Profitability of cogeneration in a chemical industry

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Abstract

A high demand of both electricity and heat exists in Arizona Chemical (a chemical plant dedicated to the distillation of Crude Tall Oil) for production processes. Due to the rising cost of resources and electricity, more and more companies are trying to decrease the energy expenses to increase their competitiveness in a global market, thus increasing their profit.

Some companies look at their energy consumption in order to diminish it or to explore the opportunity to generate their own and cheaper energy. In companies where the production of steam already takes place, cogeneration can be a good solution to palliate the cost of the energy used.

This study addresses this issue through three actions such as the characterization of the boiler, a better steam flow measurement grid and the generation of electricity.

The first one addresses the state of one of the key parts of steam production, the boiler, through the calculation of its efficiency with two different methods (direct and indirect calculation). These methods require some measurements which were provided afterwards by the company supervisor. This will allow the company to identify the weaknesses of the boiler to be able to improve it in the future.

The second one aims to improve the knowledge about the steam system. New flow measurement points were suggested after doing an analysis of the current controlled flows to have a better overview outline of the steam use.

The third one studies the generation of electricity with a Rankine cycle. The limitations in the characteristics of the steam were identified and different configurations are proposed in accordance to the restrictions identified.

An efficiency of 93% is obtained for the boiler with the direct method and 82.3% for the indirect one. The difference between them can be explained by the use of data from different timeframes for both methods. The main contributors to the losses are the ones related to the dry flue gas and the hydrogen in the fuel.

In the current status only 40% of the steam flows are identified, a number which is expected to raise with the new measurement points. It was not possible to estimate the effect of the new points due to the desire of the company to not disturb the current production.

Due to the fuel price the production of steam for only electricity was not profitable and instead the generation of both electricity and heat from the same steam is proposed.

This integrated system is now possible to implement due to its low payback time (2.3 years). This solution can generate 758 kW of electricity and provide the company with 6437 MWh of electricity each year. Then, the effect of the variation of different variables over the performance of the cycle were studied: different electricity prices, steam rate production, fuel cost and the state of the condensate recovery were discussed.

The variation of both the condensate recovery and fuel cost did not affect the payback time due to their costs being neutralised by the revenues obtained from them.

The variation of the electricity prices and steam production affects the payback but due to the high revenue that is expected it does not hamper the good nature of the investment.

The generation of electricity is recommended due to the low payback time obtained. The different variations studied in the system did not change the payback time notably and showed that the investment is highly profitable in all the scenarios considered.

The use of two smaller turbines instead of the one chosen (with a maximum rated power of 6 MW while only 758 kW is generated with the proposed solution) should be studied since the turbines would work closer to their maximum efficiency.

Keywords: Cogeneration, Boiler efficiency, Rankine Cycle, Integrated steam cycle, Electric renewable certificates
Preface

This thesis represents the final work of my Master studies at the University of Gävle. It was done in collaboration with Arizona Chemical during the spring of 2017 and represents the work done to help the company diminish their energy costs.

First of all, I want to thank my supervisors Curt Björk and Nawzad Mardan for their work revising my thesis and helping me through the realization of the project.

I would like to thank Mattias Anderson who was my supervisor in the company and helped me gathering data and answering the questions I came up with.

This year I am taking part in an international mobility program, and I want to thank both my home university (UPNA) and Högskolan I Gävle, for giving me the opportunity to have this experience and

Finally, I would like to express my gratitude to my family, my friends and my girlfriend for their essential support during this period.

Gävle, 25th May 2017

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# Contents

1  Introduction ........................................................................................................ 1  
   1.1  Background .................................................................................................. 1  
   1.2  Literature review ........................................................................................ 3  
      1.2.1  Boiler efficiency .................................................................................... 3  
      1.2.2  Cogeneration ....................................................................................... 4  
      1.2.3  Steam cycle ........................................................................................... 6  
      1.2.4  Electricity market .................................................................................. 8  
      1.2.5  Condensate reversal ............................................................................. 9  
   1.3  Aim .............................................................................................................. 10  
   1.4  Approach .................................................................................................... 10  

2  Method .................................................................................................................. 11  
   2.1  Piping measurement points ......................................................................... 11  
   2.2  Boiler parameter measurements .................................................................. 11  
   2.3  Electricity generation ................................................................................... 11  

3  Results and analysis ............................................................................................. 13  
   3.1  New measurement points ............................................................................ 13  
   3.2  Boiler description ........................................................................................ 14  
      3.2.1  Direct method ...................................................................................... 14  
      3.2.2  Indirect method ................................................................................... 15  
   3.3  Vapour cycle configuration ......................................................................... 16  
      3.3.1  Simple Rankine cycle .......................................................................... 16  
      3.3.2  Integrated electricity generation ............................................................ 18  

4  Discussion ............................................................................................................ 25  

5  Conclusions ......................................................................................................... 27  

Appendix A ................................................................................................................. 28  
   Steam cycle calculation ....................................................................................... 28  

Appendix B ................................................................................................................. 30  
   Piping diagram .................................................................................................... 30
**Table of figures**

| Figure 1-1: Aerial overview of the facility | .......................... | 1 |
| Figure 1-2: Kraton's Global Footprint[1] | ................................ | 2 |
| Figure 1-3: Indirect method for boiler efficiency [5] | ................................ | 4 |
| Figure 1-4: Comparison of separate and combined heat and power generation [7] | .......................... | 5 |
| Figure 1-5: Typical steam distribution network [12] | ................................ | 6 |
| Figure 1-6: Basic components of a simple vapor power plant [14] | .......................... | 6 |
| Figure 1-7: Temperature-entropy diagram of the ideal Rankine cycle, dashed numbers represent the use of overheated steam [14] | .......................... | 7 |
| Figure 1-8: Isentropic process vs Ideal process in a s-h diagram [14] | .......................... | 7 |
| Figure 1-9: Evolution of certificate quotas in Sweden and Norway [16] | .......................... | 8 |
| Figure 1-10: How the electricity certificate market works[16] | .......................... | 9 |
| Figure 1-11: A typical steam and condensate circuit | .......................... | 10 |
| Figure 3-1: Measured, not measured and produced steam flows (t/h) | .......................... | 13 |
| Figure 3-2: Boiler system | .......................... | 14 |
| Figure 3-3: Regenerative steam cycle | .......................... | 16 |
| Figure 3-4: Integrated steam cycle | .......................... | 19 |
| Figure 3-5: Payback time vs yearly steam change | .......................... | 24 |
| Figure 0-1: Regenerative steam cycle | .......................... | 28 |
| Figure 0-2: Expansion in a s-h diagram [14] | .......................... | 29 |
1 Introduction

In chemical plants exists a great demand of both heat and electricity for production purposes. Arizona Chemical is a company located in Sandarne (Sweden) which is dedicated to the distillation of Crude Tall Oil into different intermediate or refined products.

Due to the rising cost of resources and electricity, these energy-intensive companies are trying to decrease their energy expenses to be able to increase their profits while reducing their environmental impact.

One way of reducing the energy cost is to produce their own energy and cogeneration (generating both electricity and heat from the same fuel resource) has proved to be a good solution for this.

This thesis aims to decrease the energy expenses by studying the possibility to introduce cogeneration in Arizona Chemical and providing a better control of the boiler efficiency (which can decrease the fuel use) and steam system.

1.1 Background

The company where this project takes place in is part of Arizona Chemical, which was bought by Kraton Corporation in January 2016. It is situated in the town of Sandarne, Sweden, in Söderhamn’s municipality. The aerial overview present in Figure 1-1 was provided by the company.

![Figure 1-1: Aerial overview of the facility](image)

They are dedicated to the distillation of Crude Tall Oil (CTO) into different intermediate products like Fatty Acid and Rosin. They can also upgrade distillates to Rosin Esters and Rosin Esters dispersions.

Among their finished products are Sylfat, Sylvatal, Sylvalite, AQ FC and PF-60 (pitch fuel), which are products that are later used by other companies to manufacture other final goods.
The company is subdivided in two plants, the refinery and the upgrade plant. The first one has a total capacity of 180 000 tonnes per year of products while the second one can produce up to 40 000 tonnes per year of upgraded goods.

The boiler is situated in a separate boiler house and serves both plants. It has two identical burners with a capacity of 9.3 MW each, with a total power of 18.6 MW, but only around 8-12 MW are used currently. The boiler uses mostly pitch fuel and their intention is to stop utilizing fossil fuels since 2017. During 2016 their fuel consumption for the steam boiler amounted to 7565 tonnes of pitch fuel and only 150 tonnes of EO4 (which is a fossil fuel), this was only needed during the month of December.

The facility in Sandarne has been working as a successful refinery since 1930. Since then, it has gone through several changes and improvements. During the first years its capacity was 3000 tons/year, during the sixties it was increased to produce 90 000 tons/year and, during the seventies, its capacity was raised up to 120 000. In 1990 another upgrade was done to the plant and a maximum production of 140 000 tons/year and, finally in 2006 it got the world record of crude tall oil throughput with a total amount of 180 000 tons/year [1].

They have a strong focus on safety, quality and environmental management systems as can be seen with the ISO certificates 9001 and 14001 despite an environmental accident which happened in 2011 [2].

A European Directive [3] marks that companies with a strong energy usage must undergo an energy audit for controlling their energy use and investigate the possibility to reduce their environmental impact and increase their profitability. The energy audit performed in Arizona Chemical gives a starting point to develop different studies aimed to reduce the energy use and cost such as this thesis.

In Sandarne’s facility a great part of the energy consumption goes to the company’s processes, mainly the distillation of tall-oil. Steam is produced at 30 bar pressure in the boiler which is later reduced, cooled down and supplied at 20, 10, 4 and 3 bar pressure. The steam that is needed at 20 bar is obtained from directly decreasing the pressure of the 30 bar steam. The rest is stored in a steam accumulator at 16-17 bar. Then it is distributed and used at the required pressure. The plant has also the ability to produce 3 bar steam when cooling down certain processes, which amounts to most of the 3 bar steam used.

Steam is used for steam tracing (for keeping certain service pipes warm) and also for maintaining the temperature of storage tanks. The steam use is not controlled and monitored extensively and it is believed that it can be improved. Steam from the company is also used to warm up the church situated near the plant.
Condensate reversal occurs in some but not all systems, therefore a big part of the energy used is lost, increasing the use of primary energy and its cost. The ability to recover this steam, thus reducing the operating cost of the plant will be studied in another thesis [4].

The aim of this paper is to reduce the energy cost of the company. This will be done through a better characterization of the boiler and steam system and with the study of the generation of electricity in the plant with the installation of a steam turbine.

The main limitations of the study are the short working period (only 5 to 6 weeks of practical work) and a limited access to the plant and resources needed to perform it.

1.2 Literature review

In this chapter the literature review of the different covered areas will be explained. Five subchapters will be presented. First the boiler efficiency, then cogeneration will be explained. After, a typical steam cycle will be presented, followed by the status of the electricity market in Sweden and finally a brief introduction to the condensate reversal will be analysed.

The databases used for the literature search were: Discovery, Google Scholar, IEEE Xplore and Science Direct. The search was limited to peer-review articles at first and later expanded to other types of publications such as lectures, public documents and conference proceedings.

The search was done using the next key words or a variation of them: cogeneration, steam cycle, electricity renewable certificates, boiler efficiency, Rankine Cycle.

1.2.1 Boiler efficiency

When producing steam, one of the most important components is the boiler. A low efficiency can increase the fuel consumption making the process more expensive. Therefore, it is important to know the performance of the boiler by obtaining its efficiency. In order to calculate the efficiency two general methods are used: the direct and the indirect method.

The first one is the simplest and quickest of both, requiring three measured flows for it. Its principle is to obtain the energy transferred to the working fluid (in this case the water/steam) and to divide it by the energy of the fuel when entering the boiler.

\[
\%Eff_{boiler} = 100 \times \frac{E_{output\ steam} - E_{feed\ water}}{E_{fuel}}
\]

This method only needs the pressure and temperature data from water at the entrance and exist of the boiler as well as the fuel. It is a simple method that can be used to obtain quick results.

On the other hand, if a better description of the boiler is needed, the indirect method shall be used. This method parts from a 100% efficiency and then the different kind of heat losses present when a boiler is in operation are subtracted as depicted in Figure 1-3 [5].
%Eff\textsubscript{boiler} = 100 − (L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + L_8)

With:

- $L_1$: Loss due to dry flue gas (sensible heat)
- $L_2$: Loss due to hydrogen in fuel
- $L_3$: Loss due to moisture in fuel
- $L_4$: Loss due to moisture in air
- $L_5$: Loss due to carbon monoxide
- $L_6$: Loss due to surface radiation, convection and other unaccounted losses
- $L_7$: Unburnt losses in fly ash
- $L_8$: Unburnt losses in bottom ash

In this case the last two are ignored due to only being relevant when the fuel is solid. $L_5$ can also be ignored for this kind of fuel for normally being a low value in comparison with the rest.

The result of these two methods should be identical but due to measurement errors and assumptions it is to be expected that both values differ slightly from each other [6].

### 1.2.2 Cogeneration

Conventionally the generation of heat and electricity has been treated separately, but lately, with the increased awareness about the environment and monetary cost, a higher focus has been put into cogeneration. Cogeneration means generating both electricity and heat from the same source, if on top of that cooling is produced, it is called trigeneration.

The separate production of heat and electricity has higher separate efficiency than the combined production. This means that the electrical efficiency is higher when generating only electricity from a resource because it can be designed better for that purpose (and the same applies to the heat generation).

But the overall efficiency of Combined Heat and Power (CHP) is higher than the generation of electricity and power separately and can be highly profitable as it can be seen in Figure 1-4 [7]. This higher efficiency leads to a smaller fuel consumption and lower CO\textsubscript{2} emissions. It is currently used with success by different sectors like hospitals, industrial plants, buildings, district heating, pharmaceutical industry, for desalination and many more [8], [9]. It has also been proposed to be used for microgeneration with power as low as 1 kW [10].
Cogeneration can also serve to decentralize the generation of electricity and heat, helping to reduce the risk of blackout or energy outage. This is particularly helpful in places with a high risk of environmental catastrophes like Japan where the earthquake hazard is higher [11].

Another advantage of this system is the possibility to provide heat (for example as steam) at different levels of quality and pressure [12]. This makes this technology very attractive when electricity and heat are needed for different purposes.

When two types of energy (electricity and heat) are generated from the same source and using the same circuits, it is important to allocate the monetary cost for both electricity and heat generation [13]. One of the most utilized methods is allocating a cost proportional to the energy used in each kind of energy. The possibility to introduce a correction factor depending on the kind of fuel used can also be contemplated.

\[ C_E = \left( \frac{W_E}{W_E + W_Q} \right) * C_T \]

Being,
- \( C_E \): cost for electricity
- \( W_E \): electricity generated
- \( W_Q \): heat produced
- \( C_T \): total cost of production
As it can be seen in Figure 1-5, part of the steam is either extracted between each expansion phase to be used in the process or through a heat exchanger to extract some energy to another fluid.

### 1.2.3 Steam cycle

Nowadays there are two main techniques that are used for generating electricity involving the combustion of a fuel. These are steam and gas cycles. Since the company is already producing steam from pitch fuel, only the generation of electricity with a steam cycle will be studied.

The cycle in which the steam goes through is called Rankine cycle. It is a power cycle that uses steam to move a turbine which then moves an electrical generator. To avoid damaging the components of the cycle the water needs to be purified before producing the steam.
Both the Figure 1-6 and the Figure 1-7 show the four ideal steps that are part of this cycle:

1-2 Isentropic expansion of the steam from through the turbine from saturated vapour to the condenser pressure.
2-3 Condensation of the fluid at constant pressure.
3-4 Isentropic compression in the pump to state 4.
4-1 Heat transfer to the fluid at constant pressure.

The presence of water drops in the turbine can damage the equipment and diminish its durability. To avoid this effect, the steam can be overheated before entering the turbine. This increases both the longevity of the turbine and the efficiency of the steam cycle.

The diagram in Figure 1-7 represents the ideal Rankine cycle. The real processes are not ideal (or isentropic) and the work obtained with this process is different than ideally (lower for a turbine and higher for a pump). This is represented by the isentropic efficiency of the components, the higher the efficiency, the more similar the real process is to the ideal one. The Figure 1-8 represents the isentropic efficiency of an expansion.

All four processes share the same principle, the exchanged energy is the difference between the enthalpies of the starting and end states.

$\dot{Q}_i / \dot{m} = h_i - h_{i+1}$
With,
\[ \dot{Q}_i = \text{Heat flow transferred in the step (kW)} \]
\[ \dot{m} = \text{Mass flow (kg/s)} \]
\[ h_i = \text{Enthalpy at point } i \text{ (kJ/kgK)} \]

More details about how to perform the calculations of the cycle will be presented in the Appendix A.

The overall efficiency of this ideal cycle is rather low so there are several measures that can be implemented to slightly increase its efficiency. If the cycle is only used to generate electricity its efficiency can be up to around 30% [7], but on the other hand if the remaining heat after the expansion phase is used for heating purposes the combined overall efficiency can be over 75%, reducing the energy input needed for a certain output capacity and its cost [7].

1.2.4 Electricity market

For the economic evaluation of the turbine, the current electricity market plays a key role. Sweden is part of the so called “Nordic energy market”, a common electricity market in the Nordic countries (Denmark, Finland, Norway and Sweden) whose purpose is to balance both the power production and usage [15].

Within this common market, each country has its own legislations and measures to promote electricity generation from renewable resources. In Sweden a bonus to the renewable production was introduced back in 2003 with the creation of the “green electricity certificates”. This system was later adopted by Norway in 2012 and both countries work together in it. This system aims to develop the renewable generation amounting to 28.4 TWh by the end of 2020 [16].

A green certificate is awarded to a producer for each MWh of electricity generated from renewable sources, such as biofuel (and peat in Sweden), geothermal, solar, hydro, wind and wave energy. For a biofuel to be eligible for receiving certificates it must comply certain requirements i.e. CO2 and fuel source [17]. These certificates are awarded on the 15th of each month to the producers and do not expire.

To create demand, end electricity users are obliged to buy certificates equivalent to certain quota of their annual electricity usage. This quota is different for Sweden and Norway and changes each year, reaching a peak in 2019-2020 and disappearing in 2035. Nonetheless, the quotas are revisable by the government and can change as already happened once to approach more realistic values.

Since the necessity for households to buy their own certificates each year is not convenient or comfortable, electricity suppliers have the legal obligation to handle their customers’ quotas as long as such customers have not opted to take care of it themselves. According to the Swedish Energy Agency the break-even point for handling the obligation corresponds to a consumption of at least 25 MWh [18].

These certificates are exchanged through private deals or through market brokers, meaning that the price is variable and fixed via offer and demand. The existence of note-
sold certificates helps varying the price of the certificates, meaning that the bigger the reserve is, the lower the prices would be. Another factor that affects their price is the variable quota, a higher quota will make the prices go higher while a lower quota will reduce the retail price of each certificate.

Each year the 1st of April the certificates corresponding to the quota of the user are cancelled to create new demand for the next year, if the quota is not fulfilled a fee is applied for each certificate missing.

![Figure 1-10: How the electricity certificate market works][16]

The expectable revenue for each year is the sum of both the energy and the certificate components. Since both prices are not fixed an estimation of both was taken [19].

These prices must be taken with a grain of salt due to various reasons. The first one is the decommissioning of some of the nuclear plants in Sweden, which in total accounts for almost 50% of today’s production [7], [19]. A change in this decision can affect the price of electricity and a nuclear decommission occurs in the study that was used to extract the prices from.

Another reason is the prediction of the average price of the certificates and whether or not these certificates will be entirely sold each year. The assumption that all the certificates will be sold can easily be achieved during the first years of the starting operating point of the turbine. Since the quota will be constantly decreasing (it was assumed that the turbine would be directly installed and that it would start functioning in 2020), selling all the certificates during the last years will be difficult. This would not have a big effect in the revenue scheme due to the lower price of the certificates in the latest years in comparison with the electricity price.

The 2020 starting point for selling electricity was decided because the average time that takes for getting approved and installed this kind of projects fits with the decided timeframe [20].

### 1.2.5 Condensate reversal

When utilizing steam for different purposes sometimes the steam is released when not usable anymore (because the pressure is smaller than needed or the temperature is not high enough to keep certain fluids warm, like for example with steam tracing). The recovery of some of the heat still present in the condensate can diminish the energy usage of the company [21].
This can lead to save energy costs in steam systems and also in mixed systems with different gases [22]. This can reduce boiler fuel usage since less energy is lost in the condensate system although this reduces the overall heat transfer coefficients [23]. The recovery of the condensate diminishes the water purification requirements and water purchasing. There are other benefits like the smaller necessity of performing boiler blowdowns or that more steam can be produced from the boiler [24].

A common steam and condensate circuit can be seen in the Figure 1-11 [24]:

Even though it can be seen as an expensive investment, even the smallest condensate recovery can provide a capital recovery in a rather moderate time [24]. The increase on the condensate recovery will be studied more deeply in another thesis done during the same timeframe of this project [4].

1.3 Aim
This thesis aims to lower the energy cost of the company through three actions:
Providing tools to improve their knowledge about the steam system by installing more measuring points.
Realizing a better characterization of the boiler efficiency to point the weaknesses of the boiler for future improvements.
The possibility to generate electricity in the company by installing a steam turbine.
The main limitations of the study are the time constraint and the limitation of trying not to disturb the production plant as much as possible.

1.4 Approach
First a literature review will be done to see the current solutions to the problem in question. Then an energy and economic study will be performed to see if it is an interesting option for the company and finally a recommendation will be done about it.
2 Method

In this section the procedure that was used for each different problem will be explained. Because each measure required its own approach a section is used for each action to provide a better understanding.

2.1 Piping measurement points

As it was stated above, one of the aims of this document is to provide the staff a better overview of where the steam is being utilized so it can be later used to monitor the system and to be used as reliable data to propose further measures which this project will not cover.

First a study of the current measured steam flows was developed with the help of the company to know until which point the steam system was controlled and if the installation of new points is advisable. The data was collected the 20th and the 21st of February of 2017.

Then, a list of not properly functioning and missing measured flows was created and shared by the company’s supervisor. This list and the piping diagrams of the boiler and the 3, 4, 10 and 20 bar systems will be later used to decide the positions of the new flow measurement points.

The goal is to provide the needed measures with the least amount of sensors possible, keeping the investment low while maintaining a good system control.

2.2 Boiler parameter measurements

Two different methods will be used, the direct and the indirect one, to measure the state of the boiler and its efficiency.

First, a list of the required data for performing the calculations will be done according with the literature studied. Then, with the existing measurement points the data will be collected. If actual the data is not available, then a historical value or an approximate assumption will be made according to typical values.

The data for the direct method will be the daily averages from 30th March 2016 to 29th March 2017. For the indirect method, a combination of actual data, historical values and assumptions will be considered.

2.3 Electricity generation

First, the status of the electricity market in Sweden will be studied. This will provide the revenue scheme and the maximum possible cost for generating electricity.

Different steam cycle configurations will be examined and, considering different aspects of each setup (complexity, cost and reliability) a certain cycle will be decided. The parameters of the steam will be dependent on the current steam setup, trying not to disturb the current main pressure usage. This restriction will not allow the efficiency to be as high as it could be with a new design but it will help keeping the cost of the investment down.

After that, the different main parts that build up that particular configuration will be identified and selected. With the functioning steam parameters already decided, the thermodynamic characteristics of the cycle will be calculated. Now, both the steam and fuel flows can be obtained for finally doing an economical evaluation of the feasibility of the project. In case of a reasonable payback time (if it exists) a more detailed study can be done in the future.

For predicting the future prices of both electricity and renewable certificates the data will be taken from a study done by Ou Tang and Jakob Rehme [19].
Table 2-1: Electricity and renewable certificate prices [19]

<table>
<thead>
<tr>
<th>Year</th>
<th>Price electricity (SEK/MWh)</th>
<th>Price Certificates (SEK/certificate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>190</td>
<td>230</td>
</tr>
<tr>
<td>2021</td>
<td>260</td>
<td>237</td>
</tr>
<tr>
<td>2022</td>
<td>225</td>
<td>234</td>
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<tr>
<td>2023</td>
<td>210</td>
<td>225</td>
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<tr>
<td>2024</td>
<td>225</td>
<td>212</td>
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<tr>
<td>2025</td>
<td>275</td>
<td>200</td>
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<tr>
<td>2026</td>
<td>290</td>
<td>177</td>
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<tr>
<td>2027</td>
<td>325</td>
<td>162</td>
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<tr>
<td>2028</td>
<td>410</td>
<td>147</td>
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<td>2029</td>
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<td>50</td>
</tr>
<tr>
<td>2034</td>
<td>800</td>
<td>30</td>
</tr>
</tbody>
</table>

Since there are different currencies used through this paper, the exchange rate that will be used will be the one provided by Valuta.se during the 8th of May 2017, which amounts to 1 Euro=9.66 SEK=1.1 USD [25].

To actualize the present value of money in the future the net present value (NPV) method will be used with a discount rate of 5%. This method tries to bring the future value of money to the present so the yearly cash flows can be compared between them.

\[
C_v = \frac{R_t}{(1 + i)^t}
\]

Where,
- \(C_v\) = Current value of money
- \(t\) = the time of the cash flow
- \(i\) = the discount rate, in this case, 5%
- \(R_t\) = the net cash flow for the period \(t\)
3 Results and analysis

In this chapter the results obtained in the three areas (Flow measurement, boiler efficiency and Electricity generation) are presented and an analysis of the results is done when possible.

3.1 New measurement points

For knowing the already measured point weight within the system, the data from two days was taken, the 20th and the 21st of February of 2017. The measured flows consist of the following flows: Boiler (FI 9534.A), flow into the upgraded plant 1 and 2 (FIQ-2608 and 4608, 2606 and 4606, 20 and 10 bar respectively) and 10 bar flow of the distillation plant (FI 1611). They were later plotted into a graph.

![Figure 3-1: Measured, not measured and produced steam flows (t/h)](image)

As it can be seen the not-measured flows amount to around 60% of the total flow. This represents an average of 8.52 t/h of steam usage not being under control. The measured amount remains constant even with big variations of the total produced steam, meaning that the measured flows are constant rather than intermittent. This also means that there are some intermittent flows (like, for example, tanker heating and sooting equipment) which use a lot of steam when needed.

For being able to estimate the results of the new measurement points it would be necessary to interfere with the normal production of the plant. Therefore, it was decided in conjunction with the company’s responsible to not interrupt the production and instead, since it is a measure they will make regardless of the estimation, continue with the installation of the measurement points.

After studying the current necessities, it was decided that the following flows should be controlled in the future:

- Tanker heating flow, it is used to keep warm tanker trucks. It is not a constant flow and it is wanted to know the weight within the system.
- 4 bar flow to the upgrade plant.
- Steam tracing usage, a total consumption will be obtained and not a detailed one, further expansion of the measuring system can be done afterwards but the aim of this is to control the overall use of the steam and not an in detail study.
- Steam usage in the lab.
- Oil warming and flow to T1602.
10 bar steam that is pressure-reduced to 3 bar. This can be achieved with only one measurement point in the pipes going from 10 to 3 bar. In addition to the difference of the Flow Indicator 1611 and the new measurement point for the Steam tracing down that line, it can be calculated the amount of steam that leaves that pipe in several places to become 3 bar steam. The proposed points can be seen in the Appendix B.

3.2 Boiler description

3.2.1 Direct method

For explaining the direct method an overview of the boiler system is presented in Figure 3-2:

The useful heat transferred to the water will be the difference between the energy of the water entering the system at the measurement point PI 9545.A (since that is the entering point of the new water) and the steam at FI 9534.A and blowdown (FI 9540.A) flows. It is worth noting that the values in the picture will not be used and instead averages during the measuring period will be considered (daily averages from 30\textsuperscript{th} March 2016 to 29\textsuperscript{th} March 2017).

Due to having storage tanks it is not necessary that at every moment the input water flow must be equal to the output steam/water flows.

\[
\%\text{DirEff, boiler} = 100 \times \frac{E_{\text{output steam}} + E_{\text{blowdown water}} - E_{\text{feedwater}}}{E_{\text{fuel}}}
\]

For each flow the energy will be calculated as:

\[
E = \dot{m} \times h
\]

With \(\dot{m}\) being the mass flow and \(h\) the enthalpy. Now the typical ranges of energy of each flow will be presented.

\begin{align*}
E_{\text{feedwater}}: & \quad 2100-2400 \text{ kW} \\
E_{\text{blowdownwater}}: & \quad 250 \text{ kW} \\
E_{\text{steam}}: & \quad 11000 \text{ kW} \\
E_{\text{pitchfuel}}: & \quad 8000-10000 \text{ kW}
\end{align*}
Giving a boiler efficiency of around 93-96%, to be on the safe side when performing the economic evaluation of the turbine, the worst case scenario will be taken, using 93% as the typical efficiency.

3.2.2 Indirect method

The boiler efficiency is calculated as following with the indirect method:

\[ \%IndEff_{boiler} = 100 - (L_1 + L_2 + L_3 + L_4 + L_6) \]

With:
- \( L_1 \): Loss due to dry flue gas (sensible heat)
- \( L_2 \): Loss due to hydrogen in fuel
- \( L_3 \): Loss due to moisture in fuel
- \( L_4 \): Loss due to moisture in air
- \( L_6 \): Loss due to surface radiation, convection and other unaccounted losses

Now the result for each part is presented.

**Calculation of \( L_1 \)**

\[ L_1 = \frac{m \times C_{pflue}(T_f - T_a)}{GCV_{fuel}} \times 100 = 8.1\% \]

Where,
- \( m \) = Mass of dry flue gas in kg/kg = 18.82
- \( C_{pflue} \) = Specific heat of flue gas in kCal/kgK = 0.2597
- \( T_f \) = Flue gas temperature in °C = 163.5
- \( T_a \) = Ambient temperature in °C = 15
- \( GCV_{fuel} \) = Gross calorific value of fuel in kcal/kgK = 8962.71

**Calculation of \( L_2 \)**

\[ L_2 = \frac{9 \times H_2 \times (584 + C_{psteam} \times (T_f - T_a))}{GCV_{fuel}} \times 100 = 7.7\% \]

Where,
- \( H_2 \) = kg of hydrogen per kg of fuel = 0.115
- \( C_{psteam} \), Specific heat of superheated steam in kCal/kgK = 0.5655
- 584 = Latent heat corresponding to partial pressure of water vapour

**Calculation of \( L_3 \)**

\[ L_3 = \frac{M \times (584 + C_{psteam} \times (T_f - T_a))}{GCV_{fuel}} \times 100 = 1.1\% \]

Where,
- \( M \) = kg of moisture per kg of fuel = 0.15

**Calculation of \( L_4 \)**

\[ L_4 = \frac{AAS \times humidity \ factor \times C_p \times (T_f - T_a)}{GCV_{fuel}} \times 100 = 0.2\% \]

Where,
- \( AAS \) = Actual mass of Air Supplied per kg of fuel = 17.82
- Humidity factor = kg of water per kg of dry air = 0.012

**Calculation of \( L_6 \)**

Due to the more complicated nature of calculating the radiation losses an approximation will be done according to industrial standards. For this kind of boiler, a typical value is 0.6%. 


The indirect efficiency is equal to 82.3%, which is very different to the one obtained with the direct method. This can be due to some inaccuracies with the measures taken and the use of some historical values that might not be correct nowadays. Regardless of the discrepancies this can be used to propose efficiency improvement measures to the boiler.

3.3 Vapour cycle configuration

Two different configurations have been considered regarding the electricity generation. The first one will be a simple Rankine cycle with one turbine while the second option will use two turbines (or one with an extraction phase) with steam extraction between the expansion phases.

In the first case an extra steam production will be produced and its only use will be for generation of the desired electricity.

In the second case the turbine will be installed and used within the existing steam piping.

More details about how to calculate the steam cycle characteristics are presented in the Appendix A.

3.3.1 Simple Rankine cycle

First the installation of steam cycle with its own steam circuit apart from the production facility will be studied. Both the boiler and pump will be the existing ones but extra steam will be produced. This steam will be separated from the production steam and redirected to the turbine, which, after expansion, will be condensed and redirected to the existing feed water system for reintroducing it again in the boiler.

To maximize the work from the turbine a condensing turbine will be used, this means that the outlet pressure is less than ambient pressure. To improve the efficiency a regenerative system will be installed as well.

![Figure 3-3: Regenerative steam cycle](image)
After performing the thermodynamic calculations each point’s characteristics are as following:

Table 3-1: Characteristics of water through the Rankine cycle

<table>
<thead>
<tr>
<th>Point</th>
<th>Temperature (ºC)</th>
<th>Pressure (bar)</th>
<th>Enthalpy (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>345</td>
<td>30</td>
<td>3102.96</td>
</tr>
<tr>
<td>2</td>
<td>170</td>
<td>4</td>
<td>2753.40</td>
</tr>
<tr>
<td>3</td>
<td>41.5</td>
<td>0.08</td>
<td>2314.27</td>
</tr>
<tr>
<td>4</td>
<td>41.5</td>
<td>0.08</td>
<td>173.88</td>
</tr>
<tr>
<td>5</td>
<td>41.6</td>
<td>4</td>
<td>174.37</td>
</tr>
<tr>
<td>6</td>
<td>123</td>
<td>4</td>
<td>516</td>
</tr>
<tr>
<td>7</td>
<td>124</td>
<td>50</td>
<td>521</td>
</tr>
</tbody>
</table>

It is worth nothing that the difference between the pressure when entering the boiler and the one exiting the boiler is due to the pump being the same one than when the previous plant was in use. The rest of the equipment is prepared for functioning with 30 bar.

For these values to be true the fraction of the steam extracted has to be \( y = 0.132465 \). Therefore, the achieved efficiency for the cycle is:

\[
\eta = \frac{h_1 - h_2 + (1 - y)(h_2 - h_3)}{h_1 - h_7} = 21.87\% 
\]

For the turbine to produce 1000 kW it requires a steam flow of 1.77 kg/s and an added boiler use of 4.9 MW. The fuel consumption is 471.75 kg/h (the yearly value, considering 8200 hours of work per year, is 3868 tonnes).

For the economic analysis first a yearly cash flow can be done, opposing the fuel cost with the yearly revenue. The cost of the pitch fuel is assumed to remain constant at 228€/tonne, which translates to 2201.82 SEK/tonne. The generation of electricity is assumed to be constant during the 8200 hours the company works during the year, this means that the company will produce 8200 MWh and receive 8200 certificates each year. The cash flow during the first 15 years is:
Table 3-2: Cash flow during the firsts 15 years with the simple Rankine cycle

<table>
<thead>
<tr>
<th>Year</th>
<th>Fuel cost (SEK)</th>
<th>Price electricity (SEK/MWh)</th>
<th>Price Certificates (SEK/cert)</th>
<th>Revenue total (SEK)</th>
<th>Cash flow (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>8 467 036</td>
<td>190</td>
<td>230</td>
<td>3 444 000</td>
<td>-5 023 036</td>
</tr>
<tr>
<td>2021</td>
<td>8 467 036</td>
<td>260</td>
<td>237</td>
<td>4 075 400</td>
<td>-4 391 636</td>
</tr>
<tr>
<td>2022</td>
<td>8 467 036</td>
<td>225</td>
<td>234</td>
<td>3 763 800</td>
<td>-4 703 236</td>
</tr>
<tr>
<td>2023</td>
<td>8 467 036</td>
<td>210</td>
<td>225</td>
<td>3 567 000</td>
<td>-4 900 036</td>
</tr>
<tr>
<td>2024</td>
<td>8 467 036</td>
<td>225</td>
<td>212</td>
<td>3 583 400</td>
<td>-4 883 636</td>
</tr>
<tr>
<td>2025</td>
<td>8 467 036</td>
<td>275</td>
<td>200</td>
<td>3 895 000</td>
<td>-4 572 036</td>
</tr>
<tr>
<td>2026</td>
<td>8 467 036</td>
<td>290</td>
<td>177</td>
<td>3 829 400</td>
<td>-4 637 636</td>
</tr>
<tr>
<td>2027</td>
<td>8 467 036</td>
<td>325</td>
<td>162</td>
<td>3 993 000</td>
<td>-4 473 636</td>
</tr>
<tr>
<td>2028</td>
<td>8 467 036</td>
<td>410</td>
<td>147</td>
<td>4 567 400</td>
<td>-3 899 636</td>
</tr>
<tr>
<td>2029</td>
<td>8 467 036</td>
<td>360</td>
<td>125</td>
<td>3 977 000</td>
<td>-4 490 036</td>
</tr>
<tr>
<td>2030</td>
<td>8 467 036</td>
<td>450</td>
<td>105</td>
<td>4 551 000</td>
<td>-3 916 036</td>
</tr>
<tr>
<td>2031</td>
<td>8 467 036</td>
<td>600</td>
<td>87</td>
<td>5 633 400</td>
<td>-2 833 636</td>
</tr>
<tr>
<td>2032</td>
<td>8 467 036</td>
<td>590</td>
<td>75</td>
<td>5 453 000</td>
<td>-3 014 036</td>
</tr>
<tr>
<td>2033</td>
<td>8 467 036</td>
<td>675</td>
<td>50</td>
<td>5 945 000</td>
<td>-2 522 036</td>
</tr>
<tr>
<td>2034</td>
<td>8 467 036</td>
<td>800</td>
<td>30</td>
<td>6 806 000</td>
<td>-1 661 036</td>
</tr>
</tbody>
</table>

It is worth noting that this includes only the fuel running cost and the cash flow is already negative during the whole period, this investment is therefore not recommended and another configuration should be studied.

3.3.2 Integrated electricity generation

The second presented option was integrating the electricity in the production plant. With the current steam system energy is lost when the steam pressure is reduced to lower values. Turbines can be used to produce this pressure drop while also generating electricity without the need to produce more steam than currently done.

There are now 5 different levels of pressure used within the plant: 30 at production and 20, 10, 4 and 3 at usage. Because having a turbine between each step is not cost-wise, two pressure drops will be used with steam extraction between them. A first expansion will be done when reaching 20 bar, there the steam which is used at 20 or 10 bar will be extracted and the rest will continue to the second phase and expanded to 4 bar.
After performing the thermodynamic calculations, the characteristics for each points are:

**Table 3-3: Characteristics of water through the cycle**

<table>
<thead>
<tr>
<th>Point</th>
<th>Temperature (°C)</th>
<th>Pressure (bar)</th>
<th>Enthalpy (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>345</td>
<td>30</td>
<td>3102.96</td>
</tr>
<tr>
<td>2</td>
<td>170</td>
<td>20</td>
<td>3019.57</td>
</tr>
<tr>
<td>3</td>
<td>148</td>
<td>4</td>
<td>2748.85</td>
</tr>
<tr>
<td>4</td>
<td>124</td>
<td>50</td>
<td>521</td>
</tr>
</tbody>
</table>

The goal of this setup is to not produce more steam than it currently does, this means that the electricity generation will be dependent of the regular production, for the calculations average flows during the 20th and 21st of February 2017 were used. Due to not having all the flow measurements available, an extra 2 ton/h consumption was added to the 20/10 bar usage.

The total average flow going through the first turbine is 14 ton/h (3.95 kg/s) and through the second turbine is 6.5 ton/h (1.8 kg/s). This provides a usable work of:

\[
\dot{W} = \dot{m}_1(h_1 - h_2) + \dot{m}_1(h_2 - h_3) = 328.9 + 487.3 = 816.2 \text{ kW}
\]

Which gives an efficiency of:

\[
\eta = \frac{\dot{m}_1(h_1 - h_2) + \dot{m}_2(h_2 - h_3)}{\dot{m}_1(h_1 - h_4)} = 8\%
\]

Which is an efficiency 2.7 times lower than the first setup. But because this configuration makes use of the remaining heat after the expansions the overall efficiency is higher. For example, if the whole steam flow was used through both turbines, an efficiency of 13.7 % would be achieved, which is still lower due to not using the regenerative step and stopping the expansion at a higher pressure (4 bar instead of the previous 0.08 bar).
The turbine chosen is the model SST-060 from SIEMENS which has a cost of 5313 000 SEK and includes an integrated gearbox, oil supply unit, mechanical oil pump, electronic governor, control panel and the Synchronous generator (which has a rated efficiency of 96%). The turbine has a maximum output of 6 MW. This higher maximum output means that the turbine will not be working in its maximum efficiency point. Turbines with smaller output power should be considered but during the timeframe of the project it was not possible to obtain a quotation from the suppliers of that kind of turbines.

The energy transferred to the steam is used in two different processes, for generating electricity and for production purposes.

To assign a fuel cost, the proportional jump in enthalpy was used [26]. For that the cycle efficiency was multiplied by fuel consumption. This means that only 8% of the fuel cost will be assigned to the electricity generation, as a side effect the steam cost used for production purposes will go down to 92% from the initial 100%.

If a constant flow of 3.95 kg/s is assumed for the 8200 working hours, a yearly consumption of 8632 tonnes of fuel is expected, which corresponds with 18.895 million SEK.

\[ C_{\text{Fuel,el}} = \eta_{\text{cycle}} \times C_{\text{Fuel total, yearly}} = 1 511 629 \text{ SEK/year} \]

Since the capacity of the boiler is not used entirely it exists the possibility to produce steam that would only be used for the electricity generation. But it is not recommended due to the high cost of the fuel even with a higher electrical efficiency setup.

The cost of water purification is 50 SEK/tonne. There are no complete measurements of the total amount of condensate retrieved each year, therefore the assumption that all the water used has to be purified will be done. This time a cost of 8% of the total cost will be assigned to the electricity generation. Considering a constant use 116 604 tonnes of water will be used each year.

\[ C_{\text{Water,el}} = \eta_{\text{cycle}} \times m_{\text{water, year}} \times C_{mT} = 466 416 \text{ SEK/year} \]

After consulting similar projects [27], it was decided that a cost of 45€/kW should be allocated to model maintenance and replacement parts. The assumed installed power will be 1000 kW. No new personal will be hired for the exclusive maintenance of the turbine but the proportional cost of a maintenance technician [28] will be assigned.

\[ C_{\text{maint}} = P_{\text{installed}} \times C_{\text{maint}} + \eta_{\text{cycle}} \times C_{\text{yearly, techn}} = 461 580 \text{ SEK/year} \]

The efficiency of the generator is 96%, giving an average electric power output of 758 kW, 6437 MWh per year and 6437 certificates too.

A side effect of the electricity generation is the lower cost of the energy used for the normal production. Displacing 8% of the fuel, water purifying and salary costs to the electricity generation makes that for the refined and upgraded products the cost is 8% smaller. Which means that the cost coming from the fuel and water purifying goes down from 24 725 563 SEK per year to 22 747 518 SEK. This difference will also be considered as revenue for this study with a yearly amount of 1 978 045 SEK.

If the plant is considered to be at full capacity, this results in a decrease from 112.4 SEK/tonne to 103.4 SEK/tonne of refined or upgraded product.
The yearly cash flow is then:

Table 3-4: Cash flow during the firsts 15 years with the integrated cycle

<table>
<thead>
<tr>
<th>Year</th>
<th>Running costs (SEK)</th>
<th>Price electricity (SEK/MWh)</th>
<th>Price Certificates (SEK/cert)</th>
<th>Total revenue (SEK)</th>
<th>Cash flow (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>2 439 625</td>
<td>190</td>
<td>230</td>
<td>4 681 646</td>
<td>2 242 021</td>
</tr>
<tr>
<td>2021</td>
<td>2 439 625</td>
<td>260</td>
<td>237</td>
<td>5 177 306</td>
<td>2 737 681</td>
</tr>
<tr>
<td>2022</td>
<td>2 439 625</td>
<td>225</td>
<td>234</td>
<td>4 932 694</td>
<td>2 493 069</td>
</tr>
<tr>
<td>2023</td>
<td>2 439 625</td>
<td>210</td>
<td>225</td>
<td>4 778 203</td>
<td>2 338 578</td>
</tr>
<tr>
<td>2024</td>
<td>2 439 625</td>
<td>225</td>
<td>212</td>
<td>4 791 077</td>
<td>2 351 452</td>
</tr>
<tr>
<td>2025</td>
<td>2 439 625</td>
<td>275</td>
<td>200</td>
<td>5 035 689</td>
<td>2 596 064</td>
</tr>
<tr>
<td>2026</td>
<td>2 439 625</td>
<td>290</td>
<td>177</td>
<td>4 984 192</td>
<td>2 544 567</td>
</tr>
<tr>
<td>2027</td>
<td>2 439 625</td>
<td>325</td>
<td>162</td>
<td>5 112 934</td>
<td>2 673 309</td>
</tr>
<tr>
<td>2028</td>
<td>2 439 625</td>
<td>410</td>
<td>147</td>
<td>5 563 535</td>
<td>3 123 910</td>
</tr>
<tr>
<td>2029</td>
<td>2 439 625</td>
<td>360</td>
<td>125</td>
<td>5 100 060</td>
<td>2 660 435</td>
</tr>
<tr>
<td>2030</td>
<td>2 439 625</td>
<td>450</td>
<td>105</td>
<td>5 550 660</td>
<td>3 111 035</td>
</tr>
<tr>
<td>2031</td>
<td>2 439 625</td>
<td>600</td>
<td>87</td>
<td>6 400 363</td>
<td>3 960 738</td>
</tr>
<tr>
<td>2032</td>
<td>2 439 625</td>
<td>590</td>
<td>75</td>
<td>6 258 746</td>
<td>3 819 121</td>
</tr>
<tr>
<td>2033</td>
<td>2 439 625</td>
<td>675</td>
<td>50</td>
<td>6 644 975</td>
<td>4 205 350</td>
</tr>
<tr>
<td>2034</td>
<td>2 439 625</td>
<td>800</td>
<td>30</td>
<td>7 320 875</td>
<td>4 881 250</td>
</tr>
</tbody>
</table>

This scenario gives a payback time of 2.3 years. As it can be seen the yearly cash flow depends highly on the combined price of both MWh and certificates. Going from 420 SEK the first year to 830 SEK the last year. While the combined price only doubles itself, the cash flow gets multiplied by slightly more than two due to the fixed running costs of the turbine.

Since both prices are predictions, two scenarios more will be analysed. In the first one the electricity price will remain constant with the current cost for the company and in the second the price will get 5% higher each year. In both cases the certificate price will remain the same.
Table 3-5: Cash flow with the integrated cycle, constant price scenario

<table>
<thead>
<tr>
<th>Year</th>
<th>Running costs (SEK)</th>
<th>Price electricity (SEK/MWh)</th>
<th>Price Certificates (SEK/cert)</th>
<th>Total revenue (SEK)</th>
<th>Cash flow (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>2 439 625</td>
<td>300</td>
<td>230</td>
<td>5 389 732</td>
<td>2 950 107</td>
</tr>
<tr>
<td>2021</td>
<td>2 439 625</td>
<td>300</td>
<td>237</td>
<td>5 434 792</td>
<td>2 995 167</td>
</tr>
<tr>
<td>2022</td>
<td>2 439 625</td>
<td>300</td>
<td>234</td>
<td>5 415 480</td>
<td>2 975 855</td>
</tr>
<tr>
<td>2023</td>
<td>2 439 625</td>
<td>300</td>
<td>225</td>
<td>5 357 546</td>
<td>2 917 921</td>
</tr>
<tr>
<td>2024</td>
<td>2 439 625</td>
<td>300</td>
<td>212</td>
<td>5 273 863</td>
<td>2 834 238</td>
</tr>
<tr>
<td>2025</td>
<td>2 439 625</td>
<td>300</td>
<td>200</td>
<td>5 196 617</td>
<td>2 756 992</td>
</tr>
<tr>
<td>2026</td>
<td>2 439 625</td>
<td>300</td>
<td>177</td>
<td>5 048 563</td>
<td>2 608 938</td>
</tr>
<tr>
<td>2027</td>
<td>2 439 625</td>
<td>300</td>
<td>162</td>
<td>4 952 006</td>
<td>2 512 381</td>
</tr>
<tr>
<td>2028</td>
<td>2 439 625</td>
<td>300</td>
<td>147</td>
<td>4 855 449</td>
<td>2 415 824</td>
</tr>
<tr>
<td>2029</td>
<td>2 439 625</td>
<td>300</td>
<td>125</td>
<td>4 713 831</td>
<td>2 274 206</td>
</tr>
<tr>
<td>2030</td>
<td>2 439 625</td>
<td>300</td>
<td>105</td>
<td>4 585 089</td>
<td>2 145 464</td>
</tr>
<tr>
<td>2031</td>
<td>2 439 625</td>
<td>300</td>
<td>87</td>
<td>4 469 220</td>
<td>2 029 595</td>
</tr>
<tr>
<td>2032</td>
<td>2 439 625</td>
<td>300</td>
<td>75</td>
<td>4 391 974</td>
<td>1 952 349</td>
</tr>
<tr>
<td>2033</td>
<td>2 439 625</td>
<td>300</td>
<td>50</td>
<td>4 231 046</td>
<td>1 791 421</td>
</tr>
<tr>
<td>2034</td>
<td>2 439 625</td>
<td>300</td>
<td>30</td>
<td>4 102 303</td>
<td>1 662 678</td>
</tr>
</tbody>
</table>

In this case the payback time gets reduced to 1.83 years due to the initial higher revenue per MWh produced (530 vs 420 SEK the first year for example). On the other hand, the constant price makes that from 2027 and onwards the money received is less than in the previous scenario.
The third scenario, increasing the current electricity price each year 5% gives the next result:

*Table 3-6: Cash flow of third scenario, 5% increase each year*

<table>
<thead>
<tr>
<th>Year</th>
<th>Running costs (SEK)</th>
<th>Price electricity (SEK/MWh)</th>
<th>Price Certificates (SEK/cert)</th>
<th>Total revenue (SEK)</th>
<th>Cash flow (SEK)</th>
</tr>
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<td>594</td>
<td>30</td>
<td>5 994 691</td>
<td>3 555 066</td>
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</table>

This is the scenario with the lowest payback time with only 1.81 years and the highest profitability (392, 300 and 432 SEK/MWh as average revenue respectively).

Even though the second case can seem the worst due to the lower cash flow present from 2028 and the following years, it is an unlikely scenario due to the natural tendency of prices to go higher. And even if the electricity would follow the trend depicted in that case, the investment is still very profitable.

The drawback of this production system is that the profitability is tied to the main production of the plant. As it was shown before, the price of the fuel makes the steam production only for electricity unprofitable. This means that a change in the yearly production of steam will affect the payback time.

Now the variation in the steam production will be studied. In all the cases the yearly change will be the constant. This change will vary from -5% (roughly a 50% consumption reduction) each year to +5% year (doubling the production of steam).
This analysis highlights the integrated character of this setup. For example, an increase in the heating exchange between the steam and the product pipes would make the payback time higher. An improvement in the condensate reversal would make the system more profitable. This effect is not big (vertical axis starts at 2 years) due that the increased/decreased cost of the steam production is neglected by the correspondent cost reduction/increase in the normal production.

Contrary to what was expected, because the water purification cost affects both the revenue and the running costs for electricity equally, a change in the condensate recovery system does not affect the payback time. However, an increase in this recovery does bring substantial economic benefit, linearly with up to 5 830 200 SEK when at full recovery.

The fuel cost impact is none existent as well with this setup for the same reason as with the condensate recovery. Because the yearly cost of the fuel is 18.9 million SEK, a variation of this cost affects highly the main production.
4 Discussion

The present project has studied the possibility to generate electricity within a chemical company where the production of steam is already in place. The limits of the steam characteristics (both pressure and temperature) were both fixed from the beginning to avoid performing great changes to the existing configuration. This would later decrease the disposition possibilities lowering the future revenue of the project.

In a first approach to generate electricity with its own piping, it was seen that the combined effect of the high price of the fuel in comparison with the revenue achievable in the location made it unprofitable to produce steam for only generating electricity. Thus, it was decided to see if the combined generation of both electricity and heat would overcome the high price of the fuel.

The first effect of restraining more the pressures available (at the exit of the turbine the pressure was 4 instead of 0.08 bar) was the high decrease of the efficiency in this setup. From the initial 21.87% to 8%. The lower efficiency for the generation of electricity was expected as explained before [7].

Having the two systems working at the same time makes it important to separate the cost of both, and with a proportional allocation of the fuel costs (using the efficiency for that, 8% for the electricity generation and the remaining 92% for the heating processes) the yearly cash flow was now positive, opening the possibility to study more in depth the costs and revenues of the system.

This cost allocation has another effect, the cost of the production of the main products will get lower due to the smaller cost of the steam used (down from 100% of the steam generation cost to 92%).

The under usage of the boiler opens the option to produce extra steam which would not be used for heating purposes but this extra production is not advised for the high cost of the fuel used.

The same method allocation was used for the water purification and maintenance salaries and as in other similar studies consulted, a yearly budget for maintenance and spare parts was decided.

The obtained payback time was short (2.27 years), and the effect of different variables was studied, more precisely: electricity price variation, steam production, condensate recovery and fuel costs.

Contrary to what was expected, a variation in the fuel cost does not have an impact in the payback time due to it affecting both the cost and the revenue. Regardless of that, the fuel cost does affect the main production profitability.

The proper characterization of the boiler’s efficiency was achieved via the indirect method (obtaining an efficiency of 82.3%) and the direct method (93%) was used to control the validity of the first one. As it was expected, both numbers differ from each other due to using data at different dates. This proper evaluation provides a tool to assess where the boiler could be improved, mainly the dry flue gas and the hydrogen content of the fuel, diminishing the fuel needed for producing the steam and therefore making lower its cost.

The water used to produce the steam must be of high quality, this means the water needs to be purified before entering the system. This incurs in a cost which is not negligible and it should be avoided. It is recommended that the steam produced is recovered after its use so the running costs get lower. The topic will be covered by a thesis done by another student and can have a big impact in the final decision about the cogeneration system [4].

Due to the integrated nature of this system, it is of utmost importance to study the effect of variating the steam needed for the production process. Because the use of steam
for only electricity is not recommended, a decrease in the normal production will incur in a lesser amount of vapour going through the turbine, generating then a smaller amount of electricity over the years making the investment slightly less attractive.

This makes the prediction of the evolution of the plant to be of high importance. The smaller energy cost achievable with this measure can help improving the competitiveness of the company in the long run. Both the turbine and the boiler have plenty of capacity for increasing generation, being the boiler the first of the two to reach its peak capacity.

Since the steam flow to the second expansion phase was estimated and not known with exactitude it can be that the real figures vary from the calculated ones. As it was seen, if the quantity of steam needed in high pressure processes gets only 1 tonne/hour lower, the electricity generation goes up until 850 kW and the payback time gets reduced by 0.4 years. Highlighting the importance of a proper flow control and monitoring that is hoped to be achieved with the new measurement points.

The price of electricity in Sweden has been relatively low and, according to the studies consulted [19], it is supposed to get lower at first to raise later. This low prices make the investment less attractive because it lowers the revenue while the generation costs stay the same. Nevertheless, the current price of electricity is higher than the one used for the base study. The current cost sits at around 300 SEK/MWh during March and 275 SEK/MWh was the price estimated for 2017 in the study used. On top of that, the electricity price tends to be lower during March than during the rest of the year, for example, in 2016, the price in March was 224.2 SEK/MWh while the yearly average was 299.4 SEK/MWh.

This seems to point that the prices used were on the low side and that the future scenario will have a slowly but constantly raise in the price of the electricity, making the payback time lower and much more attractive.

The aims of the project were all of them fulfilled: the efficiency of the boiler was calculated (93%) and the two main loses were identified (dry flue gas and hydrogen in the fuel), new flow measurement points were proposed and the installation of a turbine for generating electricity is advisable due to its low payback time (2.3 years).

Further investigation into this solution should be done, for example, the possibility of using two smaller turbines instead of the big one should be studied since the turbines would work closer to their maximum efficiency.
5 Conclusions

As it could be seen in this project the possibility for the company to generate its own electricity within the plant is highly affected by the surrounding conditions, primarily of economic type.

The constraints that were put to the production (both fuel used and steam characteristics at inlet and outlet) reduced the configuration possibilities and their performance. The current electricity price in Sweden does not help and the uncertainty with the presence of nuclear power in the country makes it difficult to predict the evolution of it. In a likely scenario of rising or constant prices the own generation of both electricity and heat can result in a positive investment for companies with need for both resources.

The high cost of the fuel can be reduced by improving the two main parts where the boiler loses energy: the dry flue gas and the hydrogen in the fuel.

The control of the flows revealed to be of utmost importance in integrated setups like this one. And the results of the other thesis about the condensate return can have an impact on the economic outcome of the installation of the turbine.

The generation of electricity has a positive effect in the main plant, decreasing the production costs and making their products more competitive.

The payback time of the initial scenario is short and therefore it is recommended to invest in this system. It is important to remark that this is a worst case scenario and that with proper measures and condensate recovery the project can achieve an even better payback time than the initial.
Appendix A
Steam cycle calculation

Here a more detailed explanation of the calculation for the steam cycle will be done. Because the process followed is identical for both setups and the first one is more complex, only the first one will be written thoroughly. For the second one only the differences will be explained.

The steam properties have been consulted in the tables present in the book *Fundamentals of Engineering Thermodynamics* [14].

![Diagram](image)

**Figure 0-1: Regenerative steam cycle**

<table>
<thead>
<tr>
<th>Point</th>
<th>Temperature (°C)</th>
<th>Pressure (bar)</th>
<th>h (kJ/kg)</th>
<th>S (kJ/kgK)</th>
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<td>30</td>
<td>3102.9</td>
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</tr>
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<td>50</td>
<td>521</td>
<td>-</td>
</tr>
</tbody>
</table>

\[ y = 0.132465 \]

**Step 7-1**
The heat added at the boiler is:

\[ \dot{Q}_b = (h_1 - h_7) \cdot \dot{m}_{\text{total}} \]

In this case the entrance to the turbine is not at the same pressure as the entrance of the boiler. Both the conditions at the entrance and the exit of the boiler were known beforehand.
**Step 1-2 and 2-3**
First expansion phase, known is the pressure after the expansion and the isentropic efficiency of the turbine (will be assumed 0.8). First the isentropic expansion will be calculated for later using the efficiency to see the real point.

![Image](s-h_diagram.png)

*Figure 0-2: Expansion in a s-h diagram [14]*

First a point at 20 bar with the same entropy was found, then using its enthalpy and the isentropic efficiency the real point’s enthalpy was calculated.

$$
\eta_{\text{isentropic}} = \frac{h_1 - h_2}{h_1 - h_{2s}}
$$

**Step 3-4**
Known is the state at 3 and at 4 it is assumed to have the same pressure and the state is saturated liquid.

**Step 4-5 and 6-7**
For the compression the assumption of working with an ideal fluid will be done. The water is supposed to be saturated liquid at the input of the compressor. Therefore, the enthalpy after the compressor is calculated as following:

$$
h_{\text{after}} = h_{\text{before}} + v_f \text{before} \times (P_{\text{after}} - P_{\text{before}})
$$

Being $v_f$ the specific volume of the water at saturated liquid state.

*Open feedwater heater*
To calculate the fraction of steam extracted at 2 needed an energy balance was done knowing all the enthalpies.

$$
h_6 = y \times h_2 + (1 - y)h_5
$$
Appendix B
Piping diagram
References

