Black liquor to advanced biofuel: A techno-economic assessment

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Abstract

This thesis looked at a biorefinery pilot plant that converted lignin in black liquor into biofuel. A heat/mass balance was made which was used to create a heat/mass balance for a theoretical large-scale plant. This then created the CAPEX for building the plant. OPEX for the largescale plant and income from sold biofuels was calculated and payback time found. This was done for three different cases with different flows and yield to optimize the plant. A sensitivity analysis was then made to find the most important parameters regarding CAPEX, OPEX and payback time. [CENSORED]

Disclaimer

This master thesis was carried out in SCA Obbola. Due to the business sensitive aspect of information regarding on-going process development at SCA, part of the text in the thesis was removed from the publicly available version. Such information is highlighted as “[CENSORED]”.

The thesis with complete information was reviewed by both the supervisor at SCA and the examiner of the thesis at Luleå University of Technology.
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1 Introduction

Sweden has put up a goal to reduce its climate impact from the transport sector by 70% to 2030 compared to 2010. This gives great opportunities to anyone that can create a viable green fuel. The paper industry in Sweden is large and has big potential to implement the productions of biofuels in connection to the paper mills. This can be done in many ways and can use different feedstocks, for example, lignin and forest residue. It can be done using two major production pathways: liquefaction–hydrotreatment or gasification–catalytic synthesis.

This report will focus on lignin as feedstock with liquefaction as a method. Lignin is the second most common natural polymer in the world. It is a large crosslinked polymer that makes up approximately 17% of the mass of black liquor (BL). The other parts are 30% salts and 53% water. Paper mills burn the BL to produce heat for the mill. This report will look at the SCA paper mill in Obbola. In this plant, the energy required for running the mill is about 80% of the energy produced by burning black liquid. This gives a 20% surplus that can be used for producing biofuels.

At the Obbola paper mill they have a pilot plant biorefinery that has a process that uses the lignin in the BL and through several steps produces hydrocarbons.

The purpose of the thesis is to suggest improvements for the large-scale plant. To reach a conclusion for improvements, specific goals were set for what had to be done:

- Create a mass/energy balance model for the pilot plant.
- Use the mass/energy balance model to create a mass/energy balance for a large-scale plant with the same process with a BL flow of X tonnes/h.
- Make an economic evaluation of the large-scale plant.
- Optimize the plant to get the lowest payback time.
- Find the most important parameters for the payback time of the large-scale plant.
2 Theory

2.1 Raw Material
Black liquor is an aqueous by-product from producing chemical pulp. It consists mostly of lignin, salts, and water. Since the early 1900s, the BLs dry content is increased to about 80% wt. then burned in a recovery boiler to recycle the inorganics. The gained heat is used to run the paper mill. SCA’s mills have an excess of heat so only 80% of the lignin needs to be burned to get the required heat for the mill, the rest is sold off as district heating.

The BL used in the pilot plant has a dry solid content of X wt.%. This BL has a density of 1247 kg/m$^3$. The heat capacity is approximately 3,0 kJ/kg*K.

Lignin is the second most common natural polymer after cellulose. It is made up of three different phenyl propane monomers that can bond together in many different patterns. This together with its size makes lignin hard to predict its chemical structure.

![Figure 1](image.png)

Figure 1 The three different kinds of phenyl propane monomers that make up lignin.

2.2 Chemical properties
The biorefinery requires some different chemicals to operate. To calculate reactions, heating and mass flow some data is required for these chemicals.

2.2.1 [CENSORED]

2.2.2 [CENSORED]

2.2.3 [CENSORED]

2.2.4 Hydrocarbon
For hydrocarbon data, toluene was used. It’s molar mass is 92,141 g/mol and the density is 867 kg/m$^3$.

2.3 Reactions

There is no data for the reaction [CENSORED] to hydrocarbons either, so the standard enthalpy of formation of the [CENSORED] and toluene is used. The equation becomes:
Putting in values gives:

The heat of reaction is \( X \) kJ/mol.\(^16\) \(^17\) \(^18\)

Since the lignin is usually burned in pulp mills recovery boiler it is also important to know heat is lost for the pulp mill when the lignin is taken to the process. The lost heat is calculated by taking the mass flow of lignin to the process and subtract the heat for removing the water by evaporation. The heat value for the dry lignin is 22,88 MJ/kg. \(^19\)

2.4 OPEX

The operational costs consist of a lot of different components.

Table 1 OPEX costs for running the biorefinery. \(^20\) \(^21\)

<table>
<thead>
<tr>
<th></th>
<th>SEK/tonne</th>
<th>SEK/MWh</th>
<th>SEK/person*month</th>
<th>% of total CAPEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>458</td>
<td>340</td>
<td>60000</td>
<td>3</td>
</tr>
<tr>
<td>Wood pellet</td>
<td>300</td>
<td>340</td>
<td>60000</td>
<td>3</td>
</tr>
<tr>
<td>Steam</td>
<td>300</td>
<td>340</td>
<td>60000</td>
<td>3</td>
</tr>
<tr>
<td>Personnel</td>
<td>60000</td>
<td>340</td>
<td>60000</td>
<td>3</td>
</tr>
<tr>
<td>Maintenance</td>
<td>3</td>
<td>340</td>
<td>60000</td>
<td>3</td>
</tr>
</tbody>
</table>

2.4.1 Chemicals

To run the biorefinery some chemicals are needed, the biggest cost-wise are [CENSORED]. But [CENSORED]must also be included since the BL taken from the pulp mill removes inorganics from the process. Because the paper mill is losing these chemicals it will need to add new ones in the form of [CENSORED]. The amount needed is gained from the equation:

So there needs to be added 2 moles of [CENSORED] to the pulp mill for each mole of [CENSORED] used in the biorefinery. Hydrogen will be produced at the site and won’t need to be purchased. \(^20\)

2.4.2 Electricity

The electricity for the plant is assumed to be at a constant value of 15 MW during operation. \(^20\)

2.4.3 Wood pellet

The BL taken from the pulp mill causes not only loss of chemicals but also loss of heat since less lignin is burnt in the recovery boiler. The heat that previously was sold off as district heating no longer exists, thus it is viewed as a negative operational cost. The price of wood pellets is used to see how much revenue is lost. \(^22\)
2.4.4 *Steam*
Steam is used to calculate the cost for heating reactors and [CENSORED]. High-pressure steam is used for heating.

2.4.5 *Personnel*
In the future plant, there will be 30 shift workers and 5 engineers. Their salary costs include payroll tax.  

2.4.6 *Maintenance*
The cost for maintenance is a percentage of the total CAPEX.  

22 above 22
3 Method

3.1 Heat and mass balance
A mass balance model was created in Microsoft Excel by using given flow diagrams as a template. The input values for temperature, mass flow and pressure were taken from electrical indicators on the biorefinery during normal operating settings.

3.1.1 Experimental data
The given data was not enough to create a functioning mass balance. Some more data needed to be added for the mass balance to work. Experimental measuring was done for the units where data was missing.

The solids in the solid drain were measured by weighing a filter, then pour the sample through a filter, let it dry and then weigh the sample. This experiment did not give any usable results since the scale could only weight down to a precision of 0.5 grams. The filter weighed 2 grams and after pouring over 40 liters through the filter no weight change was observed.

3.2 Upscaling
Based on the pilot plant mass flows a model for a large-scale facility was created in excel with a BL flow of X tonnes/h. This case used the same unit [CENSORED]

Then another large-scale facility was made based on the first one but with some changes made. It was made more as it would look in reality. [CENSORED]

3.3 Pinch analysis
To be able to estimate sizes and costs for heat exchangers pinch analyses were made. One was made around the reactor were the output would heat the input.

3.4 Economic analysis

3.4.1 CAPEX
Since the excel sheet connects all results from the inflow of BL all the way to payback time the CAPEX needed to change with the mass flows, temperatures, etc. To do this a base cost (BC) for each unit was used. This BC was a set for the type of equipment and was sized close to the actual mass flow of the large-scale biorefinery. The prices were acquired from the report “Process Equipment Cost Estimation Final Report” by the U.S. Department of energy. To get the installed BC the following equation is used:\(^23\)

\[
\text{Installed } BC = BC \times (MPF + MF - 1)
\]

MPF is the materials and pressure correction factors which are calculated based on design variation, pressure, construction material, and temperature.

MF is the module factor that is the same for all equipment and is used to approximate the cost for labor, piping, instruments, accessories, etc. It is set to 2.95. \(^{24}\)
When the installed BC has been calculated the final cost for the equipment can be calculated using the following equation:

\[
\text{Final Equipment Cost} = \text{Installed BC} \times \left( \frac{\text{Actual MF}}{\text{Base MF}} \right)^{0.67} \times \frac{\text{CE index 2017}}{\text{CE index 1999}} \times \frac{\text{SEK}}{\$}
\]

This equation uses the rescaling factor of 0.67 to find the cost of equipment when changing the mass flow from the base flow used for the BC to the actual flow. Then the Chemical Engineering Plant cost index is used to get the cost for the actual year since the BC is using data from a previous year. The data used cost index from 1999, so it needs to be readjusted. The cost is also in dollars and is here converted to SEK.\(^{25}\)

After all the equipment’s cost have been calculated they are summed up and added to the cost of other equipment’s and units that are required for a large-scale facility that is not present in the pilot plant. These costs are given by SCA and include among other things site preparation, a flare, and an \(\text{H}_2\) plant.\(^{22}\)

3.4.2 *OPEX*

The OPEX is done per year and is calculated by the total amount of each operational cost used in a year multiplied by its price. Then they are all summed up and multiplied by the maintenance percentage to get the OPEX including maintenance.

3.4.3 *Payback time*

Payback time is used to see how long it will take for the total net income to exceed the CAPEX. The net income is calculated using the following equations:\(^{26}\)

\[
\begin{align*}
\text{EBITDA} & = \text{Income} - \text{OPEX} \\
\text{EBIT} & = \text{EBITDA} - \text{Depreciation Cost} \\
\text{Net Income} & = \text{EBIT} - \text{Taxes} - \text{Interest}
\end{align*}
\]

EBITDA stands for Earnings Before Interest, Taxes, Depreciation and Amortization and EBIT for Earnings Before Interest and Taxes.

The income is the sold biofuels, which has a price of 14000 SEK/tonne. The depreciation cost is the decrease in the value of the built plant. It is calculated using the sum of the years’ digit depreciation method:\(^{20}\)

\[
\text{Depreciation Cost} = \frac{N - t - 1}{N \times (N + 1)} \times \text{CAPEX}
\]

\(N\) is the number of years the useful years of the plant. Since this is hard to predict it is set to 20 years. \(t\) is the current year. The net income also considers inflation for each year.\(^{27}\)

3.4.4 *Net present value*

Net present value is the difference between cash in and outflows over a time period. It is used to see the profitability of a project. The equation used is:

\[
\text{Net present value} = \sum_{t=0}^{N} \frac{R_t}{(1 + i)^t}
\]

Where \(R_t\) is the net sum per year, the \(i\) is the interest which is set at 7\%, \(N\) is the total number of years which is set to 20 years and \(t\) is the current year.\(^{28}\)

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\(^{20}\) Section 3.4.3

\(^{21}\) Section 3.4.4

\(^{22}\) Section 3.4.2

\(^{23}\) Section 3.4.3

\(^{24}\) Section 3.4.4

\(^{25}\) Section 3.4.2

\(^{26}\) Section 3.4.3

\(^{27}\) Section 3.4.4

\(^{28}\) Section 3.4.4
3.4.5 Sensitivity assessment

To see what parameters affected the economics of the plant most a sensitivity assessment was made. It looked at the heat of reactions, residence times, costs from the economic data reports and chemical use. Each parameter was changed by a % as shown in Table 2 to see how it affected the CAPEX, OPEX and payback time.

Table 2 The changes made in the sensitivity analysis for each parameter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor heat of reaction</td>
<td>±50</td>
</tr>
<tr>
<td>Reactor residence time</td>
<td>±X</td>
</tr>
<tr>
<td>Base prices</td>
<td>±30</td>
</tr>
<tr>
<td>Scaling factors</td>
<td>±30</td>
</tr>
<tr>
<td>Dry solid content</td>
<td>±30</td>
</tr>
</tbody>
</table>

The heat of reaction and residence time has a higher sensitivity % since they are more uncertain. Since there is no data for the actual reactions of [CENSORED] lignin to [CENSORED] hydrocarbons it is more likely to be further from the used data. Residence times are also hard to predict when rescaling a plant. Some calculations were made to try to predict the residence time of the full-scale plant based on the pilot plant using the Reynolds number. But the calculations only work for at most a 10-time increase, and the increase is approximately X times the pilot plant size. No conclusions for the reactor sizes could be made and the same residence time was assumed. Changes in residence time cause the same change in reactor size (doubling the residence time doubles the reactor size). Thus, a larger sensitivity % is also made for the residence time.

3.4.6 Future fuel prices

Since the production has not started yet and will be set over many years the changes in fuel prices should also be considered. Figure 2 shows a steady increase in petrol prices with about 3.5% per year.
The price trends for petrol prices in Sweden. The grey is gross margin, red is product cost, blue is tax and green are the value-added tax. 

3.5 Cases

Three different cases were run for the large-scale plant with the realistic settings [CENSORED]. The first case was based on the pilot plants with normal operating conditions. The normal case is called normal because it had the operating conditions used when running the biorefinery was being taught, it is used as a basis to compare against the more extreme cases 2 and 3.

The second and third one was taken from another master thesis student that did a multivariable analysis around a reactor. The second case looked at maximizing [CENSORED] yield and the third case focused on [CENSORED]

Table 3 The operating conditions for the cases

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Highest yield</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>[CENSORED]</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>[CENSORED]</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
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<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Table 3 shows the settings for each case. [CENSORED]
3.6 Simplifications
Inputs [CENSORED] in the heat/mass balance are assumed to be 25 °C. This is because they come from the room the process is in and are not heated or cooled before they enter the process.

[CENSORED]^{30}

Other contents in BL except for water, salts, and lignin are ignored due to lack of data for weight percentage. This does not affect the calculations much since they make up such a small part of the total weight.

Costs for cooling are assumed to be zero since the biorefinery will be able to use the cooling towers of the pulp mill.\textsuperscript{20}
4 Results

4.1 Pilot plant mass balance

Figure 3 The inputs and outputs of the biorefinery.

Table 4 Important inputs and outputs in the process.

<table>
<thead>
<tr>
<th></th>
<th>kg/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
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<tr>
<td>[CENSORED]</td>
<td>X</td>
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<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 3 and Table 4 show the pilot plant process and its mass balance. Not all flows are shown in Table 4 since there are many vents and drains that have close to zero inputs or outputs. There is also X kg/h of water added in the decanter, but it doesn’t enter the process since it only flushes away the solids. But they are all considered and calculated for in the real mass balance and used in the techno-economic assessment.
4.2 Large-scale plant mass balance

Figure 4 Inputs and outputs as well as heating and cooling for the large-scale plant.

Table 5 Important in and outputs in the large-scale plant

<table>
<thead>
<tr>
<th></th>
<th>tonne/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL feed</td>
<td>X</td>
</tr>
<tr>
<td>H2O</td>
<td>51</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>Solid Drain</td>
<td>34</td>
</tr>
<tr>
<td>Water Drain</td>
<td>155</td>
</tr>
<tr>
<td>[CENSORED]</td>
<td>X</td>
</tr>
<tr>
<td>Hydrocarbon as Product</td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 4 and Table 5 show the large-scale plant process with its mass balance. Same as with Figure 3 and Table 4, not all flows are shown.

4.3 Heating and cooling pilot plant

Figure 5 shows how much heat is required to run the pilot plant. The largest part is around [CENSORED], it requires a lot of heating and cooling since [CENSORED] which takes much heat. The cooling is higher than the heating [CENSORED] since
there is heat released during the reactions [CENSORED]. The total heating is $X \text{ W}$ and the cooling $X \text{ W}$.

Figure 5 Heating and cooling done at each unit measured in watt.

4.4 Heating and cooling of large-scale plant

4.4.1 Energy balance

In Figure 6 the normal case requires $X \text{ MW}$ heating and $X \text{ MW}$ cooling. The increase in heating to cooling ration [CENSORED]

[CENSORED]

The highest yield case has a heating need of $X \text{ MW}$ and a cooling need of $X \text{ MW}$.

[CENSORED]

Figure 6 Heating and cooling done for the normal case measured in MW.
4.4.2 Pinch analysis

The pinch analysis for the normal case shows that in the reactors it is possible to get almost all the heating required from a heat exchanger between the inlet and outlet of the reactors. [CENSORED]

![Pinch analysis](image)

Figure 7 Pinch analysis [CENSORED]

4.5 Economics

4.5.1 CAPEX

Figure 8 shows that the normal case has a slightly lower investment cost than the Y case. This is because it has a higher solid content in its BL from the mixing vessel. Since the BL feed remains the same the normal case has less water and lower total mass flow from the BL mixing vessel [CENSORED]. The “other” part of the CAPEX remains constant since it is given values that are not connected to the flows through the biorefinery. The cost of heating equipment is a small part of the CAPEX [CENSORED]

![CAPEX](image)

Figure 8 CAPEX for the plant for the different cases.

4.5.2 OPEX

In Figure 9 it can be seen that the major parts of the OPEX are the cost for the chemicals. The chemicals make up [CENSORED]
Figure 9 OPEX for the different parts depending on the case

4.5.3 Payback time

Figure 10 Cumulative cost and income of the plant for the normal case.
Figure 11 Cumulative cost and income of the plant for the highest yield case

Figure 12 Cumulative cost and income of the plant for the Y case.

4.6 Net present value
The net present value for the normal case is X MSEK [CENSORED] The max yield case has a net present value of X MSEK. [CENSORED]

4.7 Sensitivity assessment
The sensitivity assessment was done for the Y case since it showed the most promising results. The results showed that for changing the heat of reaction and residence time in reactors as well as the amount of added water [CENSORED] had no real impact on the CAPEX, OPEX or the payback time. They are not included in and Figure 15 because of this.
4.7.1 CAPEX
Figure 13 shows that the biggest parameters for the CAPEX are the base prices, the scaling factors and, the BL dry solid content. [CENSORED] The base price and scaling factors are directly connected to the CAPEX, so it is realistic that they have the highest impact. The dry solid content has such a high impact because it is the main factor for the total mass flow through the process. An increase in dry solid content reduces the water and in turn the total mass flow which causes the purchased equipment to be smaller and cheaper.

Figure 13 The CAPEX changes when different parameters are increased or decreased by 30%.

4.7.2 OPEX
For the OPEX the base prices and the scaling factors effect are small, they mostly affect the investment cost for the equipment. [CENSORED] The dry solid content has a lower but still significant effect on the OPEX than the chemicals. This is mostly because of the extra heat needed to heat the water.

Figure 14 The OPEX changes when different parameters are increased or decreased by 30%.
4.7.3 Payback time
Since the payback time was X years the changes in OPEX have X times the impact on payback time compared to changes in CAPEX. As seen in Figure 15 the biggest factors are [CENSORED], BL dry solid content. A change by 30% for any of them causes an increase in by X years or decrease by X years in payback time.

![Figure 15](image)

Figure 15 The payback time changes when different parameters are increased or decreased by 30%.

4.8 Future fuel prices
Using the fuel price trend an estimate of future income through the sale of biofuel can be made. Figure 16 shows a scenario with a payback time of X years. [CENSORED]

![Figure 16](image)

Figure 16 The payback time for the Y case if the fuel price increase continues with 3.5 % per year.
Figure 17 shows that if we use the fuel price increase for the max yield case then the payback time becomes $X$ years. [CENSORED]

Figure 17 The payback time for the maximum yield case if the fuel price increase continues with 3.5% per year.
5 Discussion

5.1 Best case
The best case seems to be the Y case. [CENSORED] The interesting part is when the future price of fuel is considered. After the fuel price increase was added the difference in payback time [CENSORED] But if the increase in fuel price stops or decreases [CENSORED]. Therefore, it should be seen as a safer choice for the moment, although with slightly less maximum potential.

5.2 Important parameters
With the sensitivity assessment, we see the factors that have the biggest impact are [CENSORED] the dry solid content. This is good from an accuracy point of view since the data for them are relatively precise. The prices are based on SCA data and the dry solid contents effects are heating which is calculated using reliable heat equations. Other data that is more uncertain such as the base prices and heat of reactions have a lower impact on the payback time which hints of overall reliable results.

The important parameters mentioned also show the areas in which to focus future work on the process. [CENSORED]

5.3 Uncertainties
The sensitivity analysis already mentioned some of the uncertainties. The largest ones are the base prices and scaling factors used to calculate the CAPEX. The data is old, from 1999 and is for equipment in the USA. The age is being compensated as much as possible with the CE index. The difference in location has not been looked into at all, there might be a price difference for purchasing and building the equipment in Europe compared to the USA.

The heat of reaction for reactors are uncertain. They are based on similar reactions since there is no data for the relevant reaction. The sensitivity assessment, however, did show that they did not have any major impact on the economic viability of the plant.

The calculations for the residence times were inconclusive but changing them showed very little impact on the economics for the plant.

For lack of data on [CENSORED], it was assumed to share the properties of [CENSORED] because of its similar structure. No calculations made on how this could affect the economics but since the mass flow of [CENSORED]

Human error could have occurred during the experimental data collection. It can’t be any larger errors because then the mass balance would not add up. This could at most have very minor effects on economics.

The measuring equipment can show the wrong number, it could be faulty, need recalibration or be dirty by clogging. [CENSORED]

5.4 Future work
What should be prioritized in continuing this work.
5.4.1 **Optimization of the process**
Considering that a continued increase in fuel price [CENSORED] the focus should be to do more experiments on the pilot plant with smaller changes [CENSORED] The data for each new case should be put into the excel sheet to find the lowest payback time possible. Thus, optimizing the process further.

5.4.2 **Heat exchanger**
Since the reactors have an excess of heat [CENSORED] has a deficit of heat an economic assessment should be done regarding the profitability of recycling that heat in a heat exchanger.

5.4.3 **Life cycle assessment**
Since the product of the plant will be biofuels a big sale argument is that it has a smaller carbon footprint on the world compared to fossil fuels. To get a better grasp of the greenhouse gas emissions caused by this fuel a life cycle assessment of the plant should be made. Since producing the equipment and constructing the plant causes a lot of emissions it should be considered when estimating the sold fuels actual carbon footprint.

5.4.4 **Residence time**
The calculations for the residence time were inconclusive since they used only Reynolds number. A more detailed calculation should be made using the temperature and concentration dependence of the reaction rate. This would give a more accurate size of the required reactors. Other options are further experimental data at lab scale or the pilot plant, or using research from other companies and refineries.

5.4.5 **Dry solid content**
The BL taken from the pulp mill has a dry content X %. To get this dry content water is evaporated. This is done to be able to burn it in the recovery boiler. But the BL in the biorefinery has water added to it. That means that water is evaporated then added just after again. This is an unnecessary use of energy and it should be calculated how much energy can be saved by taking BL earlier from the pulp mill before too much water is evaporated. This would save both energy and money since less water would have to be evaporated for the BL going into the biorefinery.
6 Conclusion

The purpose of the thesis was to suggest improvements. The improvements suggested here are in regard to payback time. [CENSORED] But considering increases in fuel prices the maximum yield case might become equally feasible. [CENSORED] Another conclusion is that the process is economically viable. It shows great promise and has good potential.

6.1 Pilot plant mass/energy balance
The pilot plant mass/energy balance is detailed, and all cells are connected. This makes it good for future use. When a part is changed in the pilot plant it is easy to make the change in the excel document and get a good estimation of the changes occurring.

6.2 Large-scale mass/energy balance
Same as with the pilot plant it is detailed, and all the cells are connected. [CENSORED]

6.3 Economic evaluation
The CAPEX, OPEX and payback time are also connected to the mass/energy balance, so it is easy to get a new economic evaluation based on the input operating conditions. This type of calculation for CAPEX is assumed to have a 50% error margin.

6.4 Optimization of the plant
As mentioned, the best thing to do now is [CENSORED], but the further into the future and the more the fuel price increases in that time, the better the maximum yield case becomes.

6.5 Important parameters
The most important parameters [CENSORED] If they can be reduced the payback time will decrease drastically.
7 References


5. [CENSORED]


10. [CENSORED]

11. [CENSORED]

12. [CENSORED]

13. [CENSORED]


15. [CENSORED]


18 Crosby, Alan D. ‘Standard Enthalpy of Formation* for Various Compounds’, n.d.


30 [CENSORED]