«Green and Sustainable
Summer Internships 2019»

Optimized Energy Systems

Use of excess heat in Mo Industripark

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Abstract

In this study we have looked at possible ways of utilizing waste heat from companies in Mo Industripark. The excess heat was put into two categories; high and low temperature heat. For the high temperature category, all of our possible solutions were based on producing steam using Elkem's flue gas. Furthermore, we considered possibilities for using this steam for electricity generation, carbon capture storage, and a combination of the two. Exclusively generating electricity resulted in a yearly output of 75,5 GWh, which equates to annual savings of 22,7 million NOK. A pure CCS solution yielded a yearly capture potential of 620 000 tons of CO_2, which is equivalent to 174,5 million NOK in CO_2 quotas. The combined solution with district heating resulted in an electrical output of 66,4 GWh and a capture potential of 266 000 tons CO_2 per year. This translates to respective incomes 19,9 and 74,4 million NOK. Excluding district heating in the combined scenario increased the captured CO_2 to 449 000 tons while the electrical output remained unchanged.

For the low temperature category, different ways of utilizing waste heat for heating purposes is first discussed. This includes melting of ice in raw materials, drying clipfish, all year indoor gardening, algae production and insect farming. Lastly, low temperature heat for power generation and heat for cooling solutions were the topics. The cooling water from either ACDC or Celsa was considered as the best prospects for supplying either of the aforementioned low temperature solutions.

Contents

1 Introduction

UN's Sustainable Development Goal 7 (SDG7) aims to provide clean energy to all by 2030. It states that through emissions the world's energy consumption is the largest contribution to climate change today. At the same time, our need of energy is only expected to increase. This means that major energy consumers, such as the industry sector, must strive to find more renewable solutions and increase their energy efficiency. For this to be an attractive strategy, one must find an optimal solution, including both environmental, technical and economical aspects. An optimized energy system is a system where optimal energy-efficiency, use and balance of energy carriers and cost-benefit are achieved. In order to fulfill SDG7, the share of energy from renewable sources should be as high as possible and a high degree of energy circularity is desired.

1.1 Project Background

Sintef Helgeland's "Grønne bærekraftige sommerjobber 2019" is a summer project that challenge students to solve real-life problems for the local industry. The tasks are to be approached on the basis of the principle of circular economy. The five students were given three problems to be solved over the course of eighth weeks, including Digitalization and Automation, Energy System Optimization and KPI's for Sustainable Procurement. In this report, the result of the energy system optimization problem will be presented. Contributing partners for this project are Sintef Helgeland, Mo Industripark AS, Elkem Rana AS, Arctic Circle Data Center AS, Celsa Armeringsstål AS, Sintef Molab AS, Storvik AS, Arctic Cluster Team, Nord University and Nordland Fylkeskommune.

Mo Industripark (MIP) and the companies within it has already carried out several initiatives for optimizing their energy system, especially in terms of energy recovery. Celsa Armeringsstål recovers heat with hot charging technology, reducing their annual energy consumption with 30 GWh [1]. Energy from waste water is recovered with MIP's own mini power plants, and heated cooling water from Elkem Rana is used for breeding salmon smolts at Ranfjord Fiskeprodukter [2]. Residual heat from flue gases from the furnaces at Elkem Rana supplies district heating for the community of Mo i Rana [3]. In total, 400 GWh is recovered every year. MIP intend to increase this to 620 GWh, in accordance with their vision of becoming a "world-class industrial park with environmentally friendly and energy-efficient services and solutions" [4].

To contribute to this goal, we strive to find new and alternative methods for energy recovery from surplus heat, in addition to analyzing and optimizing some of today's methods in the park. By taking a holistic approach to the energy system, we focus on circularity, stability and balance between the solutions and address the potential of new ventures that can utilize the surplus energy.

2 Current Energy Solutions

2.1 MIP

Mo Industripark AS owns all the energy infrastructure within the industrial park. They are responsible for operating the different distribution grids for process water, electricity, gas and district heating. As a whole, Mo Industripark consumes about 2 TWh of electricity annually [5]. The biggest consumers within the industrial park are presented in Table 1.

Table 1: Energy consumption of the largest companies in MIP

Company	Electricity consumption [GWh]
Elkem Rana AS [6]	800
Ferroglobe Mangan AS [7]	500
Celsa Armeringsstål AS [8]	350

To cover some of this load, MIP AS operates two mini hydropower stations; Svabo and Vika. Svabo utilize the elevation difference between Andfiskvatnet and the industrial park to produce electricity, while Vika utilize the elevation difference between the park and Ranfjorden. The water running through Vika hydropower station is the waste water from the industrial park. Svabo and Vika produce 20 and 7 GWh respectively. It is also assumed to be a considerable amount of energy available as i.e. excess heat within the park, but this is not quantified as an entirety. This report focuses on utilization of selected sources of this type of energy.

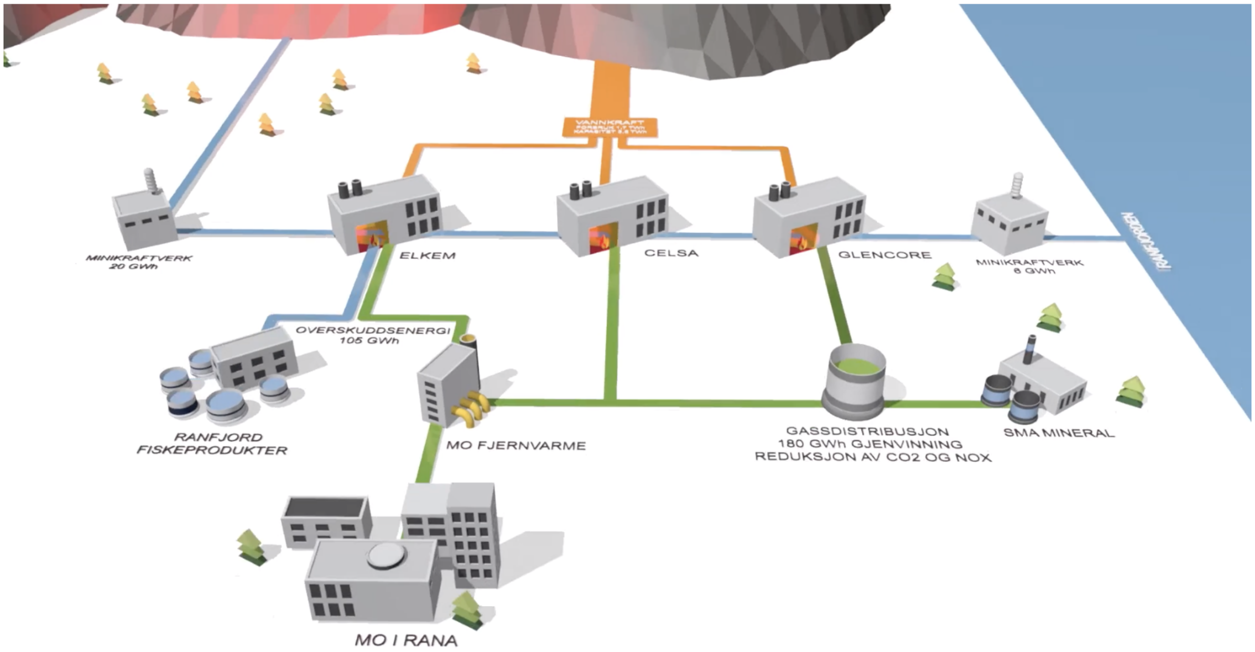


Figure 1: Energy distribution in Mo Industripark [4]

2.2 Elkem

The flue gas from the furnaces at Elkem Rana AS are transported to the boilers of Mo Fjernvarme. Here, the heat of the flue gas produces steam which heats up the district heating water using heat exchangers. With a boiler design capacity of 22 MW, this covers the base load of the district heating network in Mo i Rana. Process water is used to cool the furnaces at Elkem Rana AS. The output water holds a temperature of approximately 45 °C, which is transported and used to heat the water used for salmon smolt breeding at Rana Fiskeprodukter AS.

The temperature in the furnaces holds 1300-1400 °C, while the flue gas at the beginning of the penstock is ca. 600 °C [9]. Arriving at the district heating boiler, the flue gas temperature is reduced to 350 °C [10]. This means that approximately 17 MW of thermal energy is lost between Elkem and Mo Fjernvarme. Due to i.e. maintenance of both furnaces and district heating boiler, a flue gas availability of 8200 hours per year is assumed in further calculations.

2.3 Celsa Armeringsstål AS

Celsa Armeringsstål AS is Norway's biggest recycling company, recycling about 700 000 tons of scrap metal each year [11]. The flue gas from the steel mill holds about 300 °C and fluctuates on and off due to discontinuous operation. The water used for cooling the process holds an output temperature of 45-55 °C and has an estimated total power of 5-10 MW.

2.4 ACDC

Arctic Circle Data Centre, short "ACDC", is a provider of cloud storage and computing. Today they run a closed 1 MW data centre located in Mo Industrial park, which draws approximately 1 MW of electrical energy at all times. This equals an annual consumption of 8,8 GWh.

All of the electrical energy used is converted to thermal energy in the form of heated air at approximately 40 to 45 °C [12]. This heat must be removed from the computing equipment to ensure functionality and safety. Today all of this heat is extracted by use of a closed water cooling loop. Water absorbs heat inside the computer rig-hall by an air-to-water heat exchanger, and is cooled by a water-to-air heat exchanger in open air, making use of the natural cold surrounding climate. In an ideal system the cooling water could reach temperatures at 38 to 42 °C. The effect depends on the scale and usage of storage and computing.

As of this, an assumption is made that ACDC could provide an available, scaleable and steady heat source at approximately 40 °C at 1 MW. Possible future expansion of services may provide a higher effect.

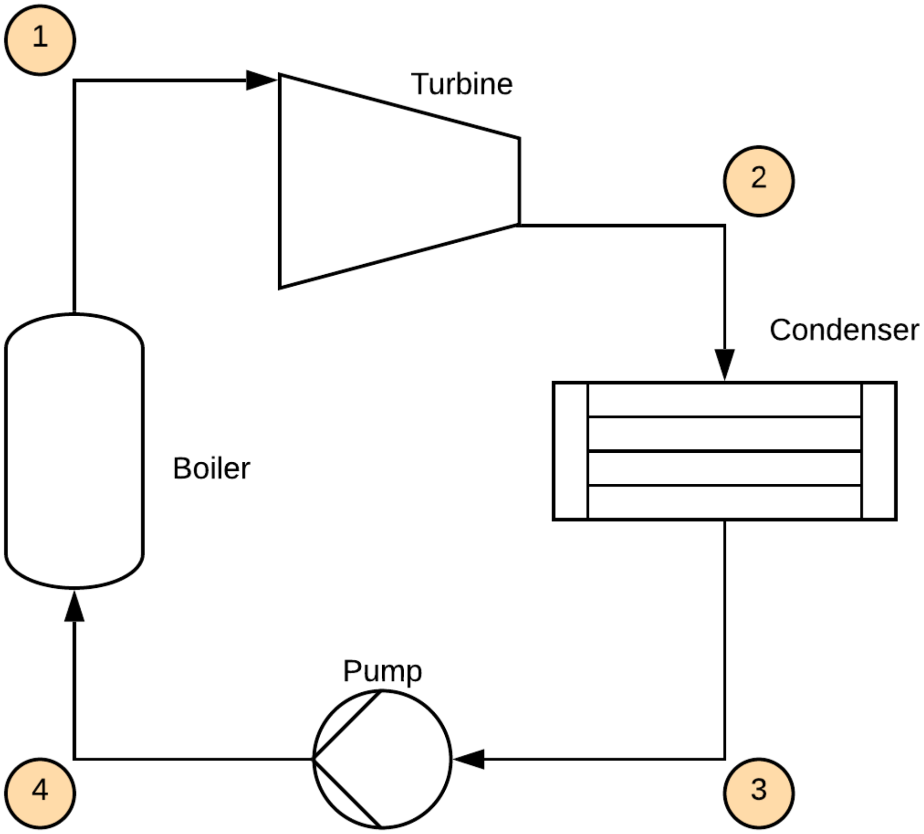
3 High and Medium Temperature Heat

This study focuses on optimizing the energy system by utilizing excess heat. More specifically, the excess heat has been categorized into 2 different categories; high-to-medium and low temperature heat, with respective temperatures 600-200 °C and under 200 °C. Possible solutions to utilize the excess heat will be presented for each category. A main focus area has been to utilize the higher level energy quality in processes where high energy quality is needed.

For the high temperature category, Elkem Rana has been the main focus point. This is due to their flue gas which holds a temperature of 600 °C. As mentioned, today the flue gas is sent to Mo Fjernvarme in order to produce steam for heating up district heating water. The temperature in the flue gas drops to 350 °C before arriving at the district heating boiler due to losses. Therefore, the goal has been to use this high temperature gas closer to its source, thus decreasing the heat losses. It should be noted that one possibility is to combine the flue gas from Elkem Rana and Celsa Armeringsstål to supply either of the solutions. The flue gas from Elkem has the advantage of being stable with little fluctuations, whereas the flue gas from Celsa is far more discontinuous. However, combining the flue gasses would allow for the supply to fluctuate around the top, compared to the flue gas supply shutting on and off if Celsa were to be the stand-alone supplier. All of our possible solutions are based on using the flue gas to produce steam in a boiler. Furthermore, we have looked at four different ways of using this steam; electricity generation and district heating, carbon capture, and two different combinations of these three uses. It should be mentioned that steam has many areas of use that could be relevant for the industry at MIP, i.e. for chemical factories. However, this has not been studied in this project.

3.1 Rankine cycle

A Rankine cycle is included in three of the proposed solutions. In all cases, the isolation in the penstock is assumed to be improved, keeping the flue gas temperature close to 600 °C. The required lower limit of 200 °C in to the microsilica filter is also considered, making the maximum temperature drop over the boiler 400 °C. The flue gas is sent to a boiler, where steam is superheated up to 500 °C. For each case, we have plotted the different outputs for different pressures at this part of the cycle. The analysis is done for 100 bar input turbine pressure. The superheated steam expands through the turbine, generating power as the pressure and temperature drops. The steam leaving the turbine then enters a condenser. Heat is transferred from the steam at constant pressure until it becomes saturated water. One obtains the maximum turbine output if the condenser pressure is set to its minimum, which is usually the saturation pressure for the temperature of the cooling liquid passing through it. This pressure is optimized for each of the three considered cases. After passing through the condenser, the water goes through a pump, increasing the pressure before entering the boiler again. The basic flowchart for a Rankine cycle is shown in Figure 2, while the T-s diagram for the cycle is shown in Figure 3.



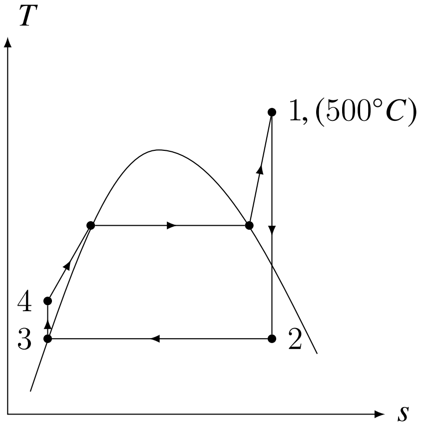


Figure 3: Ts-diagram of ideal, superheated Rankine cycle

Figure 2: Basic flowchart for a Rankine Cycle

To calculate the energy delivered or used in each of these processes, we need to know the enthalpy in each point. The pressure and temperature at the inlet of the turbine, T_1 and p_1, is chosen according to the desired design. The enthalpy h_1 and entropy s_1 is then found from a superheated steam table [13]. For simplicity, we have assumed an isentropic process through the turbine, which yields $s_2 = s_1$. The steam quality at the outlet of the turbine can then be calculated as

$$x = \frac{s_2 - s_f}{s_g - s_f} \tag{1}$$

Where s_f and s_g is the entropy for saturated water and water vapour at the corresponding pressure. The steam quality is then used to find the enthalpy as follows

$$h_2 = h_g x + (1 - x)h_f \tag{2}$$

Where h_f and h_g is the enthalpy for saturated water and water vapour at the corresponding pressure. The enthalpy h_3 after the condenser and at the inlet of the pump is the same as h_f. With the assumption of an isentropic process through the pump, the enthalpy h_4 after the pump and at the inlet of the boiler is given by

$$h_4 = h_3 + v_3(p_4 - p_3) \tag{3}$$

The heat transfer $\dot{Q}$ to the steam in the boiler is

$$\dot{Q} = \dot{m}_{steam}(h_4 - h_1) \tag{4}$$

Similarly, to calculate the heat transfer from the flue gas in the boiler, we assume a constant specific heat capacity c_p for the flue gas. The temperature difference ΔT for the flue gas at the inlet and outlet of the boiler can then be used to calculate the heat transfer to the boiler

$$\dot{Q} = 0,98\dot{m}_{fluegas}c_p\Delta T \tag{5}$$

Where we have assumed a 2 % heat loss in the boiler. Combining the two previous equations, we get an expression for the amount of steam produced in the boiler:

$$\dot{m}_{steam} = \frac{0,98\dot{m}_{fluegas}c_p\Delta T}{h_4 - h_1} \tag{6}$$

Knowing the amount of steam produced in the boiler, the power generation from the turbine can be calculated as

$$W_{el} = \dot{m}_{steam}(h_1 - h_2)\eta \tag{7}$$

Where η is the electric efficiency of the turbine.

3.2 Carbon Capture and Storage Using Amine Technology

One way of capturing carbon dioxide from flue gas is through the use of amines mixed with water. This amine solvent can be used to absorb the CO_2. First, the flue gas is sent trough a cooler to decrease the temperature to around 40 °C. The cooled flue gas is then sent to the bottom of the absorption tower, also called the absorber. The flue gas flows upwards, coming in contact with the downflowing amine liquid, thus allowing the CO_2 to bind itself to the amines. The flue gas is treated in a water wash at the top of the absorption tower to remove amines before the cleaned flue gas is released into the atmosphere. At this point, 90% of the CO_2 is removed from the flue gas.

The CO_2 rich amine liquid is then sent to the desorber where steam is used to heat the fluid to about 120 °C. This reverses the chemical reaction between the amines and

CO_2, seperating the CO_2. The seperated CO_2 is then ready for compression, transport and storage, while the CO_2 lean amine liquid is pumped back into the absorber, where the cycle is repeated. An energy efficient solution is to heat exchange the 120 °C CO_2 lean amine liquid flowing out of the desorber with the 40 °C CO_2 rich amine liquid flowing into the desorber, decreasing the heat transfer needed from the steam in the desorber. It is assumed that 3,2 GJ of steam is needed to capture 1 ton CO_2, according to CO_2-hub Nordland.

3.3 Case 1: Electricity Generation and District Heating

In this solution, the steam produced in the boiler is utilized in a steam turbine and then sent to the district heating system. We simplify this system by modelling it as the condenser in the rankine cycle. Mo Fjernvarme needs a supply temperature of 85-105 °C, and 1 bara is therefore set as the condenser pressure. For an inlet pressure of 100 bara for the turbine, we obtain the values shown in Table 2.

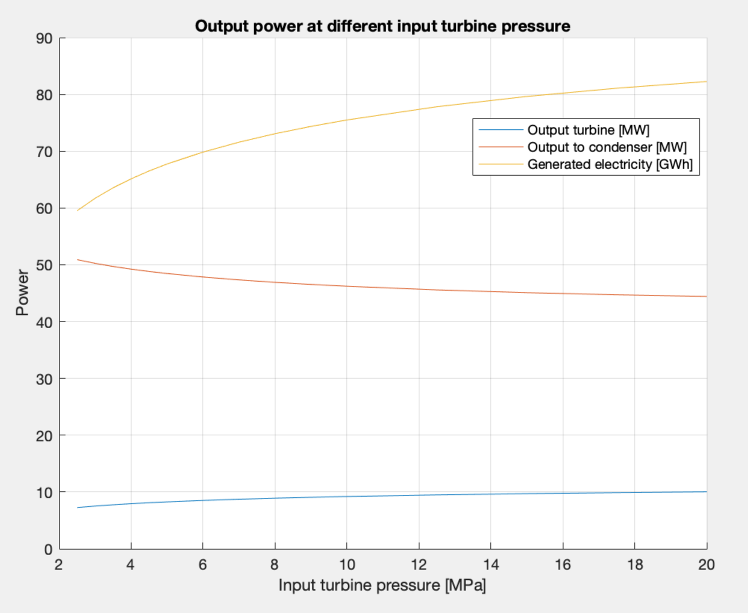


Figure 4: Power output for different inlet turbine pressures, case 1

Using these values with the equations presented in Subsection 3.1, we get an annual

Table 2: Input and output values for case 1 at 100 bara inlet turbine pressure

$\Delta T_{fluegas}$	400 K
Temp. superheated vapor	500 °C
Inlet turbine pressure	100 bara
Inlet condenser pressure	1 bara
$c_{p,fluegas}$	1,7 kJ/kg
Operational hours	8200 h
η_{el}	31 %
h_1	3375 kJ/kg
h_2	2392 kJ/kg
h_3	417,51 kJ/kg
h_4	427,84 kJ/kg
Produced steam	23,41 kg/s
Power to district heat	20 MW
Electricity generated	75,5 GWh

electricity production of 75,5 GWh. This is based on the assumption that of plant having an availability of 8200 hours per year, and a turbine efficiency of 31%. With the current electricity price being 0,30 NOK/kWh, this electricity production results in a yearly cost reduction of 22,65 million NOK. As we can see from Figure 4, the amount of generated electricity increases with the turbine inlet pressure.

Yearly costs for labour, water and maintenance to operate the power plant was estimated to 5 million NOK. With a depreciation period of 15 years and a 7% rate of return, this result in the project having a present value of 178,4 million NOK, not including the initial capital cost. This means that if the investment needed by the firm is lower than 178,4 million NOK, the project is profitable in itself. If the investment needed is higher, additional funds from i.e Enova should be sought after.

3.4 Case 2: Producing Steam for Carbon Capture

As discussed in Subsection 3.2, steam can also be used to capture CO_2. To calculate an estimate of how much steam that could be produced just by using the excess heat of the flue gas from Elkem, we assumed a 2% heat loss in both the boiler and desorber. The rate of heat transfer to the desorber is then given by

$$\dot{Q}_{desorber} = 0,96\dot{m}_{fluegas}c_p\Delta T_{fluegas} \tag{8}$$

Table 3: Input and output values for case 2

$\Delta T_{fluegas}$	400 K
$c_{p,fluegas}$	1,07 kJ/kg
Temp. vapor to desorber	130 °C
Operational hours	8200 h
Produced steam	31,7 kg/s
Heat transfer to desorber	67,6 MW
CO_2 captured	623 382 tons
With district heating:	
Power to district heat	20 MW
Heat transfer to desorber	47,6 MW
CO_2 captured	439 110 tons

This yields a rate of heat transfer to the desorber of 67,6 MW. With the assumption that 3,2 GJ of heat transfer to the desorber is needed for each ton of CO_2 captured, this results in the potential of capturing 623 382 tons of CO_2 yearly. With the current CO_2 quota price at 280 NOK/ton CO_2, this is equivalent to saving 174,5 million NOK per year.

The yearly amount of CO_2 released from the four biggest contributors in MIP are shown in Table 4. Combined, these companies account for Norway's 6th largest emissions of CO_2 from land based industry. However, it should be mentioned that not all of these emissions are possible to capture in today's situation because of too low CO_2 concentration in the flue gas. This applies for the emissions from Ferroglobe Mangan AS and $\frac{1}{3}$ of the emissions from Celsa Armeringsstål AS. This means that there are about 450 150 tons of CO_2 that is possible to catch at the industrial park.

From the results presented above, it is clear that the CCS system has a potential of capturing more CO_2 than whats available at the site. By taking the district heating demand into account, and supplying them with 20 MW of the steam produced, the potential carbon capture is reduced to 439 110 tons. This is a better match to the CO_2 emitted at MIP. The carbon credit savings for this solution is equivalent to 122,5 million NOK per year.

Table 4: CO_2 emissions from the largest companies in MIP (2018) [14]

Company	Yearly CO2-emissions [tons]
Elkem Rana AS	302 000
Celsa Armeringsstål AS	93 270
Ferroglobe Mangan AS	86 830
SMA Mineral AS	85 970
Total	568 070
Possible to capture	450 150

Installing a CCS plant in MIP would have several advantages. Firstly, there is large amounts of CO_2 available for capture. Capturing CO_2 from more than one company would provide increased security of future supply. Husebye et. al [15] performed process simulations and cost estimations to study the impact of CO_2 concentration and steam supply when capturing CO_2 with MEA-based chemical absorption. They concluded that increasing the CO_2 concentration in the interval 2,5-10 % results in a sharp reduction of both investment and operating costs. More importantly, utilizing waste heat instead of generating steam from gas fired boilers results in cost reductions in the same order of magnitude as increasing the CO_2 concentration from 2,5 % to 20 %.

Additionally, the investments costs related to the boiler would be lowered for producing steam for CCS compared to producing steam for electricity generation; the reason being that superheated steam is not needed. The lower temperatures allows the boiler to be made out of cheaper materials, and the process of evaporating water results in a better heat transfer coefficient compared to producing superheated steam. The large quantities of available waste heat is probably the most appealing factor in favour of building a CCS facility in MIP. Norcem Brevik, a large cement producer, has installed a CCS plant utilizing amine technology and excess heat to produce steam. They emit about 800 000 tons of CO_2 yearly, but only have enough waste heat to capture approximately half of that. [16].

3.5 Case 3: Combined Steam Turbine, District Heating and Carbon Capture

A combination of these two cases has also been evaluated. Here, the exhaust steam from the turbine splits into two parallel flows; one covering the demand of Mo Fjernvarme, while the other is used for carbon capture. The heat transfer to both the desorber and district heating is modelled as a condenser. For carbon capture, a steam temperature of 130 °C is required and this is set to be the exit temperature of the turbine. This corresponds to a turbine outlet pressure of 2,7 bara.

Modelling the district heating as a condenser, the amount of steam sent to district heating is given by

$$\dot{m}_{DH} = \frac{\dot{Q}_{DH}}{h_2 - h_3} \tag{9}$$

The remaining steam sent to the desorber can then be found

$$\dot{m}_{desorber} = \dot{m}_{steam} - \dot{m}_{DH} \tag{10}$$

Using this and the assumption that the desorber can be modelled as a condenser, the heat transfer to the desorber can be calculated as

$$\dot{Q}_{desorber} = \dot{m}_{desorber}(h_2 - h_3) \tag{11}$$

The enthalpy values, electric output and CCS are shown in Table 5. The idea behind this solution is to use the high temperature flue gas to produce high temperature steam

Table 5: Input and output values for case 3

$\Delta T_{fluegas}$	400 K
Temp. superheated vapor	500 °C
Temp. steam to condenser	130 °C
Inlet turbine pressure	100 bara
Outlet turbine pressure	1 bara
Operational hours	8200 h
h_1	3375 kJ/kg
h_2	2548 kJ/kg
h_3	546,38 kJ/kg
h_4	556,49 kJ/kg
Produced steam	24,48 kg/s
Steam to CCS	14,5 kg/s
Power to district heat	20 MW
Electricity generated	66,42 GWh
CO_2 captured	265 883 tonnes

for electricity generation, while simultaneously utilizing the latent heat in the lower temperature steam at the exhaust of the turbine. This results in a yearly electric output of 66,42 GWh and a capture potential of 265 883 tons CO_2 per year, which corresponds to yearly savings of 19,9 and 74,4 million NOK, respectively. The basic flow chart for a combined solution is shown in Figure 6.

3.6 Case 4: Combined Steam Turbine and Carbon Capture

In this last solution, we assume that the district heating demand is covered by another source. This means that, simplified, it's 20 MW of more steam available to be used for carbon capture.

As Table 6 shows, this does not affect the generation of electricity, but the omission

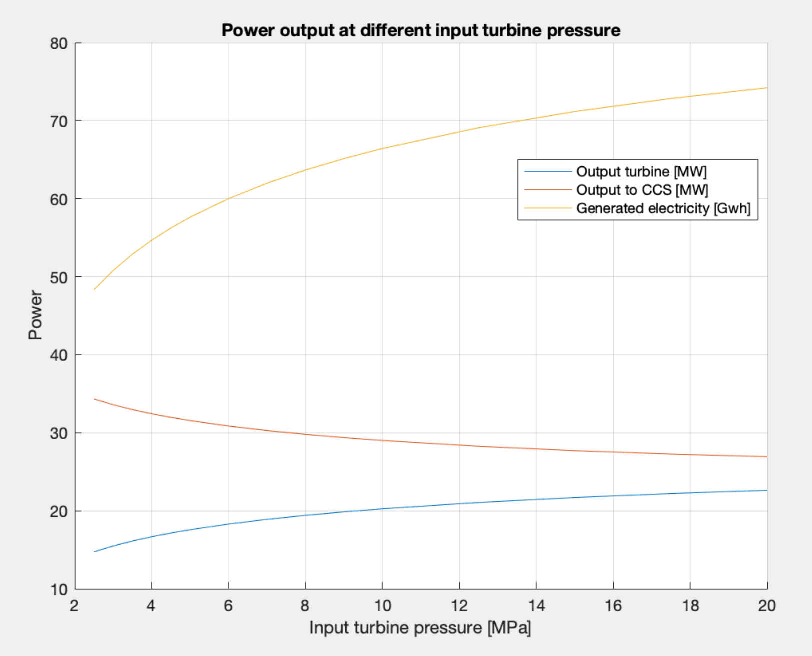


Figure 5: Power output for different inlet turbine pressures, case 3

of district heating increases the captured CO_2 from 265 883 tons to 449 237 tons per year, increasing the cost reduction from emitting CO_2 to 125,8 million NOK per year. This would however require an alternate power supply for Mo Fjernvarme. There is still large amounts of waste heat available in MIP, although it is possible that changing their energy source is neither feasible nor efficient.

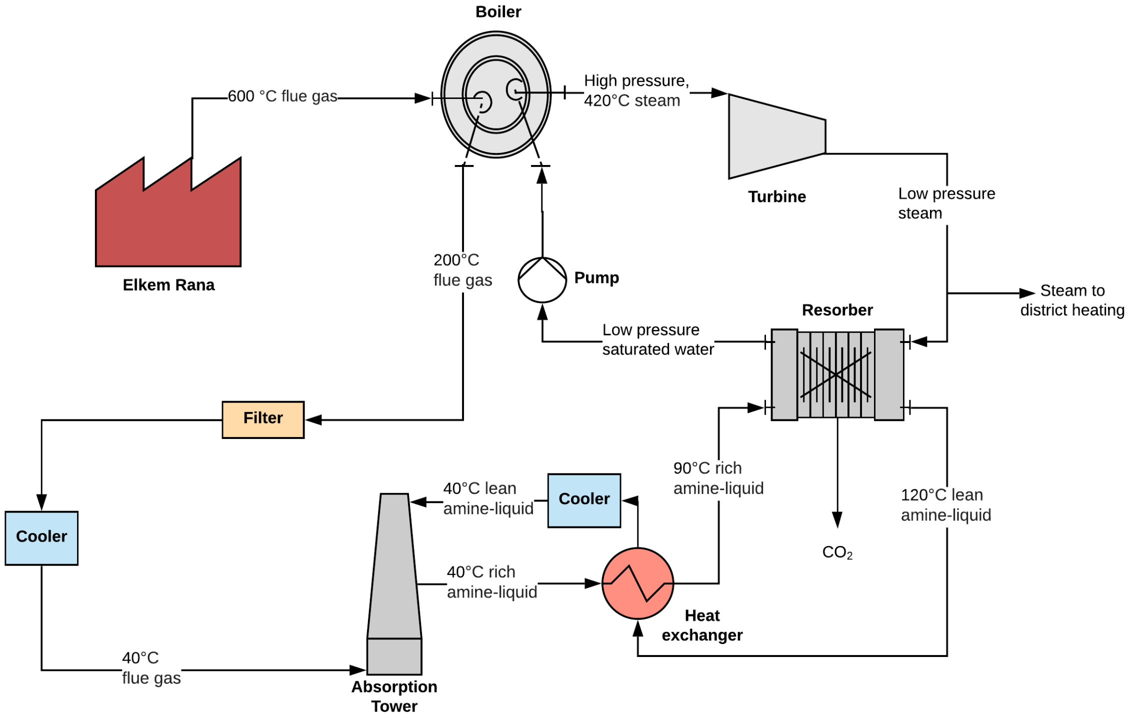


Figure 6: Flow chart for combining power generation and CCS

Table 6: Input and output values for case 4

$\Delta T_{fluegas}$	400 K
Temp. superheated steam	500 °C
Temp. steam to desorber	130 °
Inlet turbine pressure	100 bara
Outlet turbine pressure	1 bara
Operational hours	8200 h
Steam to CCS	24,48 kg/s
Output El.	66,42 GWh
CCS	449 237 tonn

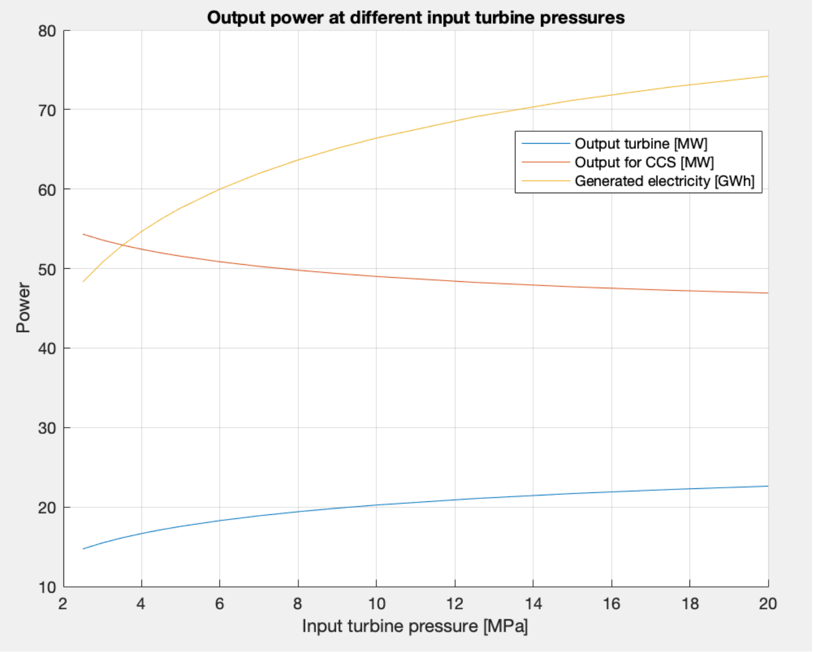


Figure 7: Power output for different inlet turbine pressures, case 4

4 Low Temperature Heat

Heat at temperatures below 200 °C is considered low temperature heat in this study. The total amount and different locations of low temperature heat present today at Mo Industripark is unknown. The holistic process of gathering information about temperature levels, effect and quantities has not been conducted, but simplified estimations based on single actors indicates that sufficient heat for proposed initiatives are present. The heat energy is spread across various sources at different temperatures. Most of this energy is available as heated cooling water, as presented in Table 7. However, a considerable amount of energy in the form of radiant heat from furnaces and lower temperature flue gases is assumed to be present in MIP, but needs to be further documented.

Table 7: Low temperature heat residual energy from selected companies at MIP

Energy source	Temperature	Power
Cooling tower flue gas, Elkem	140	-
Cooling water, Elkem	-	$>$ 45 GWh [2]
Cooling tower flue gas, Celsa	300 °C	-
Cooling water, Celsa	45-55 °C	5-10 MW
Cooling water, ACDC	38-43 °C	1 MW

4.1 Heat for heating solutions

An optimal energy system considers both energy and exergy efficiency. Therefore, a general explanation of why heat for heating solutions should be sought after when feasible is given based on exergy principles.

The theoretical maximum efficiency one can get when the heat engine is operating between two temperatures is defined by the Carnot cycle, formulated in Equation (12)[17]. It illustrates the theoretical maximum exergy - the amount that can be used for work in an energy perspective - available in a machine.

$$\eta(\%) = 1 - \frac{T_L(K)}{T_H(K)} \tag{12}$$

Where T_H is the temperature of the heat source in Kelvin, and T_L is the ambient temperature in Kelvin, set to 273K (0 °C). Note that this is purely a theoretical maximum. For real life purposes, it is extremely hard to utilize the lowest temperature levels. For temperatures below 200 °C, the maximum theoretical exergy is

$$\eta(\%) = 1 - \frac{273(K)}{473(K)} = 42,3\%. \tag{13}$$

The graph in Figure 8 illustrates how the efficiency increases with increasing temperature.

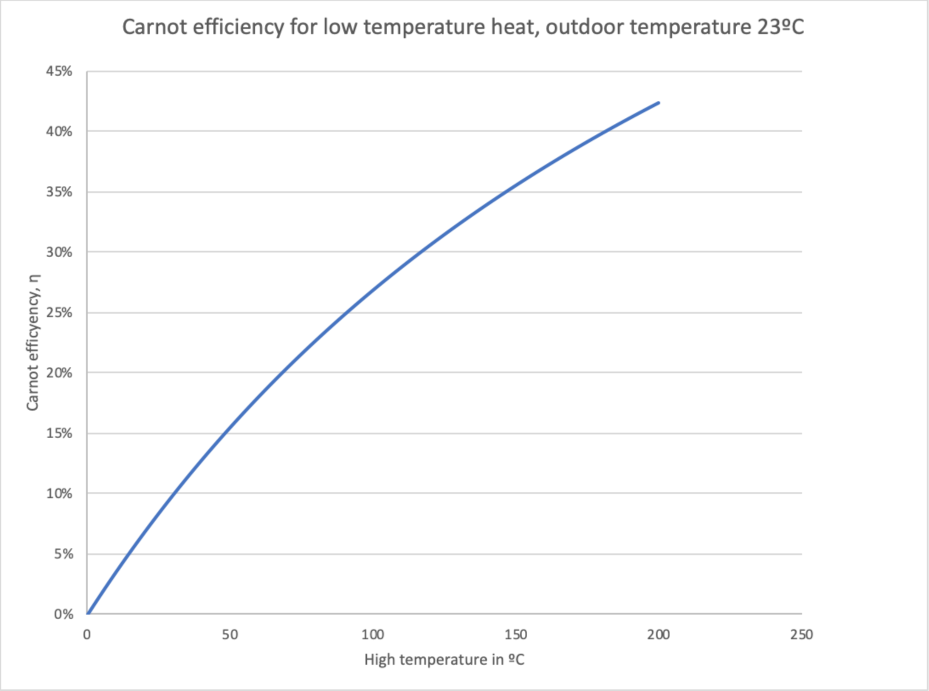


Figure 8: Carnot efficiency for low temperature heat energy

As shown, the possibility of making electricity decreases with the available temperature. Most of the heated cooling water available in this case is below 70 °C, which could only obtain an efficiency of 20 % or less. When using heat sources for direct heating purposes, one could reach a efficiency of 100 %. Therefore, solutions that utilizes already available waste heat to supply a preexisting heating demand should be the sought after use for heat, although there exists alternative solutions.

4.1.1 Melting of icing on raw materials

At Elkem Rana AS, the process of making FeSi requires different types of coke, coal and quartz. This is mostly transported from external suppliers by ship to the harbour, often exposed to rain and snow. When arriving to Elkem Ranas site in Mo Industrial Park, the raw material is occasionally placed in a storage outside, due to lack of space in the indoor storage facility. Larger pieces of ice, snow and frozen material causes challenges for Elkem as they wedge into the narrow chutes, clogging the transportation of materials between storage and ovens.

Several heating solutions have been considered to this problem, including using radiant heat from the melting process, heated cooling water and heat from flue gas. However, it was concluded that none of these methods would be economically favorable compared to solving the problem logistically or finding a way to cover the materials. It was therefore decided not to look any further into solving this problem, as a logistical solution would not be relevant to our project.

4.1.2 Drying processes

Drying processes have a heat demand that could benefit from easily available waste heat. With local traditions in mind, we have considered a solution for drying fish. Clipfish is an important export product, with a value of 4,1 billion NOK in 2017 which is expected to increase with a growing market in i.e. Brazil [18].

Today, most of the fish is captured in the northern part of Norway, but is then transported south for drying. With the expected growth in the market, it could have economical advantages to build a drying facility in Mo i Rana. A great share of the costs of clipfish production is related to the energy demand. With a need of up to 26 °C, the energy requirements vary from 130 kWh/ton to 250 kWh/ton produced [19]. If we assume that the demand equals 190 kWh/ton produced and by using i.e. the heated cooling water from ACDC, one could produce ca. 46 000 tons of clipfish in one year. This equals almost half of today's export.

4.1.3 All Year Indoor Gardening

In Helgeland, agriculture is affected by short growing seasons with a lot of light and little heat. This limits the assortment of which vegetables and fruits that can be cultivated in the area. By utilizing some of the excess heat from MIP to heat greenhouses, one could prolong the season to last almost all year, and the selection of arable goods would be expanded. This matches Nordland Fylkeskommune's goal to become self-sufficient on potatoes, vegetables and berries by 2030. Today, most of these are "imported" from the southern parts of Norway for about 117 million NOK a year [20].

For a greenhouse of 10 acres, cucumber production requires an average of 539 kW of heating and 1027 kW electricity under general Norwegian conditions [21]. This typically stands for about 30-40 % of the total annual operational costs for a greenhouse. The heated cooling water from Celsa has a temperature of 45-55 °C and equals 5-10 MW. This should be able to cover both base and peak load, shown in Figure 9. To increase the production, it is common to supply CO_2 into the greenhouse. By increasing the CO_2 concentration to 1000 ppm compared to 380 ppm in normal conditions, the production is shown to increase by 30-50 % [22]. It can therefore be an advantage to combine this solution with the CCS solution presented in Section 3.

To study the profitability of implementing such a solution, the net present value of operating a 10 acre greenhouse over 15 years was calculated. The results are shown in Table 8. It is assumed that the entire heat demand is covered by excess sources at MIP with no additional costs related to it. The capital cost covers installation of the green house building, and systems for water and electricity [23]. With these assumptions, the net present value turned negative with the electricity demand of 1027 kW. However, if this is reduced to 1000 kW, by i.e. using more efficient lighting, the project turns profitable.

A barrier that needs to be overcome before installing a greenhouse at MIP is that it typically can't stand snow and must therefore be kept free for frost all winter. In this area, this may lead to an increased heating demand compared to the demand presented above. There is also a barrier in terms of how artificial light only to an extent can replace the growing rate, color and taste produced by natural light for certain vegetables [24].

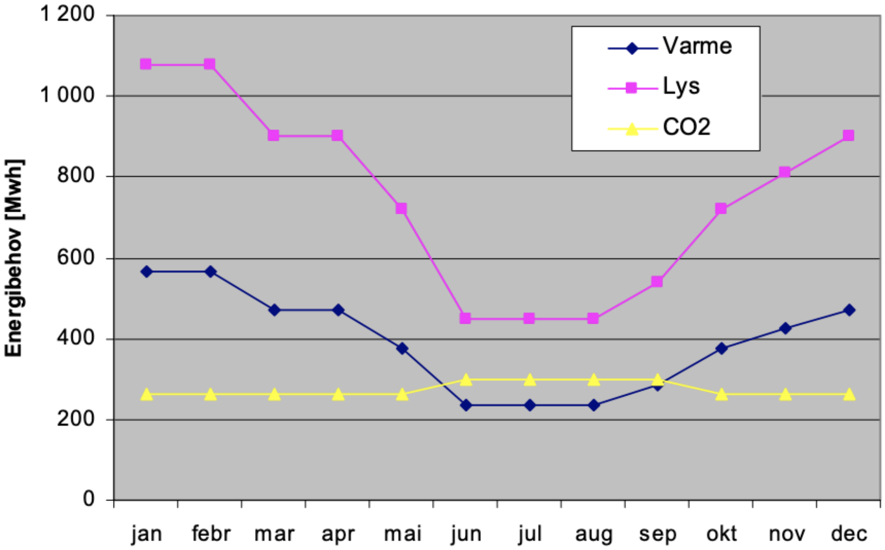


Figure 9: Energy demand in 10 acre cucumber greenhouse [21]

4.1.4 Algae Production

Algae is responsible for about 40 % of the world's photosynthesis and is an important contributor to capturing CO_2 in the atmosphere. As part of the photosynthesis, algae needs CO_2, heat, light, nitrogen and phosphorus in order to grow. In MIP, several of these components are available as excess sources. As described in Subsection 3.4, the biggest emission contributors in MIP releases in total about 570 000 tons of CO_2 each year. Algae cultivation could be an alternative for capturing this. A similar project has been established at Finnfjord AS, another FeSi-facility, where they aim to capture half of their CO_2 emissions, about 150 000 tons. The nitrogen and phosphorus can be obtained from waste water from Rana Fiskeprodukter's smolt production, and heated cooling water from i.e. ACDC could cover the heating demand [27].

Table 8: NPV for 10 acre greenhouse for cucumber production

Average heat demand	539 kW
Average el. demand	1000 kW
Energy price	42,6 øre/kWh [25]
Electricity price	30 øre/kWh
Greenhouse area	10 000 m^2
Capital cost	2000 NOK/m^2
Annual operational costs	10 665 903 NOK
Annual production	2 307 692 units [26]
Sales price	7 NOK/unit [26]
Rate of return	7%
Depreciation period	15 years
NPV	831 134,48 NOK

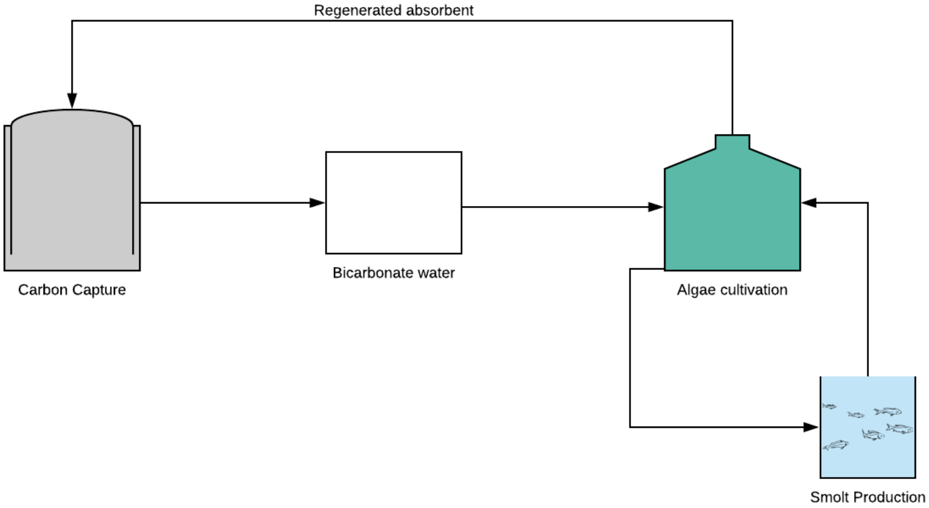


Figure 10: Flow chart of carbon capture with algae for fish feed

Algae cultivation is highly dependent on light, varying with the alga species chosen. This could be a barrier for establishment at a place like Mo i Rana, where the amount of natural light available is close to zero in the winter months. A solution to this is combining the algae production with one of the CCS solutions presented in Section 3 and storing the carbon as bicarbonate [28]. It is challenging to store CO_2 in gaseous form and this method enables storage of carbon for when the available amount of light and rate of photosynthesis in the algae is low. Another advantage of this method is the carbon regenerated in the culture process that can be reused as an absorbent in the CCS method, closing the system even more. A flow chart of this system is presented in Figure 10. It is important to note that algae carbon capture is more of a carbon utilization method, rather than permanent storage, and is therefore not the ideal environmental solution. However, the amount of CO_2 emissions is reduced indirectly by using the algae where other emission heavy sources otherwise would be used. This could include replacing soy in salmon feed or use in biofuel, medicine, fertilizers etc.

4.1.5 Insect Farming

With the world's growing demand of protein and the environmental impacts of modern farming, we need to find alternative food sources. An emerging trend is edible insect farming. Compared to beef production, mealworm production emits 83 % less CO_2, needs 95 % less area and 80 % less water. Also, a mealworm contains 49 % protein compared to 23 % in beef. In Norway, Invertapro has started a small-scale mealworm farming facility at Voss. According to them, mealworms require a temperature of ca. 30 °C, depending on stage of life. This heating demand accounts for a big portion of the production costs. Establishing a farming facility within an area with considerable amounts of excess heat as in Mo Industrial Park could therefore be beneficial.

One of the other challenges of establishing an insect farm is the availability of food waste, which is used for feeding the insects. Today, HAF is exporting the household food waste from Rana Municipality to Verdal for biogas production. This equates to around 2000 tons each year, and HAF pays 1750 NOK/ton for this delivery and transport. Some of this waste could alternatively be used in an insect farm. However, there are many regulations on the food waste content, in terms of what could be used as animal feed.

As an example, waste containing meat can not be used, making it difficult to use regular household food waste.

An alternative solution is to combine algae production and insect farming, as a nutrition source for the salmon breeding industry. Today, about 25 % of the Norwegian farmed salmon feed is made of soy [29]. A lot of the world's soy production is linked to deforesting, which has negative consequences for biodiversity, indigenous people living in the area and greenhouse gas emissions. It should therefore be a priority to find more sustainable protein sources produced closer to the breeding facilities. Even though algae have a high content of the necessary nutrients, salmon can't digest food with a high concentration of algae directly. However, studies have found that feeding black soldier fly larvae up to 50 % algae increases the concentration of omega-3, iodine and vitamins, and the larvae are able to transform these nutrients to be digestible to salmon [30]. These are important nutrients that is of low content in today's soy and rape seed feed.

An advantage of establishing this solution at MIP, in addition to the available heat, is the closeness to Rana Fiskeprodukter AS in the industry park and salmon breeding facilities at the coast of Helgeland. An example of the system is presented in Figure 11.

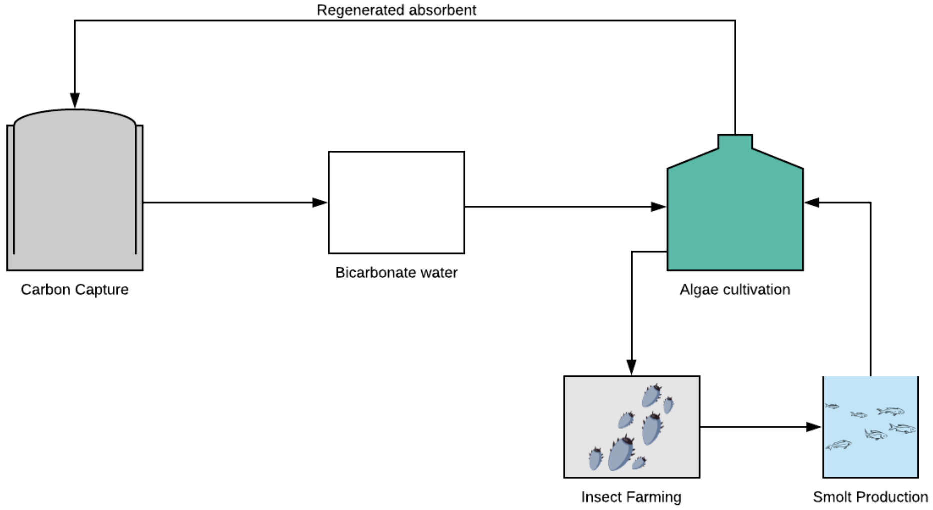


Figure 11: Flow chart combination of algae and insect solution

4.2 Heat for power generation

Electricity has very high flexibility for distribution and re-use, and all of the participants of this study use a substantial amount. Direct re-use of surplus heat is sometimes not a feasible option, for example due to lack of appropriate heat demand within reasonable geographical proximity. This is very often the case for Norwegian energy intensive industries, and thus heat-to-power conversion often becomes the remaining alternative [31]. Hence, the reduced efficiency explained in the beginning of Subsection 4.1 when converting low temperature heat to more flexible energy carriers should not be of great concern. This argument holds when the alternative is not utilizing energy from waste heat at all.

As seen in Table 7 there are several heat sources offering hot cooling water. By utilizing the temperature difference between the heated cooling water and cold cooling water in a turbine, electrical energy can be generated. As an example, an already existing solution offered by the Swedish company named Climeon is analyzed using inputs from Climeon and MIP. The solution is in use today in a Swedish steel plant in Borlänge owned by SSAB running at 300 MW, and is scalable with each module at 150 MW [32].

The process uses an organic Rankine cycle fed with used, hot cooling water ranging from 120 °C down to 60 °C on the hot side. On the cold side it is fed with cold cooling water ranging from 0 °C to 30 °C. The higher the temperature difference, the better efficiency can be reached. Climeon have provided a graph for net efficiency and power output for one module, assuming 40 l/s hot volume flow, see Figure 12.

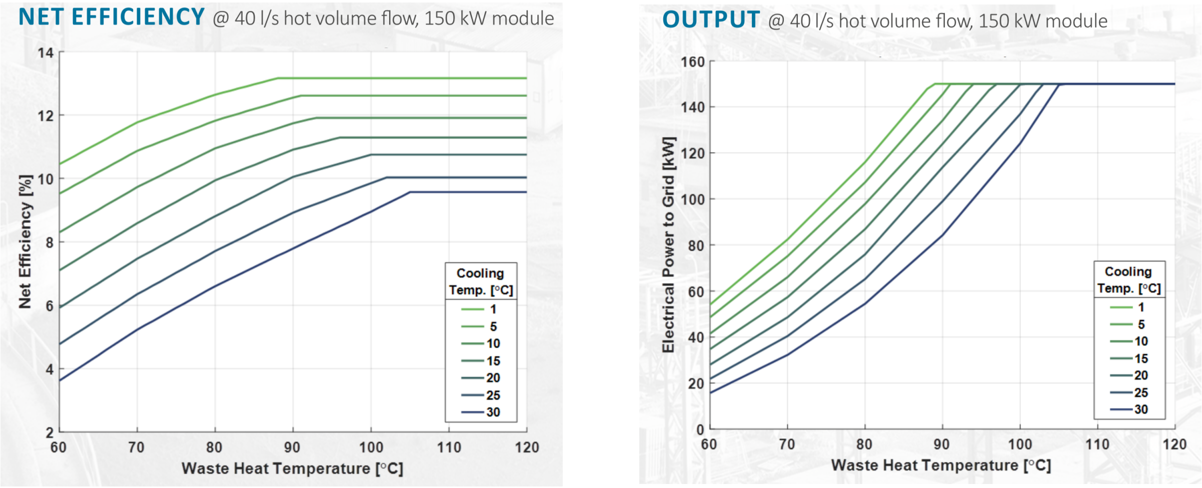


Figure 12: Net efficiency and power output for one Climeon module

Information gathered from Climeon included technical parameters, but not a focus on OPEX and CAPEX. Assumptions included availability of 8200 hours per year and a scenario generating 150 kW electricity with 1 module. This scenario would generate 1,2 GWh of electricity worth 0,37 million NOK each year assuming electricity price of 0,30 NOK/kWh. As seen in Table 7, there might be a sufficiently big surplus of low temperature heat energy to operate in big scale. This would drive costs down, which might make this a plausible solution. A full techno-economic analysis by relevant partners is recommended.

4.3 Heat for Cooling Solutions

As mentioned, ACDC has a electricity consumption of 1 MW which is expected to increase in the coming years. To prevent overheating of the servers, this means that they have an equivalent cooling demand of 1 MW. One way to supply this cooling demand could be through the use of excess heat in an absorption chiller.

The concept behind this idea is similar to that of a refrigerator. Heat is transferred to the cooling medium in the evaporator, simultaneously cooling the desired space. The evaporated cooling medium is then absorbed by an absorption medium in the absorber. This mixture is then pumped to the generator, where the cooling medium is boiled out of the mixture. This process is where the excess heat is needed. The absorption medium goes back to the absorber while the evaporated cooling medium continues to the condenser. After condensation, the cooling medium goes trough an expansion valve, dropping the pressure and temperature. It is then sent back to the evaporator again, and the cycle is repeated.

The space required and the investment costs for an absorption chiller is similar to that of a conventional cooling compressor. However, the cooling compressor typically operates at a COP of 4,0, whereas the COP for the absorption chiller is 0,7. This results in the absorption chiller being profitable if the price for heat is 1/6 of the electricity price. The immediate advantage is that this solutions uses heat, a low-grade energy source instead of electricity, the highest grade energy source.

5 Conclusion

In this report, several possible solutions for utilizing excess heat in MIP have been presented; some with better potential than others. For the high temperature cases, the solutions including CCS is considered the most promising. The area has already a considerable surplus of electrical production, thus keeping the local electricity price relatively low. It may therefore be challenging to make the case with only electrical production profitable. Stand-alone capture of CO_2 may not be profitable by itself either, but the potential of economic support from i.e. Enova and the increasing carbon credit prices may change that. Furthermore, being carbon neutral may have a strong marketing value in the future. Another aspect is the lower risk compared to the steam turbine, since there are more available sources that could supply the CCS system with the lower temperature requirement. The presence of expertise in CO_2 hub Nordland is also a positive factor for applying this solution. However, since the CCS solution has a potential of capturing CO_2 from several of the industries in MIP, there might be a dilemma in terms of who should finance the solution and who should operate it. By only taking the savings into account with today's electricity and carbon credit prices, we can see from Table 9 that the CCS only solution is the most profitable.

Table 9: Results for the different solutions for high temperature heat

Solution	Electricity produced	CO_2 captured	Annual savings
Electricity + District heating	75,5 GWh	-	22,7 mill.NOK
CCS only	-	620 000 tons	174,5 mill.NOK
Electricity + CCS + District heating	66,4 GWh	266 000 tons	94,3 mill.NOK
Electricity + CCS	66,4 GWh	449 000 tons	145,7 mill.NOK

For the low temperature excess heat, several of the proposed solutions are considered practically feasible. Using excess heat to melt icing in raw materials is possible, but we concluded that this was primarily a logistical problem instead of a heat problem. Moving the drying process of clipfish closer to the harvesting area to meet the growing market or contributing to Nordland being more self-sufficient on vegetables may both be sustainable

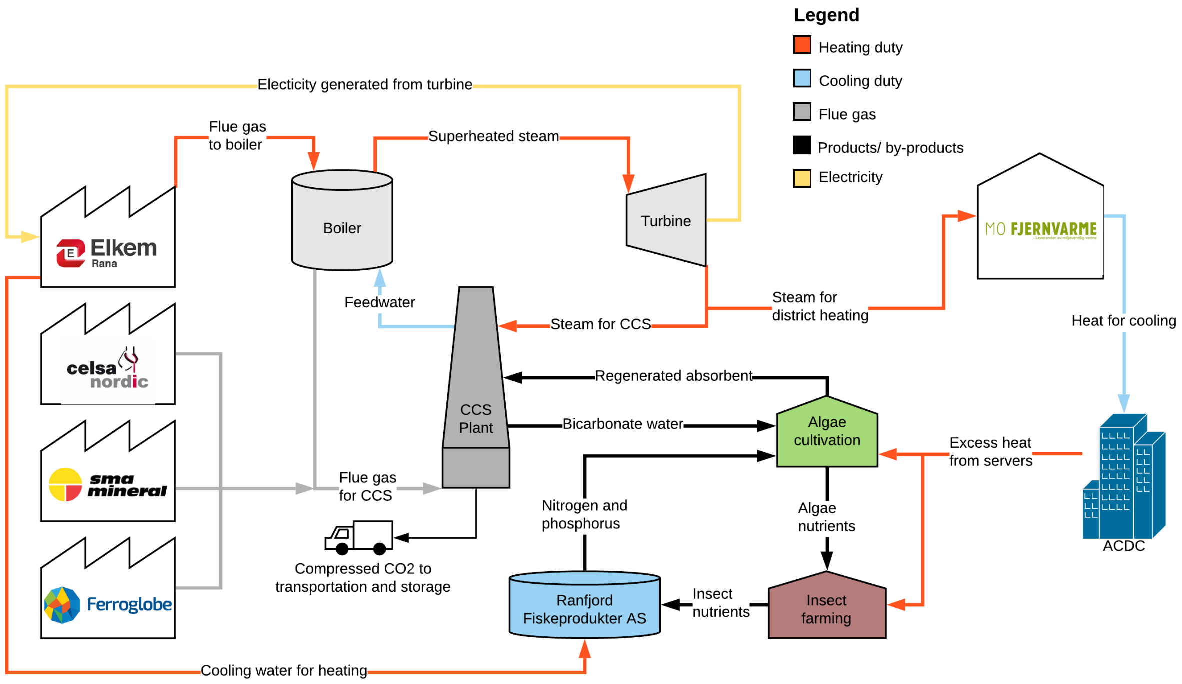


Figure 13: Proposition of future combinations of energy solutions in MIP

choices, i.e. by reducing transport. Producing electricity of the low temperature heat is also considered a plausible solution, but the yield may not be enough compared to all the other uses of the available heat. In this case however, considering the amount of excess heat, one solution does not exclude another.

The group find the case with combined algae and insect production for salmon feed most interesting in terms of innovativeness and sustainability. The main advantage is the linkage with the CCS solution, and the presence of the already operating smolt facility. The lack of light during winter and how it affects the algae's ability to capture carbon is however a barrier that needs to be looked further into. An illustration of how the complete system can look like, with selected solutions for both high and low temperature heat is presented in Figure 13.

Collecting realistic data about the economical aspects of the cases has been difficult, and a proper conclusion of which solution is optimal cannot be made without it.

5.1 Further Work

One of the main difficulties in working with the high temperature category was determining pricing of processing equipment and the associated operating costs. This made conducting a realistic techno-economic analysis nearly impossible due to the lacking economical aspect. Therefore, our primary suggestion for further research is that the companies retrieve actual offers regarding prices for boilers, turbines and a full-scale CCS plant, in addition to estimating operating costs. The companies can then conduct a present value analysis for each of the cases to determine the profitability. If the projects in themselves aren't profitable, ENOVA should be contacted for financial support. In regards of the CCS plant, there also needs to be a discussion around who has the responsibility to finance and operate the plant.

The low temperature part also included the difficulty of figuring out actual costs. For further research, this should be done in order to study the profitability. Compared to the high temperature category, we didn't go as deep into the technical aspects, meaning that further study of possible production amounts and technical barriers is needed. The combined algae and insect solution is a different and relevant solution for today's salmon breeding industry. We therefore recommend further research into this, possibly with already established feed producers as project owners.

References

[1] Mo Industripark AS. Hot charging sparer 30 GWh. `https://www.mip.no/2016/hot-charging-sparer-30-gwh/`, 2016.

[2] T. Nermark. Mo Industripark - en grønn industripark i verdensklasse. PowerPoint slides, 2018.

[3] Mo Fjernvarme AS. Produksjonsanlegg. `https://mofjernvarme.no/?page_id=54`, 2019.

[4] MIP Bærekraft. Satsingsområder for MIP Bærekraft. `https://www.mip.no/mip-baerekraft/`, 2019.

[5] Mo Industripark AS. Mo Industripark: Nøkkeltall. `https://www.mip.no/mo-industripark/#nokkel`, 2016.

[6] Miljødirektoratet. Energiforbuk: Elektrisk kraft, Elkem Rana AS. `https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=5122`, 2018.

[7] Miljødirektoratet. Energiforbuk: Elektrisk kraft, Ferroglobe Mangan AS. `https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=6476`, 2018.

[8] Miljødirektoratet. Energiforbuk: Elektrisk kraft, Celsa Armeringsstål AS. `https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=6474`, 2018.

[9] D.M. Flathagen. Mo Industripark: Grønn industriklynge med verdensambisjoner. `https://www.enova.no/bedrift/industri-og-anlegg/historier/mo-industripark-gronn-industriklynge-med-verdensambisjoner/`, 2017.

[10] Mo Industripark AS. Kraft i bruk - nyttig spillvarme. `https://www.mip.no/2012/kraft-i-bruk-fra-vann-til-verk/`, 2012.

[11] Celsa Group AS. Celsa Armeringsstål. `https://celsa-steelservice.no/hvem-er-vi/celsa-armerongsstal-var-leverandor/`, 2019.

[12] D. Gjetrang. Email correspondence.

[13] M.J. Moran, H.N. Shapiro, and D.D. Boettner. *Principles of Engineering Thermodynamics*. John Wiley Sons, 8 edition, 2015.

[14] Miljødirektoratet. År 2018 : Landbasert industri: Utslipp av karbondioksid (co2). `https://www.norskeutslipp.no/no/Komponenter/Utslipp/Karbondioksyd/?ComponentType=utslipp&ComponentPageID=51`, 2018.

[15] J Huseby, A.L. Brunsvold, S. Roussanaly, and X. Zhang. Techno economic evaluation of amine base co2 capture: impact of co2 concentration and steam supply. *SINTEF Energi AS*, 2012.

[16] Gassnova. Norcem brevik. `https://www.gassnova.no/no/prosjekter52/Fangst/norcem`, 2014.

[17] T.D. Eastop and A. McConkey. *Applied Thermodynamics for Engineering Technologists*. Pearson Education, Ltd., 5 edition, 2010.

[18] Norges Sjømatråd. Nok et rekordår for hvitfisk. `https://seafood.no/aktuelt/nyheter/nok-et-rekordar-for-hvitfisk/`, 2018.

[19] O.M. Magnussen and I.C. Claussen. Optimal klippfisktørking. *SINTEF Energiforskning AS*, 2008.

[20] Nordland Fylkeskommune. Et bærekraftig og nyskapende landbruk i nordland - regional plan for landbruk i nordland 2018-2030. 2018.

[21] O.A. Bævre, Ø.L. Bø, R. Jelsa, E. Randeberg, and M. Verheul. Energi til norsk veksthusnæring. *Bioforsk rapport, Vol.1 Nr. 119*, 2006.

[22] Norsk Gartnerforbunds energiside. CO_2. `http://ngfenergi.no/node/125`, 2014.

[23] K. Grjotheim. Reduksjon av utslipp av klimagasser fra veksthusnæringen. *Zero-rapport*, 2009.

[24] H. Skarstein. Vekstmuligheter i grøntsektoren. *Statens landbruksforvaltning*, 2012.

[25] Norsk Gartnerforbund. Prosjekt for innsamling av erfaringer og driftsdata fra pilotanlegg biobrensel og varmepumper i veksthus - sluttrapport. 2011.

[26] K.M Hovland. Ekstraregning for næringslivet: Disse rammes av den rekorddyre strømmen. `https://e24.no/energi/stroem/ekstraregning-for-naeringslivet-disse-rammes-av-den-rekorddyre-stroemmen/24548132`, 2019.

[27] O. Hess-Erga, I. Gjesteland, S.A. Wolff, and E. Vikingstad. Utnyttelse av oppløst og partikulært avfall fra smoltproduksjon i et resirkulasjonssystem. *Norsk institutt for vannforskning*, 2013.

[28] C. Zhanyou, J.V O'Fallon, and C. Shulin. Bicarbonate produced from carbon capture for algae culture. *Trends in Biotechnology*, 2011.

[29] Norges sjømatråd and Sjømat Norge. Soya og laksefôr. `https://laksefakta.no/hva-spiser-laksen/soya-og-laksefor/`, 2018.

[30] Erik-Jan Lock. Insekter gjør alger til nyttig laksefôr. `https://www.imr.no/hi/nyheter/2017/11/insekter-gjor-alger-til-nyttig-laksefor`, 2017.

[31] Trond Andresen. COPRO. `https://www.sintef.no/en/projects/copro/`, 2017.

[32] Climeon AB. Technical sheet climeon. `https://climeon.com/wp-content/uploads/2017/04/Climeon-Tech-Product-Sheet.pdf`, 2019.