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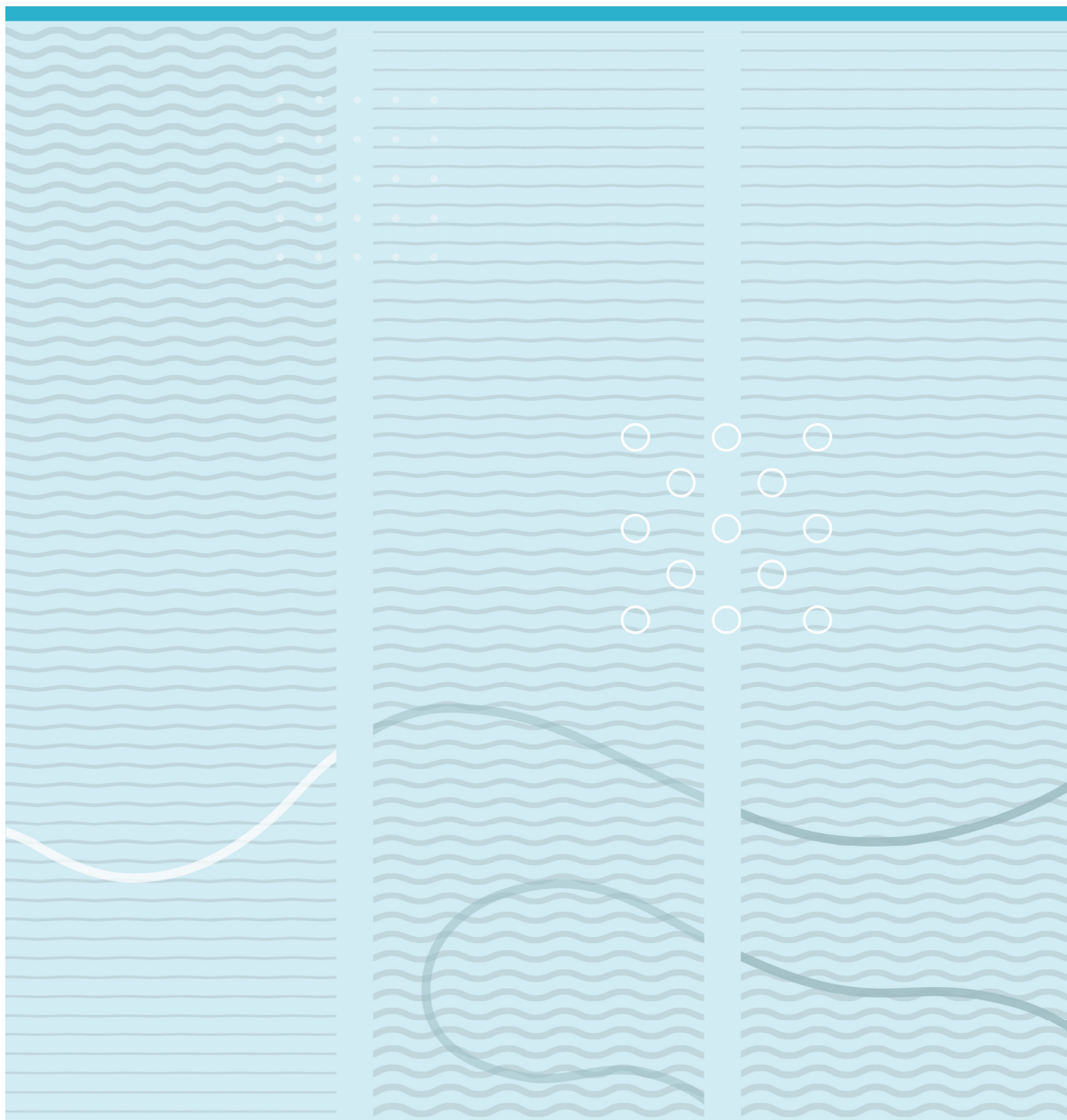
Paul Rune Bekkhus

Utilization of waste heat from cement kiln exhaust gases for regeneration of loaded CO$_2$ capture media

Sammendrag (in Norwegian)

Dette prosjektet var basert på noe som skjer på Norcem Brevik, hvor de er interissert i å bygge et CO_2-fangstanlegg. Og så har det seg det at de har veldig varmt eksosutslipp fra sementproduksjonen. Denne varmen er Norcem, og jeg, interissert i å utnytte for å redusere kostnadene som Norcem legger på seg når man såvidt tenker miljøvennlig. Oppgaven bestod av å designe, og beregne på et varmefangstanlegg. Dette har jeg gjort, med noen overaskende gode resultater.

Først så er det designet av denne Avfallsvarmeanlegget. To varmevekslere tar plassen der kjøletårnene står i dag, varmevekslerene ble designet etter Base Case verdier som ble gitt av Lars-André Tokheim. Hver av varmevekslerene har sin egen varmeoverføringsmengde ettersom parameterene er annerledes på hver, så den ene veksleren er større enn den andre, på $6200m^2$ og $1400m^2$. Den totale varmen tilgjengelig ble beregnet til å være 92085 MJ/h som tilsvarer 25579 kWh som ikke blir brukt til noe som helst. Men med disse varmevekslerene installert kan Norcem spare opp til 60 MNOK i året på utgifter. Dette ble beregnet ved a sammenligne hvor mye det hadde kostet å drive fangstanlegget i året uten å utnytte den ektra varmen fra eksosen.

Det ble gjort litt eksperimentering med hva som kunne være mest kosteffektivt, og det ble gjortforbedringer gjennom hele prosjektet. Mye kostnat tabeller som ble brukt var gamle å måtte rettstilles med inflasjonsfaktorer. Og det ble gjort mye automatisering av beregningene i Microsoft Excel med å erstatte vanskelige variable med relativt simple funksjoner i form av polynom og power funksjoner.

Denne rapporten kan potensielt vise veldig klart at det er veldig lønnsomt å tappe inn i denne gullgruven som gjemmer seg i skorsteinen på Norcem Brevik. Invisteringskostnadene endte opp på 84 MNOK, som hadde blir tilbakebetalt på under to år takket være reduserte oppvarmingskostnader i CO_2-fangstanlegget. Definitivt noe Norcem burde legge til på invisteringslisten sin om de bestemmer seg for å bygge et full-skala fangstanlegg.

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Preface

Som student på Høyskolen i Sørøst-Norge så måtte dagen komme. Jeg har gledet meg til å jobbe med en oppgave som denne en stund, og var veldig spendt på den. Og den skuffet ikke. Jeg hadde det gøy med denne oppgaven, og det var morro å jobbe med noe som var så lokalt som Norcem i Brevik, ettersom jeg har bodd i Porsgrunn hele livet selv.

Jeg følte at dette prosjektet var veldig relevant for fremtidig ingeniørarbeid. Veldig mye knoting med tall og oppslag i tabeller, som til slutt endte opp som fine resultater som kan deles med de som er interisserte.

Rapporten er strukturert i samme rekkefølge som tallene strømmet inn. Men de fleste tallene som ble brukt til utregninger og grafer ligger bakerst i Appendixene.

Takk for meg

Paul Rune B. Bekkhus.

1 Introduction

1.1 Background

The plant at Norcem Brevik produces cement in Kiln 6, a rotary kiln burner that was upgraded in 1989 with new preheater strings. Kiln 6 is connected to a precalciner and four stages of cyclones, in which the raw materials are fed from the top, and heated on the way down before it reaches the combustion chamber. The exhaust from the precalciner is sent into the preheater cyclone strings where it heats the new incoming raw materials. Fuel is fed into the combustion chamber where it is burned to achieve a 90% calcination of the preheated meal, which is completely calcined near the kiln inlet. The precalcined meal goes into the rotary kiln where at the peak temperatures of over 2000 °C forms clinker.

The combustion part of this process potentially introduces a lot of CO_2 into the atmosphere where it can contribute to global warming. Because of increased awareness of climate change, it has been a topic of interest for many companies around the world to reduce the emissions of greenhouse gases. In this project, a study will be performed to see how excess heat from a cement production plant can be used to assist operating a CO_2 capture plant. This will be done by calculating how much heat that can be extracted from the exhaust gas of the process, then comparing that number to how much heat is needed to capture a set percentage of the CO_2 produced.

The making of clinker produces a lot of heat. Although the preheater system is efficient at using the waste heat from the combustion to heat the raw materials, the exhaust still exits at temperatures of 380 °C with a lot of energy to spare. This energy could aid in running a regeneration unit of an amine CO_2 capture plant. Amine based CO_2 capture utilizes amines like MEA (Ethanolamine) to absorb CO_2 from a gas stream under cold conditions. The CO_2-rich amine can then be transported by pipe to another column where it is heated to then release the CO_2 in more or less pure form. The amine, now with low concentrations of CO_2 within it, is cooled and transported back to the absorption column to complete the cycle. The regeneration unit requires a lot of energy to heat the amine solution to regenerate CO_2, and some of this energy could come for "free" by exploiting waste heat from the cement production.

By installing a Waste Heat Recovery Unit (WHRU), some of the excess heat from the plant could be converted to steam to help run the regeneration of CO_2. This would reduce the operational costs of CO_2 capture at Norcem, or any other plant that has high CO_2 emissions and available waste heat.

1.2 Problem description

If Norcem was to install a CO_2 capture unit based on amine technology, the regeneration column would require a lot of energy to be able to recover the CO_2 from the MEA solution. This could be procured by using electricity to create steam in a standalone solution, where all the energy would come from an outside source. Or, it could be partially acquired by using heat exchangers to capture the waste heat in the exhaust gas to produce low pressure steam to be used in the regenerating the CO_2.

By installing a WHRU to produce steam, the operational cost of an amine CO_2 capture plant could potentially be reduced. To find which solution is better, both will be evaluated, with the focus in this report being on the WHRU solution.

In the case of a cement production plant, this brings with it one complication. The exhaust gas from the precalciner contains particles that would make some types of heat exchangers unusable, in the sense that the dust might partially or completely block the air paths.

1.3 Objectives

This thesis will focus on finding out whether or not it would be advantageous to integrate waste heat capture with a planned amine CO_2 capture plant. In the example of Norcem, would using the excess heat from the precalciner exhaust stream reduce the operational costs of a regeneration column of such a CO_2 capture plant. And secondly, finding out how many percent of the CO_2 the plant produces today could be captured by using only the available excess heat from the cement production.

Along the way the report will go further into how this integrated system may look, including system specifications, and what kind of heat exchangers would be best suited for the job. The costs and benefits of the waste heat capture solution will also be evaluated by looking at investment costs when comparing the integration and a standalone solution.

1.4 Structure of the report

This report will work toward its goal first by explaining the concepts it is working with, the processes involved in the calculations. Then the concept of the Waste Heat Recovery Unit is described and explained in detail, how it will work, and how it ties the processes together.

When the introduction to the processes are out of the way, the calculations on the process parameters will be next. Calculating the amount of energy the WHRU has available to be convert into steam, followed by how much water is needed to convert it all.

When the amount of waste heat has been calculated, converted to steam and transported to the amine reboiler, it is time to find out how much of the CO_2 can be captured using this energy. This will be used later in the report to calculate how much money can be saved over time, as the operational cost of the reboiler is lessened thanks to this new source of "free" energy. It is not completely free, as it will come apparent in the report as the CAPEX is calculated from how the WHRU-system is designed.

This all will be for the sake of finding out whether investing WHRU is a bad, a good or a great idea. Using the answers found in this report a conclusion shall be drawn if it is worth the investment or not.

2 System description

Now that the processes involved have been presented, it is time to see how they will all fit together, this chapter will be focused on describing how they intertwine, as well as the calculations leading to finding the specifications of the process.

2.1 Concept

The excess heat in the exhaust gas from the cement production will be captured using shell and tube heat exchangers, which transfers the energy to cooling water and converts it into low-pressure steam. This steam is used to heat the CO_2-rich amine in the reboiler of the carbon capture process.

This concept can serve one of two purposes. The first would be to cut down the energy cost of the capture process by a significant amount, and serve as an overall cost improvement, as the reduction of OPEX would outweigh the CAPEX significantly on a 20-year period. The second purpose would be to remove the cost of steam completely, as a scenario where there would be no additional steam supplied to capture CO_2 and would rely solely on the steam produced from the waste heat of the cement production process.

The WHRU will mainly consist of two heat exchangers, each connected to one of the exhaust gas pipes on the cement power plant, after the reheating of the incoming material, and before the exhaust cleaning.
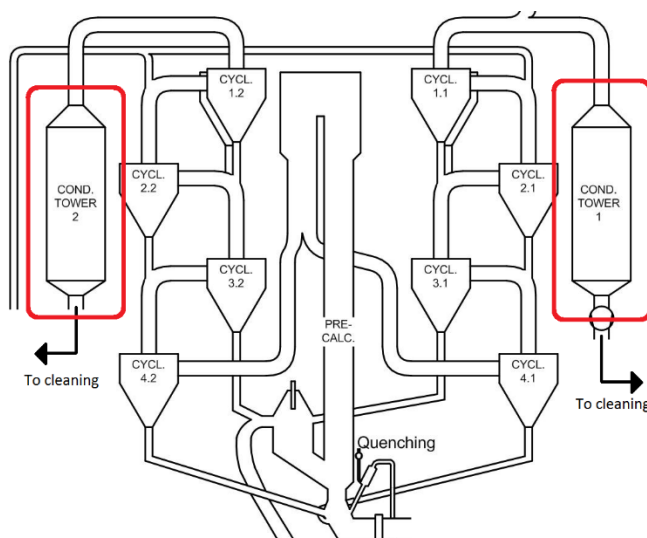
Figure 1 The calcination and heating parts of the cement production at Norcem. As well as the cooling towers for the exhaust gas.

In Figure 1 the cooling towers for the exhaust gas are marked in red. Today these cool the exhaust gas so it does not damage the environment or the cleaning equipment. The point of the WHRU is getting the exhaust gas down to a manageable temperature, while at the same time using the leftover energy to something useful; in this case, it is running a CO_2 capture plant based on amine technology by supplying the reboiler with heat. The cooling towers will be replaced with large heat exchangers capable of converting all of the excess energy into useful steam that can be transported a short distance to be used to capture CO_2 produced by the same plant.

2.2 Design basis

This project is based around a project currently located at Norcem Brevik, where they are experimenting with the idea of capturing CO_2 using amine technology. Since capturing CO_2 is quite costly it is smart to look for clever solutions wherever they might hide. In this case, it is the hot flue gas coming out of the calcination process.

Numbers supplied from supervisor Lars-André Tokheim, former employer and current adviser for Norcem, will be used to determine the parameters and come to a conclusion about whether or not to install a Waste Heat Recovery Unit.

Numbers supplied:

Table 1 Base case values for Norcem.

Point	Units	1	2	3	4
Gas Flow Rate	Nm³/h	132250	132250	132250	132250
Temperature	°C	386	120	386	224
Flue Gas component		Nitrogen	Oxygen	CO2	Vapour
Vol%	%	61	7	23	9

The numbers in Table 1 are constants this project have to work with, with the exceptions of the outlet temperatures of the flue gas, as these might vary in the actual process depending on necessity.
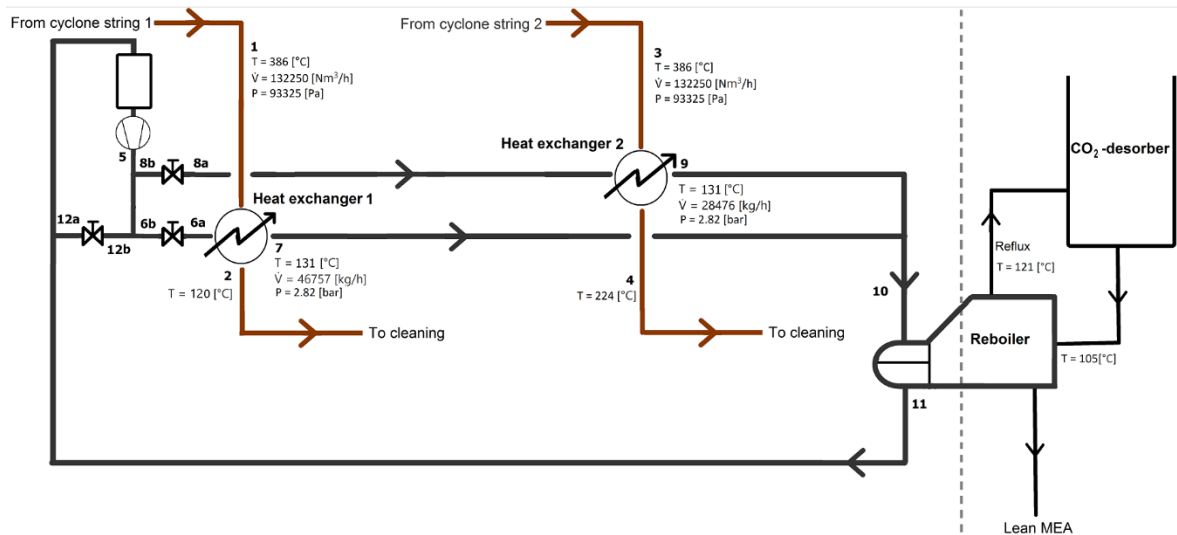
Figure 2 The Waste Heat Recovery Unit PFD integrated with the cement plant Norcem and their new CO_2 Capture plant.

In Figure 2 above, the heat exchangers of the recovery system is integrated with the exhaust gas from Norcem at streams 1, 2, 3 and 4 where it produces steam from the excess heat. It is also integrated with the amine reboiler of the CO_2 capture plant in between streams 10 and 11, where it supplies the energy it gets from the exhaust gas in the form of steam. The steam production should happen on the inside of the tubes, as the volumetric flow of flue gas is high.

For this project, the heat exchanger that will be used is the Shell and Tube heat exchanger. The figure below shows the basic components of a Shell and Tube heat exchanger.
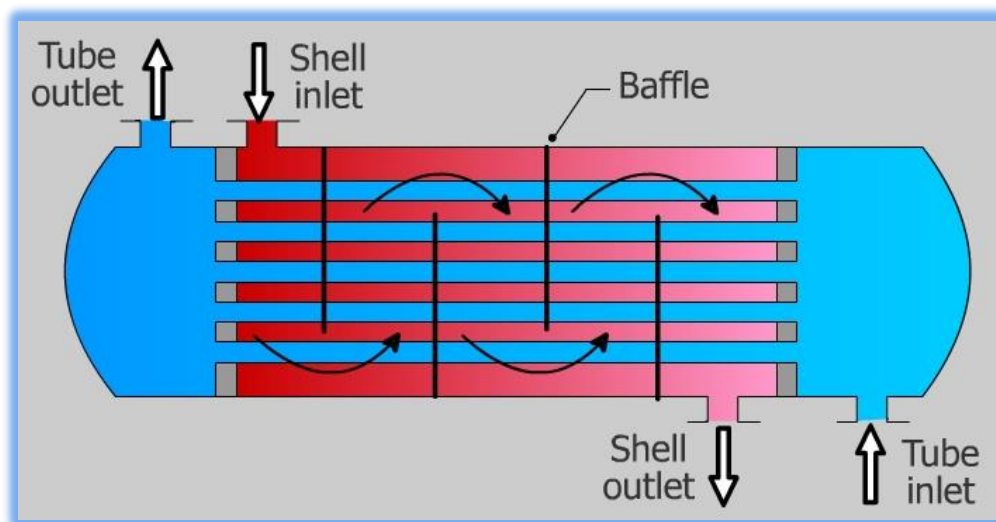

Figure 3 simplified diagram of a Shell and tube heat exchanger[1]

Feil! Fant ikke referansekilden. shows the two separated systems of tube and shell, where two fluids are exposed to each other with a very large increase in surface area. The type of heat exchanger that will be used in this project are cross-flow shell and tube heat exchangers.

All necessary stream parameters were calculated and put into a table located on APPENDIX B, such as stream volumes, temperatures, pressures, and densities.

There are three valves underneath a water collection tank and pump. The pump pumps water out from the collection tank and into pipes leading to the heat exchangers. The stream is split into two, where valves 8 and 6 control the volume flow into each one. Valve 12 is a safety valve that should be pressure sensitive. If one of the valves fail, and pressure builds up because the pump is not being turned off, Valve 12 releases the pressure into a closed loop between the pump and the collection tank. This makes sure that the pipes, the valves and the pump is not damaged from sudden failure [9].

As for the CO_2 capture plant parameters, the values given is the temperature of the amine in and out of the reboiler, as well as the specific reboiler duty. The temperature into the reboiler is 105 °C and out is 121 °C. The specific reboiler duty is assumed to be 4.2 $MJ/kgCO_2$.

2.3 Steam production

The production of steam depends on temperature out of the heat exchanger, which in turn answers to the area of the heat exchanger and the flow of cooling water. To calculate the amount of steam that can be produced from the waste heat, the temperature of the steam will have to be calculated. The base case indicates the minimum temperature needed is 121 °C. To get the inlet temperature needed for the steam the delta T must be added.

$T_{HX,in} = 121°C + 10°C = 131°C$ *Equation 1*

That gives 131 °C as the minimum temperature of the steam needed. The delta T can be set as 10 °C for the time being. Decreasing it would increase the surface area in the heat exchanger, in turn increasing the size and cost. The temperature of the steam out should be the lowest amine temperature in plus the delta T.

$T_{HX,in} = 105°C + 10°C = 115°C$ *Equation 2*

The heat exchanger is to be properly designed to condense all the steam, and cool it down to the temperature acquired in Equation 2. If the steam temperature is higher or lower than the wanted temperature, then the heat exchanger would need to be redesigned with more or less surface area to fit the system specifications. In that regard, if the temperature is higher than specified it means that the reboiler is not receiving all the energy the amine needs to release the CO_2, which in turn means that the lean amine re-entering the absorption column is less able to absorb new matter as there is a concentration of CO_2 in it already. (Not to mention that the new flow of amine would have a higher concentration of CO_2 in it, which would

require even more energy to release it all, in a reboiler already not able to meet the energy demand.)

Now that the in and out temperatures of the steam are established, and the exhaust temperatures are defined in our base case in chapter 2.2 and APPENDIX B, the amount of water that needs to be pumped into the heat exchangers to absorb all the available excess energy can be calculated. To calculate this, the flow of hot exhaust gas is needed, and is supplied by the base case as a constant 132250 Nm^3/h. To convert the units from Normal value to actual values, as the pressure and temperature are not atmospheric, the equation below is used.

$$\text{Real Value} = \text{Normal Value} * \left(\frac{T}{T_0}\right) * \left(\frac{P_0}{P}\right) \qquad Equation\ 3$$

Where T_0 and P_0 represents the atmospheric values 293.15K and 101325 Pa respectively. Here, T is the exhaust gas temperature in Kelvin, and P is the real pressure in Pascal. The Normal value is the standardized value for the gas flow at standard conditions and has the units Nm^3/h. From base case, it is known that the temperature T is 386 °C, and P is 93325 Pa, these values are in the table in APPENDIX B.

$$\text{Real Value} = 132250 \frac{\text{Nm}^3}{\text{h}} * \left(\frac{293.15\ \text{K}}{(386+273.15)\text{K}}\right) * \left(\frac{101326\ \text{Pa}}{93325\ \text{Pa}}\right) = 346495 \frac{\text{m}^3}{\text{h}} \qquad Equation\ 4$$

There are two of these streams, but the outlet temperatures from the heat exchangers are different, so the amount of energy that can be extracted from each one has to be calculated separately and summed up at the end.

The beauty of standardized volume flow is that it will remain at the same value if the temperature and pressure are altered. This means the same kind of calculation can be used to find the volume flows of exhaust gas out of the heat exchangers. So for stream two and four the volumetric flow are found to be 206667 m^3/h and 261337 m^3/h using the same calculation method, as their temperatures are lower than the input of streams one and three.

From the non-standardized volume flow the mass flow can be achieved by multiplying the volume flow with the gas density. All the volume flows are known, and the densities are found by using ideal gas law.

$$\rho = \frac{P * \overline{M_W}}{R * T} \qquad Equation\ 5$$

Where ρ is the density [kg/m^3], P is the gas pressure [Pa], R is the gas constant [m^3·Pa/(K·mol)], T is the gas temperature [K]. M is the average molar mass [kg/kmol] and is calculated by using the volume percentages given in the base case.

$$\overline{M_W} = \Sigma(M_{W,i} * x_i) \hspace{4cm} \textit{Equation 6}$$

By inserting values for, for example, one of the inlet streams into the ideal gas law equation for density we get:

$$\rho = \frac{\left(93325\ Pa * 31.07 \frac{kg}{kmol}\right)}{\left(\left(8.314 \frac{m3 \cdot Pa}{K \cdot mol}\right) * (386\ {}^\circ C + 273.15\ K)\right)} = 0.529\ \frac{kg}{m^3} \hspace{2cm} \textit{Equation 7}$$

The density is multiplied with the volumetric flow to get the mass flow. This can be done with any of the four streams, since fundamentally they have the same amount of gas in them, to get 183335 kg/h in each of the two strings. Doubling the value gives:

$\dot{m}_{tot}$ = 183335 kg/h · 2 = 366670 kg/h,

and is the total amount of exhaust gas emitted by the cement production.

Now that the mass of hot exhaust gas, and the temperatures before and after cooling is known, it is possible to calculate the amount of energy Norcem can extract. The energy in the two strings can be calculated by seeing the difference in energy between the two states of high and low temperatures, using the equation:

$$\Delta \dot{E} = \dot{m} * Cp * (T2 - T1) \hspace{4cm} \textit{Equation 8}$$

Where $\Delta \dot{E}$ is the difference in energy [MJ/h] between the two temperatures T_1 [°C] and T_2 [°C], the mass flow [kg/h], $\dot{m}$, is as found in APPENDIX B. C_p is the specific heat of the gas [kJ/kg·K)]. Now, these will have to be calculated once for each string as the desired outlet temperatures are different the two. To get results that are more accurate in the calculations, the temperature variation will have to be taken into account when calculating the specific heat.

The specific heat, C_p, will directly affect the result we get for energy output, and can vary with up to 10% from standard conditions to the base case conditions. The way chosen to go about the calculation of a mean specific heat is by using external data sheets with values of specific heats for each element at different temperatures. Then by inserting them into tables in Microsoft Excel, a graph will be made to represent the data before a polynomial trendline is made that can be used to calculate a more accurate C_p. The trendline equation is displayed in the graphs below. These polynomial equations will then be used to find the average specific heat for each individual stream.

By using the polynomial equations displayed on the graphs in APPENDIX C, the following values for C_p are achieved.

Table 2 Showing the results for the polynomial equations for the specific heat for all the components in the exhaust gas, as well as liquid water.

Stream	1	2	3	4	5	6	7	8	9	10	11	12
Temperature [°C]	386	120	386	224	115	115	131	115	131	131	115	115
Nitrogen [C_p]	1.09	1.04	1.09	1.05	-	-	-	-	-	-	-	-
Oxygen [C_p]	0.97	0.94	0.97	0.96	-	-	-	-	-	-	-	-
CO_2 [C_p]	1.12	0.94	1.12	1.02	-	-	-	-	-	-	-	-
Vapour [C_p]	2.06	1.90	2.06	1.96	1.90	1.90	1.91	1.90	1.91	1.91	1.90	1.90
Water [C_p]	-	-	-	-	4.21	4.21	4.18	4.21	4.18	4.18	4.21	4.21
Average [C_p]	1.17	1.09	1.17	1.12	4.21	4.21	1.91	4.21	1.91	1.91	4.21	4.21

Table 2 uses the volume percentages from the base case of each gas to calculate the average specific heat of the flue gas. The liquid water and steam streams are calculated purely by inserting the temperature into the respectable polynomial equation as there is only one component in streams 5 to 12. The stream numbers are referred to in Figure 2 and APPENDIX B.

Now that Cp has been acquired it can be inserted into Equation 8.

$$\Delta \dot{E} = 183335 \frac{kg}{h} * 1.17 \frac{kJ}{kg \cdot K} * (120 - 386)K = 57230000 \frac{kJ}{h} = 57230 \frac{MJ}{h} \quad \text{Equation 9}$$

Using the same method for the other exhaust string that exits the heat exchanger at a higher temperature, 224 °C, one would expect that the energy output is less than the first. This is exactly what can be seen as it yields 34855 MJ/h. The total excess energy available in correlation to the base case is 92085 MJ/h

The amount of water needed to cool the exhaust gas while being evaporates and heated to the previously specified and calculated values can now be found. The energy in the exhaust gas transfers through the steel tubes of the heat exchangers and into the water. First, it will cause the water at 115°C to boil until there is no more liquid flowing in the heat exchanger's pipes. After that, the steam heats further to reach the afore-calculated 131°C. Which means:

$$\text{Energy Transferred} = \text{Evaporated Water} + \text{Heated Steam} \quad \text{Equation 10}$$

The amount of heat transferred is already calculated, but the mass flow of water remain unknown. Inserting equation for heating and evaporation yields:

$$\Delta \dot{E} = \dot{m} \cdot \Delta hvap + \dot{m} \cdot Cp \cdot \Delta T \quad \text{Equation 11}$$

Where $\Delta hvap$ is 40.65 [8]. Solving for $\dot{m}$ yields:

$$\Delta \dot{E} \ = \ \dot{m} \left(\frac{\overline{Mw}}{\Delta hvap} \ + \ Cp \cdot \Delta T \right) \qquad\qquad \textit{Equation 12}$$

$$\dot{m} \ = \ \frac{\Delta \dot{E}}{\left(\frac{\overline{Mw}}{\Delta hvap} + Cp \cdot \Delta T \right)} \qquad\qquad \textit{Equation 13}$$

Here we have all the values needed to calculate the mass flow of water required.

$$\dot{m} \ = \ \frac{\left(57230000 \frac{kJ}{h} \right)}{\left(\left(\frac{18.02 \frac{kg}{kmol}}{40.65 \frac{kJ}{kmol}} \right) + 1.907 \frac{kJ}{kg*K} * (131-115)K \right)} \ = \ 25031 \frac{kg}{h} \qquad \textit{Equation 14}$$

The second exhaust stream needs less water as it requires less cooling to reach 224°C. Inserting 34855 MJ/h into the same equation gives 15245 kg/h for the hotter string. These two strings of exhaust gas cool in parallel, so the total amount of cooling water needed will be:

$$\dot{m}_{tot} \ = \ 25031 \frac{kg}{h} + \ 15245 \frac{kg}{h} \ = \ 40276 \frac{kg}{h} \qquad\qquad \textit{Equation 15}$$

So by feeding 40 tons of cooling water into the heat exchangers, 25 tons to the first and 15 tons to the second, simply controlled with a pump and two valves, the WHRU would produce steam while cooling the exhaust according to the limits given by Norcem.

The table of streams in APPENDIX B gives an image of the sizing compared to what is already implemented for the flue gas. Compared to the flow of gas in volume per hour. The pipes would be around 10% the size of the smallest exhaust pipes.

2.4 CO_2 recovery using waste heat

According to a study done by Lars-André Tokheim, Nils Eldrup and Anette Mathisen in 2015, the required heating in a reboiler on a CO_2 capture plant based on amine technology, is 3.7-4.2 MJ/kgCO_2 [11]. To be a bit conservative when it comes to expectations of the technology, this report will proceed with the worst-case scenario of a 4.2 MJ/kgCO_2. This is in an attempt to make sure the energy demand is not underestimated. The technology itself might improve in the next few years, and the energy demand may even not be as high as this.

Using this number as a basis for the calculations, it is as simple to find how much CO_2 the energy supplied by the excess heat of the cement production as to divide the energy we have converted into steam by the amount of energy needed to capture one kilo of CO_2 gas.

$$CO_2 \text{ Captured using only excess energy } = \frac{\text{Excess Energy}}{\text{Specific reboiler duty}} \qquad \textit{Equation 16}$$

Inserting numbers into this equation yields:

$$CO_2 \text{ Captured using excess energy } = \frac{\left(92085\frac{MJ}{h}\right)}{\left(4.2\frac{MJ}{kgCO_2}\right)} = 21925\,\frac{kg\,CO_2}{h} \qquad \textit{Equation 17}$$

That is 22 tons of CO_2 per hour captured using energy that would otherwise be wasted. The cement factory in Brevik produces a total of:

$$\dot{m}_{CO2,produced} = \text{ Total Volume Flow } * x_{CO2} * \rho_e \qquad \textit{Equation 18}$$

Where x_{CO2} is the volume percent of CO_2, and ρ_e is the density of the exhaust. Inputting all the numbers gives:

$$\dot{m}_{CO2,produced} = 346495\,\frac{m3}{h} * 2 * 0.23 * 0.529\frac{kg}{m3} = 84334\,\frac{kgCO2}{h} \qquad \textit{Equation 19}$$

Which means the excess energy alone is able to capture **26%** of the produced CO_2. What this could mean is that installing the WHRU could very possibly be a big save on the operational costs of the reboiler, the unit responsible for the largest energy consumption when it comes to amine capture technology.

When building the capture plant it could be scaled to capture what percent CO_2 Norcem seems fit. If they decided that the operational costs of the reboiler were too taxing, building a capture unit utilizing only the excess energy from the cement production would reduce it to zero. Alternatively, they invest in a WHRU next to a full-scale capture plant that would reduce the operational cost. This is the main topic in chapter 3.1.

3 Cost estimation

This chapter is all about why Norcem should invest in a WHRU system. How the operational costs and capital cost are affected by the addition of a WHRU will be looked into, as well as different cases for what might be more "profitable".

3.1 CAPEX

Investing in a process that can utilize energy as to reduce the overall operational costs is not always profitable. If the amount of energy available were not high enough, the investment will not be paid back in the form of reduced expenses.

The investment cost of the WHRU-system will be found by calculating the cost of each individual equipment using the equation

$$\text{Log}(C_p^0) = K_1 + K_2 \log(A) + K_3 (\log(A))^2 \text{ [2]} \qquad\qquad \textit{Equation 20}$$

Where C_p^0 is the equipment cost in USD. The K values are data acquired from surveys of equipment manufacturers in 2001 and A is the size parameter for the equipment. Solving for the equipment cost gives the formula:

$$C_p^0 = 10^{\ K_1 + K_2 \log(A) + K_3 (\log(A))^2} \qquad\qquad \textit{Equation 21}$$

The cost found using the K values in table A.1 are those found during surveys in 2001, so since these are used in this chapter, an inflation factor must be used to convert the prices to today's market. Looking at inflation date online, the CPI (Consumer Price Index) for 2001 is around 178, and 237 for recent 2016 data [7]. The correction formula for inflation is shown below.

$$\text{New Cost} = \text{Old Cost} * \frac{Index\ New}{Index\ Old} \qquad\qquad \textit{Equation 22}$$

The factor that should be used on the equipment cost found with Equation 22 is then:

$$\text{Inflation factor } (2001 - 2016) = \frac{Index\ New}{Index\ Old} = \frac{237}{178} = 1.33 \qquad\qquad \textit{Equation 23}$$

This correction factor is multiplied with all equipment cost before any other factors are applied, such as material factors and installation factors.

Installation factor

Each equipment cost only represents the flat price on them, how much they cost from the manufacturer. To find the total cost it takes to have the equipment bought, transported and installed, the cost is multiplied by a general installation factor that depends on the price of

the equipment. In this report, the installation factor is calculated using a installation factor chart. This chart take all significant factors into account before adding them up.

Since the prices of the equipment varies a lot for each one, and since it is interesting to look at different cases for each equipment, it is preferred to have an equation that can easily calculate the installation factor. This was achieved using the trendline function in Microsoft Excel to get a polynomial function that represents the data on the chart.

Because the installation factor chart is represented in intervals, the mean value for each interval is used to represent a point value. These are then paired with the installation factor for its represented interval to make a graph.

Table 3 Table showing averaged intervals for installation factor. The values are found using the installation factor table made by [Nils Henrik Edrup, 2013, Porsgrunn] Found in APPENDIX D.

Price Interval (kNOK)	0-20	20-100	100-500	500-1000	1000-2000	2000-5000	5000-15000	15000-
Min	0	20	100	500	1000	2000	5000	15000
Max	20	100	500	1000	2000	5000	15000	45000
Mean	10	60	300	750	1500	3500	10000	30000
Inst. Factor	23.63	12.13	7.57	6.02	5.16	4.28	3.89	3.11

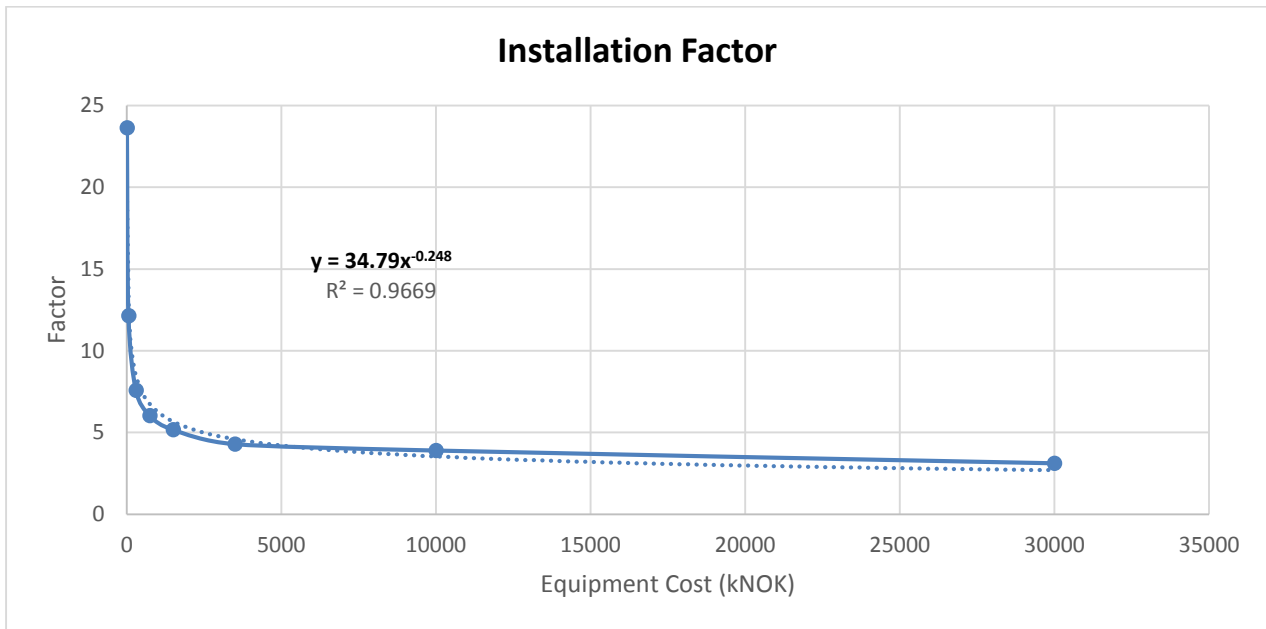From the table above, the following graph and trendline is achieved.

Figure 4 Graph showing trendline for installation factor.

For this graph, the best fitting trendline is the Power trendline:

$$y = 34.79 * x^{-0.248} \qquad \textit{Equation 24}$$

where x is the cost of the equipment in kNOK, and y is the installation factor that should be multiplied with the manufacturing cost.

The heat exchangers

The equipment that will represent the largest portion of the WHRU investment cost will be the two steam producing heat exchangers. To be able to use the Equation 21 to find the cost of these heat exchangers, the A will have to be found, which in this case is the surface area of the heat exchanger.

The equation that is used to find the area of the heat exchangers:

$$E = U * A * \Delta Tm \qquad \textit{Equation 25}$$

$$A = \frac{E}{U * \Delta Tm} \qquad \textit{Equation 26}$$

Where E is the energy transferred from the flue gas to produce steam. U is the overall heat transfer coefficient, and ΔT_m is a value found with the equation

$$\Delta T_m = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln\left(\frac{T_1 - t_2}{T_2 - t_1}\right)} \qquad \textit{Equation 27}$$

Where T_1 and T_2 are the temperatures of the flue gas, and t_1 and t_2 are the temperatures of the cooling water in and out of the heat exchanger.

Inserting numbers from previous chapters gives us a ΔT_m of 63.58 for the heat exchanger with a flue gas outlet of 120 °C and 171.8 for the one with 224°C. We get surface areas of 6251m^2 and 1409m^2.

Table 4 Showing the acquired ΔT$_m$ and area for the two heat exchangers,

		HX 1	HX 2	Total
Energy available	MJ/h	57230	34855	92085
ΔT_m	°C	63.58	171.8	
Area	m^2	**6251**	**1409**	

Now, in the table we are using for calculating the cost [2], the maximum area per heat exchanger is 1000 m^2, which means that we need to run several heat exchangers in parallel to reach the area needed to extract all the available energy. One way of doing this is to calculate the amount of heat exchangers needed for a sequence of areas to fulfill the criteria, and then calculate the installation cost of each area, and represent the results in a graph.

With the size of the heat exchangers calculated, the values can be inserted into equation 21 to find the 2001 cost of the heat exchangers. The K values chosen are in Table A.1 and are listed below.

K1	K2	K3
4.8306	-0.8509	0.3187

Inserting these values for different areas gives the table below.

Table 5 showing the results from the cost equation when inserting different heat exchanger surface areas.

Max A	Cost HX1	Cost HX2	Total Cost
100	161.99	38.57	200.56
125	141.82	33.37	175.19
150	125.51	29.88	155.39
175	114.97	28.74	143.71
200	108.69	27.17	135.87
225	100.75	25.19	125.93
250	98.75	22.79	121.53
275	91.92	23.98	115.90
300	88.08	20.97	109.05
325	87.82	21.95	109.77
350	82.57	22.94	105.50
375	81.30	19.13	100.44
400	79.64	19.91	99.56
425	77.59	20.69	98.28
450	75.14	21.47	96.61
475	77.86	16.69	94.55
500	74.83	17.27	92.10
525	71.41	17.85	89.26

Max A	Cost HX1	Cost HX2	Total Cost
550	73.74	18.44	92.18
575	69.74	19.02	88.76
600	71.88	19.60	91.48
625	74.02	20.19	94.21
650	69.25	20.77	90.02
675	71.20	21.36	92.56
700	65.84	21.95	87.79
725	67.61	15.02	82.63
750	69.37	15.42	84.79
775	71.14	15.81	86.95
800	64.82	16.20	81.02
825	66.40	16.60	82.99
850	67.98	16.99	84.97
875	69.57	17.39	86.96
900	62.26	17.79	80.05
925	63.66	18.19	81.84
950	65.05	18.59	83.64
975	66.45	18.99	85.44
1000	67.86	19.39	87.25

From the table it shows that the best size for the heat exchangers is 900 m^2 with a total investment cost of 80.05 MNOK. But there is a way of reducing the cost a little bit more, and that is to use the least costly areas for the heat exchangers separately. This gives that heat exchanger number one is 900m^2 at 62.26 MNOK, and the second at 15.02 MNOK with a surface area of 725m^2. Ending up on a total of 77.28 MNOK for the heat exchangers.

Pump

To calculate the cost of the pump using the equation above, the power required of the pump is needed, and is calculated using

$$P_{pump} = \frac{Q*\rho*g*h}{(3.6\cdot10^6)} \hspace{4cm} \textit{Equation 28}$$

Where Q is the volume flow [m3/h], ρ is the density of the fluid [kg/m3], g is the gravity constant and h is the total height the pump has to push the water. The pump power this equation gives is given in kW, and none of the efficiencies are included and will have to be taken into account. [https://neutrium.net/equipment/pump-power-calculation/] Inserting all these values gives;

$$P_{pump} = \frac{40.66*990*9.807*50}{3.6\cdot10^6} = 5.483 \text{ kW} \qquad\qquad\qquad\text{Equation 29}$$

Now since the efficiencies of a pump can vary down as low as 80% from the losses from shaft work, gearbox and other factors, we can with safe assumptions say that we would at least need a pump working at 8 kW. Using this value in equation 21 gives 5 k$.

Tank, Valves and Piping

The rest of the equipment are calculated the same way. The collection tank is chosen to be $100m^3$ since the volumetric flow would be close to $40m^3$/h. This way, the tank could stay at a safe level, and still have plenty of wiggle room to increase or reduce the flow a little without a problem. The size could also be smaller, but it would affect the overall price of the WHRU by less than half a percent. In this case, the price would go from 2.9 MNOK to 2.7 MNOK with the size cut by half.

The cost of the valves were found using a catalogue from 2014[3]. The inflation factor is found to be 1.02(REF). The design has 3 valves and the diameter is chosen to be 10 inches for a 40 m^3/h water flow. This will have the water flow at safe velocity inside the pipes.

$$Pi * \left(\frac{0.254m}{2}\right)^2 = 0.02533 \text{ m}^2 \qquad\qquad\qquad\text{Equation 30}$$

$$\frac{40\frac{m3}{h}}{0.02533 \text{ m}^2} = 1579\frac{m}{h} = 1579\frac{m}{h} * \frac{60min}{h} * \frac{60s}{min} = 0.4386\frac{m}{s} \qquad\text{Equation 31}$$

For a 10-inch pipe, it is recommended to not go above 1 m/s for water, and 50 m/s for saturated steam. [4] The same calculation is done for the steam pipes, but with 20-inch inner diameter.

$$Pi * \left(\frac{0.508m}{2}\right)^2 = 0.2027 \text{ m}^2 \qquad\qquad\qquad\text{Equation 32}$$

$$\frac{26018\frac{m^3}{h}}{0.2027m^2} = 128357\frac{m}{h} = \frac{\left(128357\frac{m}{h}\right)}{\left(3600\frac{s}{h}\right)} = 35.65\frac{m}{s} \qquad\text{Equation 33}$$

The steam needs pipes at 20 inches to stay safely within recommended velocities. Of course, it is possible to insert the maximum velocity recommendations into the equations to find the minimum pipe diameter, but for simplicity, and for the sake of being on the very safe side, choosing sizes that are a little too large is fine. [4]

After a quick surveying of the Norcem plant, approximately 50 meters of piping is required for the steam, and 100 meters for the water. The cost of 10- and 20-inch piping is found online by looking at actual costs in America.[5] The cost of 20-inch piping are found using

the average of 16 and 24-inch. The prices found this way includes installation costs and does not need to be multiplied by any other factor than inflation that was found to be 1.31[7]. The costs of piping was found to be 273 $/ft and 113 $/ft for the 20- and 10-inch pipe respectively. Before inserting the lengths into the equations, the length units are converted to feet.

$$50 \text{ m } = 50 \text{ m } \cdot 3.281 \frac{\text{ft}}{\text{m}} = 164.04 \text{ ft} \qquad \qquad \textit{Equation 34}$$

$$100 \text{ m } = 100 \text{ m } \cdot 3.281 \frac{\text{ft}}{\text{m}} = 328.08 \text{ ft} \qquad \qquad \textit{Equation 35}$$

The cost of steel piping comes to 475 kNOK for the steam portion of the system, and 394 kNOK for the water part, to make a total of 869 kNOK. Design expenses may still apply, but are not included in this report [5].

Total

Below is the table with the cost of every component in the WHRU-system. In APPENDIX D the full table can be viewed for all the middle values and other information it took to calculate them.

Table 6 Displays the road to calculating the investment cost of the WHRU-system, with each component shown separately.

System	Equipment	Cost per Unit (k$)	2016 cost	Inst. Factor	Final Cost (kNOK)
WHRU	Heat Exchangers				
	HX1	125	167	6.57	62261
	HX2	101	134	6.89	15024
	Collection tank	43	57	8.33	3877
	Pump	6	7	13.56	762
	Valves	6	6	13.97	2076
	Piping (Steam)	0.27	0.36	-	144.85
	Piping (Water)	0.11	0.15	-	120.12
	Total Cost (MNOK)				**84.26**

As the cost of a CO_2-capture plant alone can reach the investment cost of a billion NOK or more, 84.26 MNOK does not seem like a big extra expense. The next chapter will calculate the operational costs a WHRU might save a plant.

3.2 OPEX

The only operational costs of the WHRU-system that is to be installed at Norcem are the power required by the pump, and the maintenance costs. The electricity supplied to the pump can be calculated using data from SSB's website, and the maintenance cost is usually calculated using a percentage of the capital investment.

Pump Power

Assuming the plant runs for 8000 hours a year, and knowing the electricity price is in 2016 4th quarter at 0.318 NOK/kWh,[6] the cost of running the pump every year can be calculated.

$$\text{Operational Cost}_{pump} = \frac{8 \text{ kW} * 8000 \text{ hours} * 0.318 \left(\frac{NOK}{kWh}\right)}{1000 \frac{NOK}{kNOK}} = 20.35 \frac{kNOK}{yr} \qquad \textit{Equation 36}$$

Maintenance

The yearly maintenance cost is calculated by using a standard percentage of the investment cost. It is a function of the investment cost because the more expensive the plant, the larger and more complex it is, usually. In this report the standard 4% of the investment cost is used.

$$\text{Maintenance Cost} = 84260 \text{ kNOK} * 0.04 = 3370 \frac{kNOK}{yr} \qquad \textit{Equation 37}$$

As a total, the OPEX of the WHRU is less than 5% of its capital cost at 3390 kNOK per year.

The Benefit of WHRU

A WHRU-system is not installed the fun of it. The installation of this system makes use of energy that would go to waste, energy that would otherwise have to be paid for, either through investment in some other way of producing the energy in the form it is needed, or by purchasing it directly. The WHRU is a relatively passive system that works in the background, supplying the energy where it is needed.

Now, using what was calculated earlier in chapter 2.4, the amount of energy saved will be calculated, and how much this will save the plant annually.

Table 7 Representing the numbers found in chapter 2.4.

Captured CO_2 as calculated in chapter 2.4.		
4.2	MJ/kg CO_2	
3.7	MJ/kg CO_2	
21925	kg CO_2/h	$\approx$ 22 tons of CO_2 every hour captured.
84334	kg CO_2/h	Total CO_2 produced.
26.0	%	CO_2 captured using all the avalable heat from exhaust.

The amount of CO_2 captured should not be less than 80% of the quantity produced. "If you're going to do something, do it right." Of course, this is not a criteria as capturing CO_2 is quite expensive with today's technology. Regardless, with the assumption that the amount captured should be no less than 80%, the amount of CO_2 this represents is calculated.

Using the values in Table 4, the amount of energy needed to capture 80% of the CO_2 can be found:

$$\text{Required Energy} = 4.2 \frac{MJ}{kgCO_2} * 84334 \frac{kgCO_2}{h} * 0.8 = 283362 \frac{MJ}{h} \qquad \textit{Equation 38}$$

The energy recovered from the flue gas can be subtracted from the total required energy to see how much extra energy needs to be supplied to the reboiler.

$$\text{Unobtained Energy} = 283362 \frac{MJ}{h} - 92085 \frac{MJ}{h} = 191278 \frac{MJ}{h} \qquad \textit{Equation 39}$$

This energy needs to be acquired by other means. The simplest option might be to purchase the steam needed to run the reboiler directly. The steam does not need to be warmer than 150 °C, and it will be cooled and condensed before being disposed of, or redirected back to the producer of the steam to be reheated.

Assuming the steam is condensed and cooled to 115 °C, the equation for finding the amount of steam appears as so:

$$\dot{m} = \frac{\dot{E}}{\left(\left(\frac{\Delta h_{vap}}{M_W}\right) + (Cp * (T_1 - T_2))\right)} \qquad \textit{Equation 40}$$

$$\dot{m} = \frac{191278 \frac{MJ}{h}}{\left(\left(\frac{40.65 \frac{kJ}{mol}}{18.02 \frac{kg}{kmol} * 1000 \frac{mol}{kmol}}\right) + \left(\left(\frac{1.907}{1000}\right)(150 - 115)\right)\right)} = 82356 \frac{kg}{h} \qquad \textit{Equation 41}$$

If cost of 200 NOK/ton is assumed for steam at 150 °C, the yearly cost of steam can be calculated.

Table 8 Table presenting results for Steam cost calculations.

OPEX reduction		
200	NOK/ton	Cost of steam.
82356	kg/h	How much extra steam is needed.
16471	NOK/h	Cost of steam per hour.
132	MNOK/yr	Cost of steam for an 8000-hour year w/ WHRU.
195	MNOK/yr	Cost of steam for an 8000-hour year w/o WHRU.
63	MNOK/yr	OPEX reduction thanks to WHRU.

Table 5 shows that thanks to the WHRU supplying the reboiler with steam to heat the amine, it effectively saves 63 MNOK per year. The WHRU does have some expenses each year and brings it down to:

$$\text{OPEX reduction } = \ 3.39 \frac{\text{MNOK}}{\text{yr}} - \ 63 \frac{\text{MNOK}}{\text{yr}} \approx \ 60 \frac{\text{MNOK}}{\text{yr}} \qquad\qquad Equation\ 42$$

Of course, there are other ways of getting the extra energy needed. The plant could invest in boilers that produced their own steam using coal. But these boilers are expensive and making enough of them to supply the whole extra energy demand would cost four times more than the WHRU itself according the same equation as was used to find the heat exchangers.

Equation 43 Investment cost of boilers to supply the remaining heat needed for CO_2 capture.

Equipment	K1	K2	K3	kW	k$	k$	MNOK
boiler	6.9617	-1.4800	0.3161	9000	1499	8994	284.80

4 Discussion

Electricity vs Steam generation

Early in the project there was talk about using the excess heat to make high-pressure steam to run a turbine on the side. This turbine could have run a heater that would do the same job as the low-pressure steam. Although in most plants that use WHRUs to produce some free electricity on the side, for the purpose of heating amine in a reboiler it would not be a very good way of using the energy as there would be losses in every conversion. From heat losses to mechanical drag and friction, the efficiencies would add up and a percent of the heat would help the universe increase its entropy. Making steam to directly heat the MEA in the reboiler is a sure way to make sure as much heat as possible is being utilized. Now the turbine solution is certainly the most general one. It could do anything from heating a building, to operating the staff kitchen, to power all the lights in the plant. But for this project where the need is so specific, the production of steam is the best solution.

26% capture plant

In this case the amount of captured CO_2 would be limited, but at least there would be no concern about where the extra energy came from, as the additional heat needed to capture more CO_2 would have to be produced somehow. A simple way of doing do would be using a coal furnace to produce the extra steam, which would increase the amount CO_2 in the exhaust gas, and would increase the energy needed to capture a set percentage of CO_2. This loop would stabilize, but could be avoided if the steam was purchased from elsewhere. Still, the steam would have to be produced somewhere.

Payback Period Reduction

The capture of CO_2 is not yet a profitable business plan, but reducing its cost is always an option. Without a waste heat recovery unit, the OPEX of the reboiler alone is 195 MNOK per year. Installing the WHRU reduces that cost by 60 MNOK per year. That means after less than 2 years, it has already payed for itself, and Norcem has made much better use of the fuel they are burning, as well as capturing it for cheaper.

5 Conclusion

From the results that came from this project, there is little reason to not integrate a waste heat recovery unit to the back end of the cement production plant. There is a lot of heat in the flue gas going to waste, and it is relatively cheap to invest in the WHRU if there are plans of making a CO_2-capture plant. Since the WHRU pays for itself in less than two years, integrating it is a very good investment next to a demanding process like CO_2-removal using amines.

The investment cost is low, as the only major components are two heat exchangers, and the alternative methods of getting the energy are more expensive, even with no CAPEX like the option with pure purchase of 200 NOK/ton steam, the WRHU comes out ahead with its short payback time.

The managers of Norcem Brevik can also sleep better knowing the fuel they burn don't go to waste, as the cooling towers that are there today cost money to run as well as throw away perfectly good heat.

Future work

It might be interesting to look into the installation of a waste heat recovery unit that produces high pressure steam to run a turbine. The energy is there, and it should be utilized if at all possible.

6 References

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[6] Thomas Aanensen and S. H. Moe. (2016, May). *Elektrisitetspriser, 4. kvartal 2015*. Available: https://www.ssb.no/energi-og-industri/statistikker/elkraftpris/kvartal/2016-02-25

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[10] Lars-André Tokheim, Nils Eldrup and Anette Mathisen, "Benchmark Study – Commercial Scale Perspective – Preliminary results from WP7 Benchmark Study", Norcem CO2 capture project: International CCS Conference, Langesund, 20-21 May 2015

[11] A. M. Lars-André Tokheim, "Thechnical Note: A Generic MEA-Based CO2 Capture Process," 2015.

[12] The Engineering ToolBox. (2016). *Positive Displacement Pumps*. Available: http://www.engineeringtoolbox.com/positive-displacement-pumps-d_414.html

7 Appendix

7.1 Appendix A

Integrated WHRU diagram (PFD).
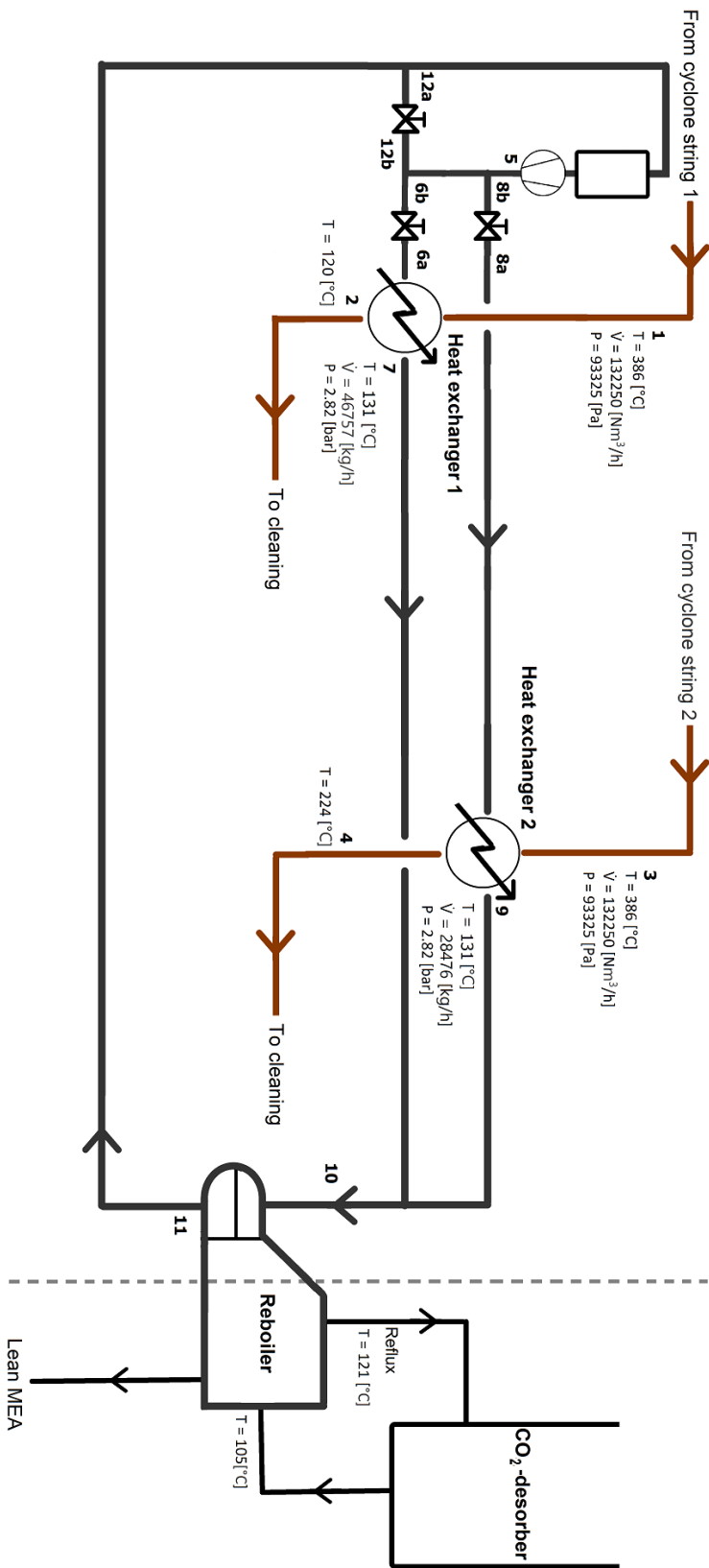
7.2 Appendix B

Appendix B Stream index sheet.

Point	Units	1	2	3	4	5	6	7	8	9	10	11
Gas Flow Rate	Nm³/h	**132250**	**132250**	**132250**	**132250**	-	-	30442	-	18540	48982	-
	m³/h	346495	206667	346495	261337	-	-	16170	-	9848	26018	-
	kg/h	183335	183335	183335	183335	-	-	25031	-	15245	40276	-
	kmol/h	5901	5901	5901	5901	-	-	1389	-	846	2235	-
Liquid Flow Rate	m³/h	-	-	-	-	40.66	25.27	-	15.39	-	-	-
	kg/h	-	-	-	-	40276	25031	-	15245	-	-	40276
	kmol/h	-	-	-	-	2235	1389	-	846	-	-	2235
Temperature	°C	**386**	**120**	**386**	**224**	115	115	131	115	131	131	115
	K	659	393	659	497	388	388	404	388	404	404	388
Pressure	mbarg	-80	-80	-80	-80	682	682	1809	682	1809	1809	682
	Pa	93325	93325	93325	93325	169486	169486	282240	169486	282240	282240	169486
Density	kg/m³	0.529	0.887	0.529	0.702	990.58	990.58	1.548	990.58	1.548	1.548	990.58
Molar Weight (avg)	kg/kmol	31.07	31.07	31.07	31.07	18.02	18.02	18.02	18.02	18.02	18.02	18.02
Specific Heat, Cp	kJ/(kg*K)	1.174	1.088	1.174	1.121	4.214	4.214	1.907	4.214	1.907	1.907	4.214

7.3 Appendix C

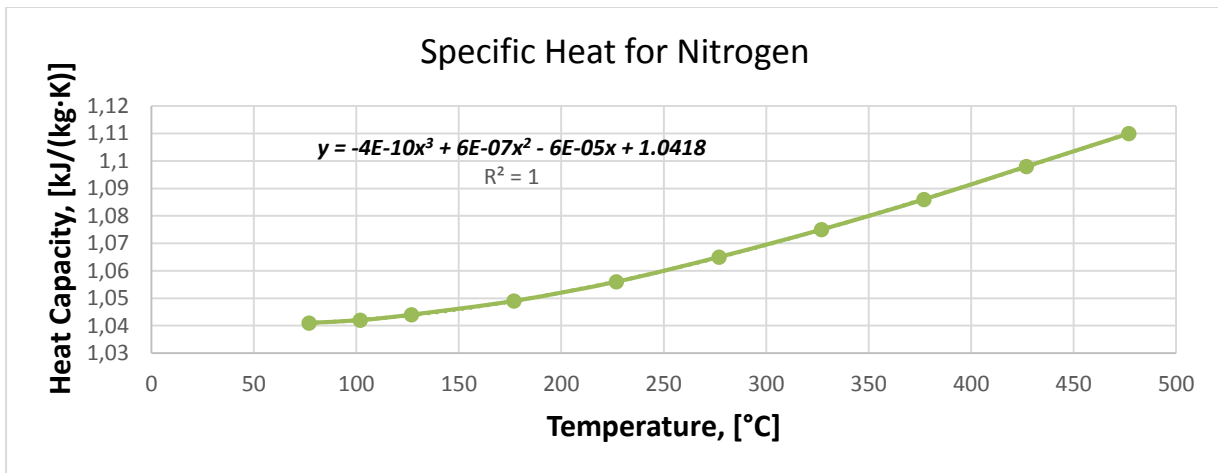Calculation of dynamic C_p.

Figure 5 Graph showing the relation between specific heat and temperature for Nitrogen gas.
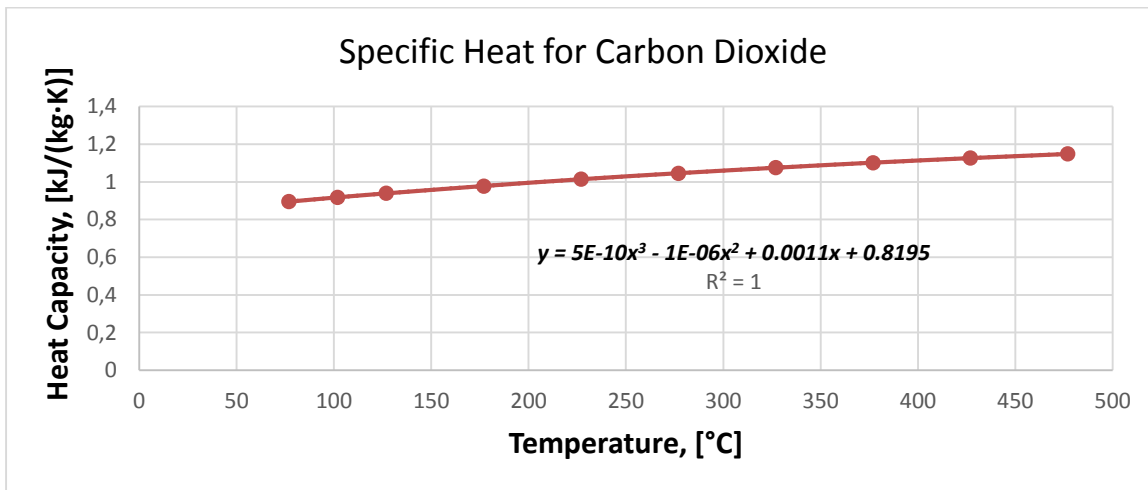

Figure 6 Graph showing the relation between specific heat and temperature for Carbon Dioxide gas.
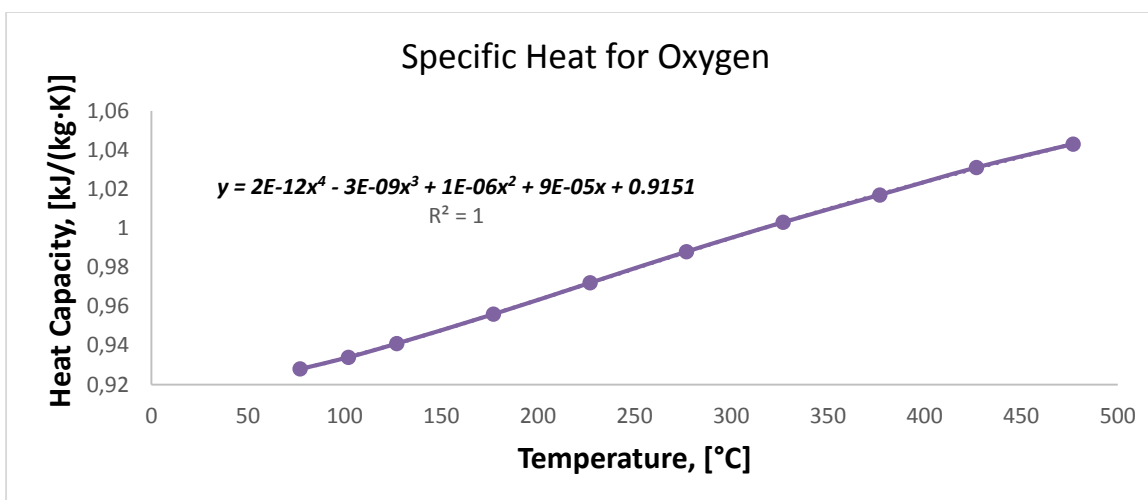

Figure 7 Graph showing the relation between specific heat and temperature for Oxygen gas.
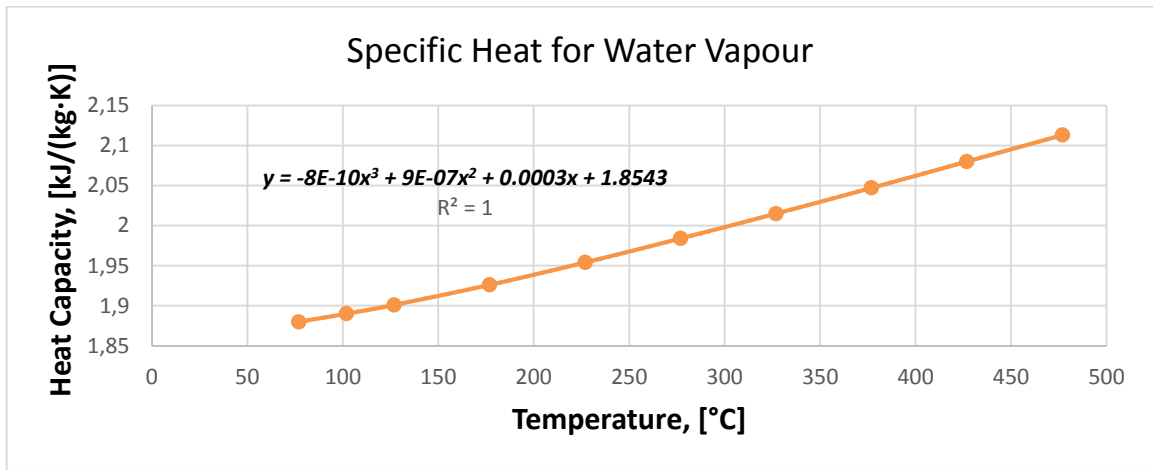
Figure 8 Graph showing the relation between specific heat and temperature for water vapour.
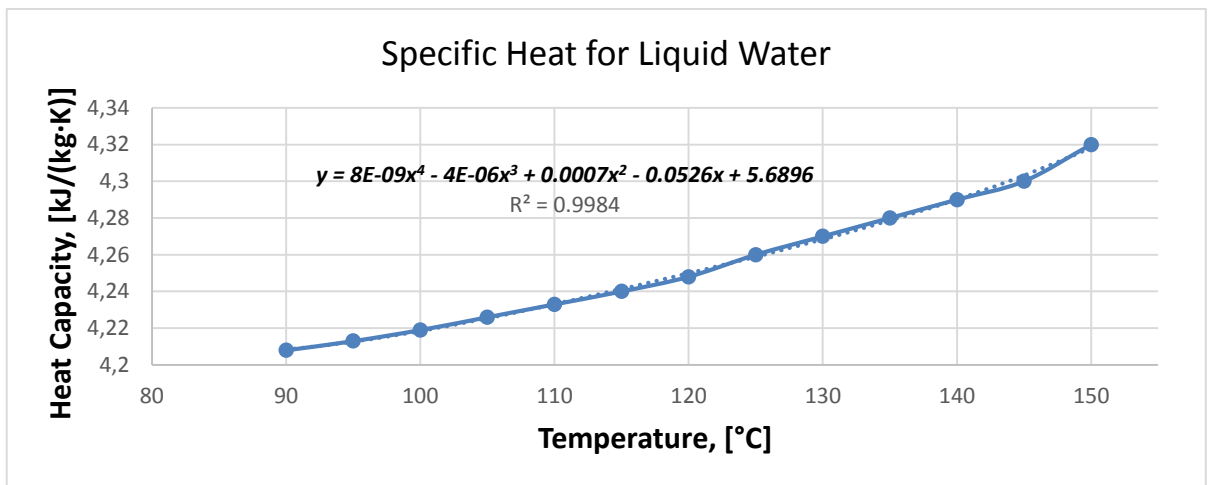

Figure 9 Graph showing the relation between specific heat and temperature for liquid water.

The figures 1 to 5 above shows the change of C_P with temperature in each of the relevant gasses in the process as well as liquid water. These trendlines are very useful since the outlet temperatures might vary with different temperature demands. The trendline equations inserted into excel makes the whole process of calculating the specific heat automatic. In Figure 5, the heat capacity for liquid water can be seen to change significantly with temperature, which strengthens the decision to consider the non-standard conditions when it comes to the specific heat values. The values for the gasses also vary around 5-10% inside the base case parameters.
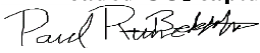
7.4 Appendix D

System	Equipment	Flow	Relevant Dimension			k values			Number of Units	Cost per Unit (k$)	2016 cost	Cost (k$)	Rate	Cost (kNOK)	Factors				Final Cost (kNOK)
			Volume	Area	Power	1	2	3							Inflation	Installation	Material	Total	
	Heat Exchangers																		
	HX1	25.27	-	900	-	4.8306	-0.8509	0.3187	7	125	167	1167	8.119	9479	1.33	5.82	1.75	6.57	62261
	HX2	-	725	-	4.8306	-0.8509	0.3187	2	101	134	269	8.119	2181	1.33	6.14	1.75	6.89	15024
	Collection tank	40.66	100	-	-	4.8509	-0.3973	0.1445	1	43	57	57	8.119	465	1.33	7.58	1.75	8.33	3877
WHRU	Pump	40.66	-	-	10	3.4771	0.135	0.1438	1	6	8	8	8.119	62	1.33	12.52	1.75	13.27	817
	Valves	25.27	-	-	-	-	-	-	3	6	6.10	18	8.119	149	1.02	13.22	1.75	13.97	2076
	Piping	40.66	-	-	-	-	-	-	50	0.27	0.36	18	8.119	145	1.31	-	-	-	145
		40.66	-	-	-	-	-	-	100	0.11	0.15	15	8.119	120	1.31	-	-	-	120
Total Cost																			84.32 MNOK

HSN
University College of Southeast Norway

MASTER'S THESIS, COURSE CODE FMH606

Student:	**Paul Rune Bekkhus**
Thesis title:	**Utilization of waste heat from cement kiln exhaust gases for regeneration of loaded CO₂ capture media**
Signature:	. . . .
Number of pages:	**37**
Keywords:	CO2 Capture, Waste Heat, Heat Exchanger, Cost estimation . . . .
Supervisor:	Lars-André Tohkeim Sign.: . . . .
2ⁿᵈ supervisor:	\<name\> Sign.: . . . .
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External partner:	\<name\> Sign.: . . . .
Availability:	\<Open/Secret\>

Archive approval (supervisor signature)**:** Sign.: . . . .   **Date :** . . . .

Abstract:

Norcem Brevik is planning on installing a CO2-capture plant and are looking for ways to do so more efficiently. The task carried out in this thesis is about integrating the hot flue gas being released by the cement production into useful energy for the Amine technology capture plant. The way this will be done is to replace the cooling towers already in place with two heat exchangers, who's job it is to convert the heat in the exhaust into useful steam that can be used by the amine reboiler. The other part of the task is to design this waste heat recovery unit, make a PFD, and calculate the investment cost.

The most interesting point with the project is whether or not it is profitable to invest in this heat utilization unit instead of just buying the steam to use in the reboiler. These two options, as well as some others will be weighed up against each other.