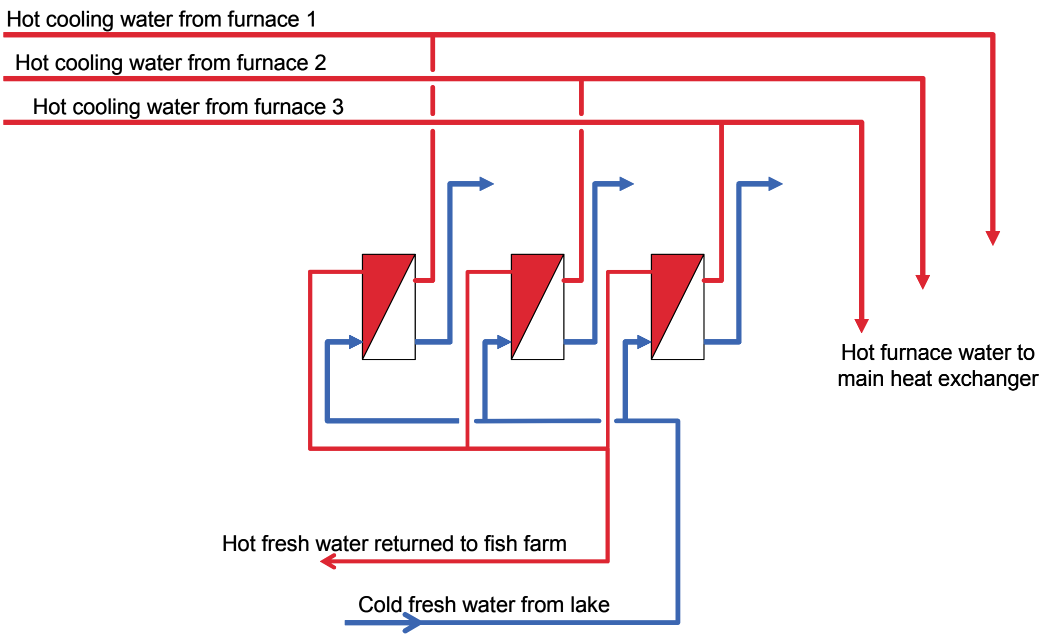

Figure 9: Principle sketch of fishfarm heat exchanging

5 SUMMARY

Energy balance for furnace

The energy balance for the furnace shows considerable opportunities for energy recovery projects. Both hot off-gas and large amounts of hot cooling water are available and the installation of a steam-based energy recovery system would give an extra source for thermal energy through "new" hot cooling water from the turbine and generator.

The analysis of the overall energy balance shows that of a total energy (electric 10 MW and chemical 11.7 MW) input of 21.7 MW we recover 7.3 MW (34 %) in the product and energy recoveries are: 2.1 MW (9.6 %) as electrical power, 2.9 MW (13 %) for district heating with a further potential of 6.3 MW (29 %). In case of the installation of a more efficient energy recovery system, this would replace a coal-fired energy plant of 11.3 MW generating in the order of 76 000 tonnes CO_2 emissions, assuming an emission of 0.77 tonnes CO_2/MWh [2].

Table 1: Summary of thermal and electric energy potentials per 10 MW electric input load

	Available thermal energy [MW]	Available recovered electric energy [MW]	Potential CO_2 emission savings with energy recovery [tonnes/year]
Today's situation	2.87	-	
With energy recovery installed	9.2	2.1	76 220

Use of low quality energy

The energy in the hot cooling water from the plant together with the courage and consistency of owners and investors has created a win-win solution for both parties. As a result, businesses in sectors that normally would be located in a warmer climate, such as the greenhouse complex are growing. It has also provided opportunities for use of low quality energy in fish farming.

The total use of low quality energy from the plant is summed up in the following table, together with the equivalent CO_2 emissions this recovered energy would give; assumed direct heating with fossil fuel (e.g. coal).

Table 2: Summary of low quality energy

Customer	Energy consumption [MW]	Equivalent CO_2 emissions [tonnes/year]
Greenhouse (Sisoflor)	0.295[1]	1 990
Sports arena	0.628	4 236
Fishfarm (Sisomar)	4.514[2]	30 448
In total	5.437	36 674

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[9] Personal communication with Sisoflor.
[10] Information board at sports arena.
[11] Personal communication with Sisomar.

[1] Total energy outtake from inside greenhouse and from reheating of cooling water
[2] The numbers are based on 7.5 months with "winter" conditions and 4.5 months with "summer" conditions