LCA of producing dissolving pulp from agricultural residue

Master's thesis in Industrial Ecology

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ABSTRACT

The textile industry is wrought with sustainability challenges and the production of raw materials have a significant contribution to different environmental impacts. The two major raw materials used today for textile fibre production are cotton, and synthetic fibre. Cotton consumes a huge number of resources like land and water, while synthetic fibres are derived from fossil fuels. There is a need to shift away from them.

Wood based fibres are making a comeback in the textile industry, as they are seen as renewable. Wood can be converted to dissolving pulp from which rayon and viscose can be produced. However, other industries compete for wood as a raw material, and there is expected to be a situation where demand for wood exceeds supply.

This calls for alternate materials, which is the context for this thesis. Agricultural residue such as oat husks and wheat straw have shown promising results in producing dissolving pulp. The study conducted in this thesis was to assess potential environmental impacts that could arise when scaling up the production of dissolving pulp from wheat straw via the soda cooking process.

The environmental impacts were assessed using the Life Cycle Analysis tool, where modelling was conducted in the software GaBi. The results obtained were also compared to the impacts arising from producing dissolving pulp from wood.

The results obtained show that wheat cultivation dominates most of the environmental impacts studied followed by the production of chemicals. From a climate change perspective, production of chemicals, the use of water and steam from natural gas in the system were found to be contributing the highest. Sensitivity analysis done show that changing to steam production from biomass and recycling 60% of the waste water could lower climate impacts by 17%.

When comparing with wood-based fibre, there is higher climate change impact and water deprivation for dissolving pulp produced from wheat straw. However, in other impact categories, like acidification potential and photochemical oxidant formation potential, wheat straw-based pulp performs better.

Keywords: Life Cycle Assessment, GaBi, dissolving pulp, Wheat straw, textile industry.

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Manuel Mammen Parayil, Gothenburg, May 2023

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1 INTRODUCTION

In 2015 the United Nations member states adopted the 2030 Agenda for sustainable development which proposed 17 goas towards sustainable development referred to as the Sustainable Development Goals (SDGs). Goal 13, ‘Take urgent action to combat climate change and its impacts’ points out the need to reduce greenhouse gas emissions to limit global warming in order to ensure sustainable development (United Nations, n.d.).

The textile industry is known to emit huge greenhouse gas emissions. The European Parliamentary Research Service (EPRS, 2019) reported that 1715 million tons of carbon di oxide was emitted in the year 2015 by the textile industry. The industry also has other sustainability challenges such as huge water consumption and large use of finite resources (Sandin et al., 2019). It was one of the first industries to be affected by the industrial revolution, where continuous improvement in technology resulted in mass production of clothing (Shishoo, 2012). The economic policies of the last few decades have made the textile industry globally interconnected with cheap labour in Asian countries while also increasing resources used in production. The fast fashion industry of the late 90s have influenced the industry to transition to one of very high turnover and mass consumption which are highly unsustainable (Scheffer, 2012). In fact, Roos (2016) reports that the production of textile fabrics is around 100 million tonnes annually, which is expected to increase as the global population is set to be 8 billion by 2030 (OECD-FAO, 2022). This rise in demand will only worsen sustainability issues unless steps are taken to address them.

There are different measures that can be taken to address sustainability issues within the textile industry. For instance, improving recycling rates, increasing lifetime of clothes, and raising awareness amongst users to name a few. But it has been found that raw material production in the textile industry contribute to environmental impacts, particularly the use of cotton and synthetic fibres, the two largest fabrics used in in the industry (EPRS, 2019). Cotton consumes tremendous amounts of water, land, and fertilizers (EPRS, 2019) whereas synthetic fibres although cost effective, are derived from fossil fuels, which negatively impact climate change. Hence there is a great opportunity to study alternative raw materials that could possibly have lower climate and environmental impacts.

The challenges with cotton and synthetic fibre, has resulted in an increase in the share of wood-based fibres in the textile industry as these are seen as renewable (Kallio, 2021). The most common use is to convert wood to dissolving pulp which can be further used to produce textile fibres. However, an increase in demand for wood-based textile production, puts a constrain on forests as it caters to other sectors as well (Kallio, 2021).

Sweden has plenty of forest land available due to its geography (Formas, 2012) but as reported by Material Economics (2020), the demand for wood-based biomass is set to grow significantly in Sweden and there will reach a situation where demand exceeds supply of wood. This calls for better resource management and other strategies which are not in the scope of this report but underpins the need to shift from wood as starting material in bio-based products.

Agricultural residue is seen as an alternative to wood to produce dissolving pulp and a study conducted by Jahan et al., (2021) shows different non-wood materials like wheat straw, rice straw and bamboo among others that can be used to produce dissolving pulp, often achieving yields close to 50%.

The issues and challenges in the textile industry and resource constrains with forests, set the context of this master thesis. The CircuCel project between TreeToTextile, Chalmers and IVL is tasked with studying such agricultural residues for producing dissolving pulp and in the previous year promising results were seen with wheat straw and oat husk to produce dissolving pulp at a lab scale. The results of this study would help TreeToTextile in understanding the different environmental impacts of raw material choices in producing dissolving pulp, as this is later used as their starting material to produce textile related fibres (TreeToTextile, 2023).

1.1 Aim

The aim of this master thesis is to assess the potential environmental impacts of scaling up lab trials to an industrial process to produce dissolving pulp from wheat straw via the soda cooking process. The impacts will be studied using a life cycle assessment methodology. The aim also includes comparing the environmental impacts with a benchmark case of dissolving pulp from wood.

2 BACKGROUND

2.1 Dissolving pulp

All plant biomass contain cellulose as a major component in its cell wall and it is the most largely available organic material on earth (Rowell, 2012). It also contains other carbohydrate structures such as hemicellulose and lignin (Ek et. al., 2009). Due to its high degree of polymerization, cellulose has unique properties which make it highly valuable in the chemical industry, however it needs to be separated out from the other carbohydrates present (Ek et. al., 2009). Dissolving pulp is pulp that has high cellulose content (95%) produced after subjecting plant biomass to chemical pulping processes that break down lignocellulosic content. The pulp produced can then be used to derive other material such as rayon and viscose, which are important to the textile industry (Beirmann,1996).

2.2 Chemical pulping processes

In order to separate and produce high cellulose content in dissolving pulp, various chemical processes exist. Some of the most common methods used today are the soda pulping process, the kraft pulping process, and the sulphite pulping process (Beirmann,1996).

- Soda cooking process – In the soda cooking process the biomass is cooked with sodium hydroxide and then bleached to produce dissolving pulp. It was one of the first methods in the pulping industry and is mainly used when using straw based biomass as raw material (Beirmann,1996).

- Kraft pulping process – The Kraft pulping process differs from the soda cooking process in that sodium hydroxide and sodium sulphite chemicals are both used to cook biomass at around 180°C to give stronger pulp. The advantage is its usefulness in cooking most wood species. However, pulps produced from this step are harder to bleach, have low yield and the presence of harmful sulphur residue. It is often preceded by an acid pre-hydrolysis step in which the plant biomass is subjected to sulphuric acid to liberate cell fibres and dissolve hemicellulose content. This makes it easier to extract cellulose in the cooking step (Beirmann,1996).

- Sulphite pulping process – In this process, biomass is treated with sulphurous acid along with its alkali salts to separate lignin by forming lignosulfonates. This process is common in Swedish pulp mills and is suitable for most wood species. Pulps produced by this process are bright and easily bleached compared to the ones from the kraft process, however they are not as strong (Beirmann,1996).

2.3 Dissolving pulp from wheat straw via soda pulping process (lab scale)

This section further explains how dissolving pulp can be produced from wheat straw via the soda cooking process. The soda cooking process as mentioned in the previous section is useful for straw based raw materials.
The lab-based processes are described below (Sjöstedt, 2022).

1. **Acid pre-hydrolysis**
   Acid pre-hydrolysis is conducted with sulphuric acid (0.1% concentration) at elevated temperature (160 °C) to open up the cell structures in the lignocellulosic biomass. This ensures that the lignin is accessible for further processing with sodium hydroxide. The sulphuric acid hydrolyses hemicellulose because of their short-chained structures to their respective monomers which can be recovered for further processing if required.

2. **Soda cooking**
   As mentioned earlier, in the soda cooking process the biomass is treated with sodium hydroxide (6% concentration) at a temperature of 170°C. This ensures delignification takes place and high-grade cellulose is obtained. The by-product of this step is black liquor which mostly is used to recover energy and chemicals in industrial processes.

3. **Bleaching**
   In this step all unwanted impurities are removed to give the pulp its desired purity. Within the pulping industry chlorine bleaching was mostly used but due to its high impacts on the environment, industries switched to chlorine dioxide bleaching. Using absolutely no traces of chlorine is the best option and, in this study, bleaching via hydrogen peroxide step was studied. There is also the need to use chelating compounds like Ethylenediaminetetraacetic acid (EDTA) to inhibit transition metals that can affect the yield of the bleaching process.

   The conclusions from lab trials were that for the case of wheat straw harsher bleaching steps are required to meet the desired quality for dissolving grade pulp. This was later improved at lab experiments with a two-step bleaching process using hydrogen peroxide of 3% and 5% concentration, respectively.

2.4 Life Cycle assessment framework

A Life Cycle Assessment (LCA) is useful to understand the environmental impacts occurring along the Life cycle of a product, from when the materials are extracted to its production and disposal at the end of life. LCA can help in understanding why one product is better than the other, while also looking at more global level impacts rather than site specific. In the process industry, LCA is usually conducted with a cradle to gate approach. This is because in process industries, the main application of LCA is to look at what are some environmentally better design or process options. LCA in the process industry has also helped in process improvements ultimately leading to better environmental performance (Baumann & Tillman, 2004). There are four main steps in an LCA namely - goal and scope definition, inventory analysis, impact assessment, and interpretation of results which are often iterative in nature.

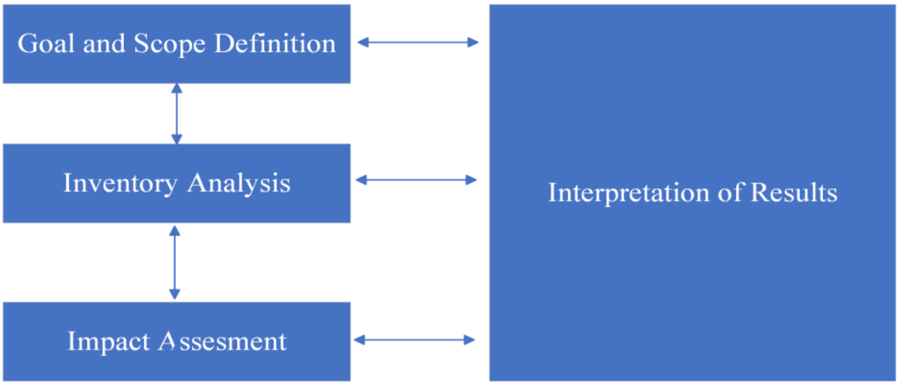

Figure 1. 1: Different Steps in a Life Cycle Assessment (Baumann & Tillman, 2004)

2.4.1 Goal and scope

In the goal and scope definition the reason for carrying out the study is specified and along with it all other contextual information about the product or process is studied. It is necessary that specific goals are set for the LCA study and not a vague description. The goal and scope step also include information on the type of LCA to be conducted and the environmental impacts that will be considered (Baumann & Tillman, 2004).

An important part is to define the functional unit of the system under study. A functional unit is a unit with which all other flows in the system are related to and all impacts will be quantified in relation to the functional unit. The choice of functional unit must be representative of the function of the system. In the goal and scope step other aspects like time horizon, geographical scope, data requirements and system boundaries must be specified (Baumann & Tillman, 2004).

2.4.2 Inventory analysis

In this step all environmentally relevant flows are collected and built up as per the different processes present in the system. This includes energy flows, material flows emissions and others entering and leaving the system boundary which must reflect the goal and scope defined. Once all relevant data is collected, they must be normalised in relation to the functional unit.

The inventory analysis step is often considered as the most time-consuming step in an LCA study (Baumann & Tillman, 2004).

2.4.3 Impact assessment

In this step all the flows quantified in the inventory analysis are related to its environmental impacts. This also means that a lot of environmental loads will be classified and aggregated to represent the studied impacts and convey relevant information. This is done by multiplying the environmental load with a characterisation factor. These will significantly depend on the impact assessment method used in the study (Baumann & Tillman, 2004).

2.4.4 Interpretation of results

In this step the results of the impact assessment and inventory data are refined and presented to best reflect the goal and scope definition. This might include showing different graphs and diagrams that answer the specific questions in the goal and scope definition. It must also convey results that are relevant for the intended audience. It is often common that sensitivity analysis and scenario analysis are conducted to conclude the findings of the LCA study (Baumann & Tillman, 2004).

2.5 Prospective life cycle analysis

According to Arvidsson et al. (2018) , a prospective LCA is an LCA conducted to provide environmental guidance in early development of a process or technology where potential environmental impacts can be detected. This allows for more freedom in changes or alterations that would be difficult to implement later once the technology matures. However, at early stages of development, knowledge of how a technology will behave or impact the environment is limited although high degree of freedom exists. This conflict in freedom of change versus knowledge at maturity is referred to as a Collingridge dilemma (Figure 2.1, Arvidsson et al., 2018).

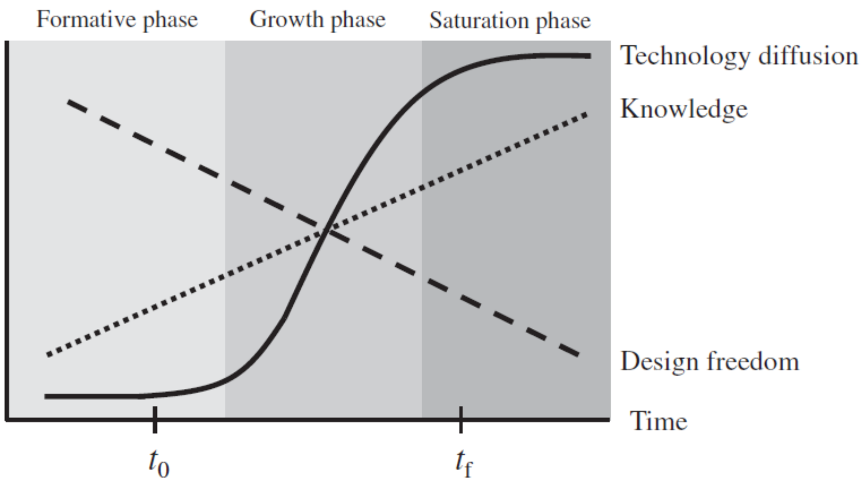

Figure 2.1: Graph showing the Collingridge Dilemma, where as knowledge of a technology increases, the design freedom decreases. Taken from (Arvidsson et al., 2018).

3 LIFE CYCLE ASSESSMENT

In this section the LCA of dissolving pulp production from wheat straw is described. The LCA for the benchmark case (dissolving pulp from wood) can be found in Appendix B.

3.1 Goal and scope

The goal of this LCA is to investigate the environmental impact of producing dissolving pulp from wheat straw. The process has been scaled up from laboratory to industrial scale using ASPEN PLUS. The modelling in ASPEN PLUS is not part of this master thesis and more details can be found in a separate master thesis (Linnea, 2023). The results will also be compared to a benchmark (dissolving pulp). Information and data present in the environmental reports of Domsjö Fabriker plant in Sweden will serve as a benchmark, representing a generic model for dissolving pulp produced from wood.

More specifically the LCA will try to answer the following questions –

1. What processes or steps contribute to the environmental impacts?
2. Are there any measures or changes in the process that can lower the environmental impact?
3. How does the environmental performance of the dissolving pulp from wheat straw compare against dissolving pulp from wood (benchmark).

The scope of this study is a **cradle – gate prospective attributional** LCA study in which the processing of all chemicals required and other materials including their transport to the industry up to the point where dissolving pulp leaves the gate of the industry is considered. The cultivation of wheat will also be considered within the scope of this study since wheat straw residue is generated from this step. The use phase along with its transportation is not considered, as these impacts will be independent of the process route through which dissolving pulp is produced.

3.1.1 Functional unit

The functional unit was considered as **1 tonne of dissolving pulp (93% dry)** produced from the entire process. This is appropriate as the function of the system under study is to produce dissolving pulp and therefore quantifying impacts in terms of amount produced is logical. However, a note must be made regarding the quality of the pulp produced. From the results obtained through lab trials the purity of dissolving pulp needs to be slightly improved before it can be considered as a good grade of material for further use. This qualitative difference with respect to the LCA of dissolving pulp from wood based raw materials is not captured in the functional unit. In this study the reference flow is the same as the functional unit.

3.1.2 System boundaries

As mentioned, the system boundary of the LCA is a cradle to gate study. The background system has been identified as the production and transport of raw materials which in this case is wheat straw along with all the required chemicals. The foreground system includes the entire industrial process along with the wastewater treatment plant and energy recovery unit in which the black liquor produced from the soda cooking step is sent to recover energy and part of the sodium hydroxide used.

Geographical boundaries – The plant will be assumed to be set up in Sweden, Skåne county (Nymölla) as TreeToTextile already has an existing pilot plant for converting dissolved pulp into cellulose fibre. The area is also close to other industrial clusters which may have potential symbiosis opportunities later. It was assumed that wheat straw is sourced from within the Skåne county while chemicals required, span the entire European union region. The electricity mix from Sweden is considered.

Time horizon – Since this is a prospective study, the time period for the operation of this plant was assumed to be approximately 5 years from now with an operational life of 10-12 years.

Other boundaries – Capital goods and personnel are beyond the scope of this study and will be excluded from the system. The construction impacts will also not be considered and can be part of a separate study. This is justified because inclusion of these would have no significant difference to the impacts of the product and would make sense to consider only at a more realistic stage of the implementation of the plant and not early on when looking at different process options.

3.1.3 Indicators and impact categories studied

A list of impact categories and indicators with their assessment methods are given in Table 3.1and Table 3. 2 below. Wherever possible the Environmental Footprint 3.0 assessment method was chosen to calculate impacts for the respective categories. The reason being that the European commission recommends this method as common practice for LCA impacts of goods and services (EU Commission, 2021). In all other cases the indicators proposed in the Environmental Product Declaration (EPD) international system were chosen.

Table 3.1: List of environmental impacts studied and their assessment methodology

Impact Category	Unit	Method
Climate Change (CC)	kg CO_2 eq.	Environmental Footprint 3.0
Abiotic Depletion Potential, non-fossil resources (ADP)	kg Sb eq.	EN15804+A1
Eutrophication Potential (EP)	kg Phosphate eq.	CML 2001
Photochemical oxidation formation (POF)	kg NMVOC eq.	ReCiPe 1.05 Midpoint (H)
Acidification Potential (AP)	mole H^+ eq.	Environmental Footprint 3.0
Ozone Depletion Potential (ODP)	kg CFC -11 eq.	Environmental Footprint 3.0
Water deprivation	m^3 world eq.	Environmental Footprint 3.0

Table 3. 2: Energy indicators studied and their assessment methodology

Indicator	**Unit**	**Method**
Total use of renewable primary energy (PERT)	MJ	EN15804+A1
Total use of non-renewable primary energy (PENRT)	MJ	EN15804+A1

The importance of climate change impact is clear and more so since the textile industry is known to emit large amounts of greenhouse gases. The cultivation of wheat implies the use of fertilizers and fuel which makes it relevant to study acidification and eutrophication potential. The industrial process will use a tremendous amount of energy and hence the energy indicators total use of renewable and non-renewable primary energy were chosen. The use of different chemicals implies different resources used and hence abiotic depletion potential was also studied.

A detailed description of the different indicators used can be found in Appendix A.

3.1.4 Data requirements

Data required for this study will mainly be obtained from the process simulation and modelling of lab data in ASPEN PLUS. The simulation work is done in parallel by another master thesis student and hence a complete dataset was hard to gather. However, all the major material flows into the different processes were obtained and used in the LCA modelling. Wherever data was a challenge, estimations and assumptions from literature were performed and experts at IVL were consulted. The data for background processes, like wheat cultivation and other chemicals, were taken as regionalized averages representative of what is common in Europe. The background processes were selected from the GaBi database provided and the data hierarchy procedure at IVL.

3.1.5 Sensitivity analysis

Based on the results obtained from the impact assessment, sensitivity analysis will also be conducted. Focus is given on climate change impact and how sensitive the results are to different scenarios. Steam required for the processes can either come from natural gas or biomass. The base case assumes steam to come from natural gas and a sensitivity analysis based on steam from biomass will be studied. The system has a huge water demand and the base case does not include any recycling of water within the system. A sensitivity analysis based on recycling water will also be studied. Finally, a sensitivity analysis based on allocating no burden on the wheat straw will also be studied.

3.1.6 Assumptions and limitations

- Wheat straw was assumed to be supplied from Skåne county and that there is enough supply of it although Gunnarsson et al, (2020) shows that in order to maintain soil fertility for the Skåne region it is best to let the wheat straw remain in the fields.
- Wheat straw supply was assumed to be only from four of the biggest wheat farms from Skåne (Casimir & Lund, 2020).
- The data set used for wheat cultivation is obtained from Ecoinvent 3.8 which is data representative for wheat cultivation in Switzerland. This was chosen because of few

wheat straw based LCA literature following the same manner (Borrion et al., 2012) , (Janssen et al., 2014).

- The Ecoinvent data-set for wheat cultivation allocates 95% of the burden to wheat and 5 % to wheat straw (Ecoinvent 3.8, accessed May 15th, 2023).
- When comparing the yield reported for wheat cultivation in Sweden by Nilsson & Bernesson (2009) with the Ecoinvent dataset used, these were found to be similar and assumed to not make a difference.
- It was assumed that all chemicals were bought and transported to the factory in concentrated form and that dilution occurs on site.
- The plant was assumed to be operational for 8400 hours in a year to account for maintenance and shutdown activities.
- Operational issues with different processes were not considered to affect the production of dissolving pulp.
- Steam required was assumed to be produced from natural gas.
- Biogenic carbon was not included in emission calculations. This is because the uptake and emissions of biogenic carbon are considered to be net zero over a long period of time.

3.2 Life cycle inventory analysis

This section describes more on how the data for the system were gathered and estimated. A detailed inventory table for each system is given in Table C. 1**.** It consists of raw data received from the process simulation in ASPEN PLUS and normalised to the functional unit of 1 tonne dissolving pulp. The modelling of the system was carried out in the software GaBi. A list of datasets used in the software can be found in Table D. 1.

3.2.1 Flowchart for system

The flowchart to produce dissolving pulp from wheat straw is shown below in Figure 3.1. The dashed lines indicate the system boundary and as mentioned the use phase does not fall within the system boundary. The entire emissions for the system are indicated as an arrow leaving the system boundary. The background system consists of the production of chemicals and wheat cultivation, while the foreground system includes all operations that treat the wheat straw to convert it into dissolving pulp.

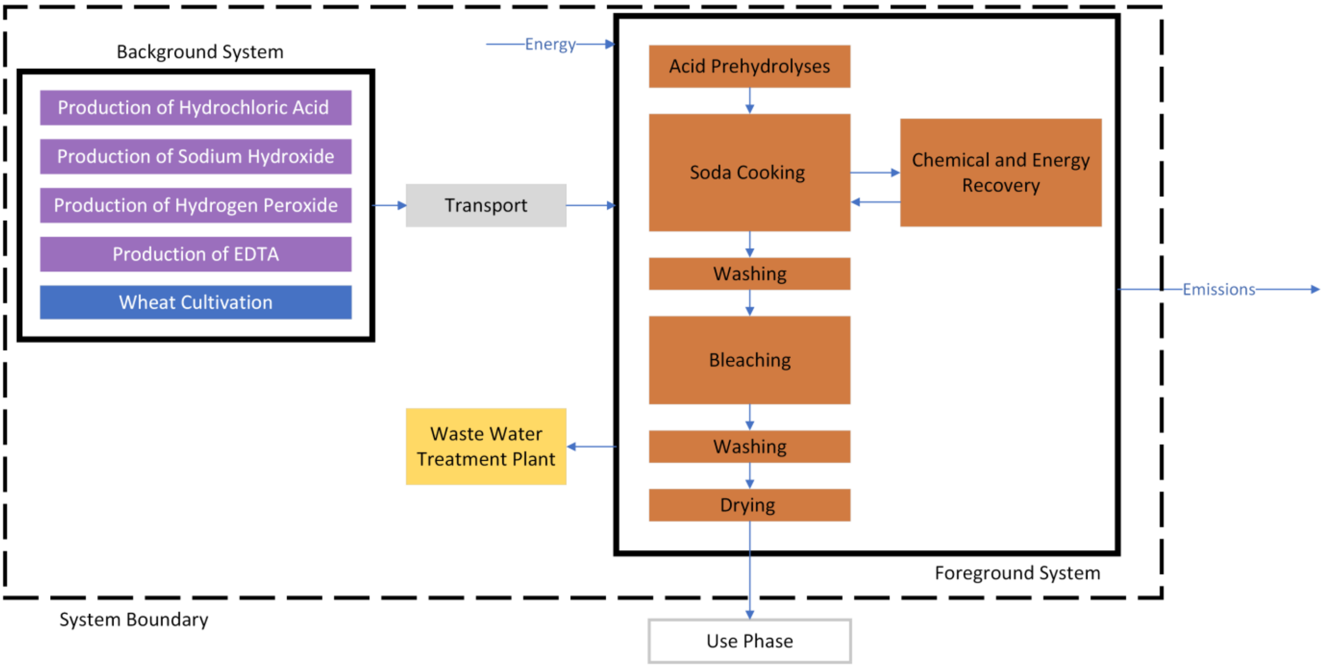

Figure 3.1: Flowchart showing the different processes involved in producing dissolving pulp from wheat straw

3.2.2 Description of activities

This section briefly describes the different activities modelled.

3.2.2.1 Wheat straw cultivation

The wheat straw required for this system is assumed to come from Skåne county and the required amount of raw material needed for 1 tonne dissolving pulp was calculated to be approximately 2.5 tons. The moisture content for the wheat straw was 11% as this is what was used in lab trials. To model the background system in GaBi, the wheat cultivation process, *Wheat production, Swiss integrated production, intensive* from the Ecoinvent database 3.8 was used. The moisture content for this process is 15% in straw and a help process was created to get the moisture content down to desired 11% for the study.

3.2.2.2 Transport of wheat straw

The wheat straw needed to be transported to the plant at Nymölla was assumed to take place only by trucks. In order to calculate the distance, the four biggest wheat farms in Skåne county were found out as per Casimir & Lund (2020). The distance was then calculated as 120 kms, which is the average distance from these farms to Nymölla using google maps. The transport specifications can be found in Table D. 2.

3.2.2.3 Transport of all other chemicals

All chemicals transported to the plant are assumed to be from a distance of 1500kms. This distance is considered since it accounts for the farthest regions in the EU. Transport specifications can be found in Table D. 3.

3.2.2.4 Acid pre-hydrolysis

In this process, wheat straw is mixed with hydrochloric acid solution (0.125%) in a digester at 160°C and pressure 7 bar. This causes mainly hemicellulose to dissolve in the acid solution. Waste liquor is generated in this step which is sent to the waste water treatment plant.

3.2.2.5 Soda cooking

The treated wheat straw is then mixed with sodium hydroxide solution (7.4%) 170° C and 8 bar pressure. It is usually carried out in batch reactors. This step separates most of the lignin which is found in the black liquor. The pulp produced is sent further for bleaching. The black liquor is sent to an energy recovery unit where it is burned to recover energy that meets most of the demand in the plant. The smelt that remains consists of sodium salts which are further processed to recover sodium hydroxide.

3.2.2.6 Washing number-1

Before the pulp is sent for bleaching it is subjected to counter current washing in order to remove chemicals and other dissolved content especially lignin. Usually, a set of 3-4 washers are used. The wastewater from this step is sent to wastewater treatment plant and the washed pulp is sent further for bleaching.

3.2.2.7 Two step hydrogen peroxide bleaching

The washed pulp is now sent for bleaching. A bleaching step is used so that the pulp can be brought to its desired brightness as there is still some lignin present in the pulp. The pulp in this system is bleached with a hydrogen peroxide of 0.62% solution and 0.37% solution along with the complexing agent ethylenediaminetetraacetic acid (EDTA). EDTA is used so that metals present in the pulp do not form ions with hydrogen peroxide and inhibit bleaching. The reaction is usually carried out in atmospheric pressure and at 80-110°C temperature (Ulefors, 2022).

3.2.2.8 Washing number-2

A washing step similar to the previous washing step is done once again to get rid of impurities, and the waste stream is sent to the wastewater treatment plant. The washed pulp is finally sent for drying.

3.2.2.9 Drying

The washed pulp is dried to about 7% moisture content. The drying operation consumes a lot of energy part of which was supplied by the energy recovered from burning black liquor and the rest by steam from natural gas. The waste stream from the drying step is sent to the wastewater treatment plant.

In order to calculate the energy requirements for drying, the mass of water needed to be removed was taken as the water flow that came out of the dryer (Table C. 1). It was assumed that a mechanical press removes 50% of the water before it enters the dryer (Sundin, 2011). The energy required to evaporate the remaining water at 100°C was calculated with equation

(1) assuming a latent heat of vaporisation of 2257.92 kJ/kg steam (Engineering toolbox, 2003). The energy required was calculated as **5.4 GJ/ tonne of dissolving pulp.**

3.2.2.10 Energy and chemical recovery

In this step the black liquor from the soda cooking process is further processed. Initially, the black liquor is sent to a series of evaporators to concentrate it further. This allows for efficient burning and production of energy. After that it is sent to a recovery boiler where it is burned with air to generate energy (Beirmann,1996). The energy recovered is used to supply the energy demands for the evaporators as well as for the drying process. After burning, the smelt that remains consist of sodium salts which is then sent to a causticizing plant where it is mixed with calcium oxide to get sodium hydroxide which is recycled back to the soda cooking step (Beirmann,1996). The recovery efficiency of sodium hydroxide was assumed to be 97% of sodium salts entering the boiler based on literature (Tran and Vakkilainnen, n.d.). The chemicals needed for the causticizing plant were not considered in the model due to time constrains.

3.2.2.10.1 Chemical recovery data

In order to recover chemicals from black liquor, a mass balance of sodium hydroxide (NaOH) used within the system was calculated. It was found that approximately 28% of initial NaOH used is lost. From the sodium hydroxide present in black liquor 97% of it is recovered based on the assumption mentioned above. It was found that 70% of NaOH initially used could be recovered and only the lost amount of NaOH needs to be accounted for in the LCA model.

3.2.2.10.2 Energy recovered from black liquor

The energy recovered from burning black liquor in the recovery boiler was calculated by assuming a steam potential of 3.5 kg steam/kg black liquor solids (Valmet, 2017). Steam produced was assumed to be medium pressure (MP) steam at 180°C. The latent heat of vaporisation at this temperature was assumed to be 2013.56 kJ/kg steam (Engineering toolbox, 2003).

The total energy recovered can then be calculated using equation 1 –

$$Energy = total\ mass\ of\ steam * Latent\ heat\ of\ vaporisation\ of\ steam \qquad (1)$$

For this process it was calculated to be around **8.4GJ/ tonne dissolving pulp**.

3.2.2.10.3 Energy demand - evaporators

The evaporators increase the concentration of black liquor to the recovery boiler and they use a significant amount of energy as well. The pressure at which evaporators operate was assumed as 4 bar with a demand of 2.5-ton steam/ tonne dissolving pulp (Orr, 2009). At 4 bar pressure the latent heat of vaporisation of steam was taken as 2132.95 kJ/kg (Engineering toolbox, 2003). Using equation (1) energy required for the evaporators were calculated as **4.3 GJ/tonne dissolving pulp.**

3.2.2.10.4 Emissions from recovery boiler

The emissions from recovery boiler were calculated as per the information given in European Commission's Best Available Technique (BAT) guidelines for the paper and pulp industry (Suhr et al., 2015). The main emissions are to air and the quantities are shown in Table 3.3 below.

Table 3.3: Emissions from Recovery Boiler

Pollutant	Amount (kg/tonne DP)
Sulphur di oxide	0.002-0.65
Total reduced Sulphur	0.0007-0.4
Nitrogen oxides	0.73-2.0
Particulates	0.02-1.6

The average values of the given ranges were entered in the energy and chemical recovery process. It is also important to note that biogenic carbon di oxide is released as well. But this is considered not to contribute to any environmental impact. To calculate the amount of biogenic carbon, it was assumed that 31% of the solid biomass in the black liquor consists of carbon (Suhr et al., 2015). Assuming that all carbon gets converted to carbon di oxide, **760 kg CO_2 / tonne of dissolving pulp** is released.

3.2.2.11 Wastewater treatment plant

All the waste streams from the process were sent to a wastewater treatment plant. The modelling of this step was assumed by adding a process that treats wastewater from municipal waste representative for an average EU plant. This is because no industrial level wastewater treatment processes were found in GaBi and to model a treatment plant from scratch is out of scope due to time constraints.

3.3 Energy data

The energy required for the different process steps are given below in Table 3. 4. These values were calculated based on data provided by Ulefors (2022). It was assumed that the energy requirements for each step would not differ much from oat husk or wheat straw as raw material. Data from the simulation of the process should be used but since it is time consuming and to avoid unnecessary wait time to proceed with LCA, calculations from the previous year was used.

Table 3. 4: Energy Demand per ton of dissolving pulp for different steps

Process	Type	Demand per tonne DP (MJ)
Prehydrolysis	MP Steam	6.1
Soda Cooking	MP Steam	3.8
Bleaching	MP Steam	0.2
Pumps	Electricity	0.01

4 RESULTS AND DISCUSSION

This section presents the results of the LCA and discusses the different observations. Firstly, the results for dissolving pulp from wheat straw along with individual contributions are presented in section 4.1 while also taking a closer look into the climate change impact category. Based on the observations, sensitivity analysis was conducted for different scenarios and their results are presented in sections 4.1.2 to section 4.1.5. Finally, the results of wheat straw pulp are compared with the results of the benchmark pulp from wood in section 4.2.

4.1 Results for dissolving pulp from wheat straw

The results for the indicators mentioned in Table 3.1 are presented below in Table 4.1, all based on producing 1 tonne dissolving pulp. The results are for the base case in which all the energy demands are by steam from natural gas. Contribution of all the processes to the different impact categories and indicators are shown below in Figure 4. 1.

Table 4.1: Impact assessment and inventory results per tonne dissolving pulp for the different indicators studied (base case)

Impact Category	Units	Total Amount
Abiotic Depletion Potential, non -fossil resources	kg Sb eq.	0.0014
Eutrophication Potential	kg Phosphate eq.	2.5
Photochemical Oxidant Formation Potential	kg NMVOC eq.	2.6
Total use of Renewable Primary Energy	MJ	8600
Total use of Non-Renewable Primary energy	MJ	1300
Acidification Potential	moles H^+ eq.	5.0
Climate Change	kg CO_2 eq.	780
Ozone Depletion Potential	kg CFC-11 eq.	1.4 E-05
Water Deprivation	m^3 world eq.	35

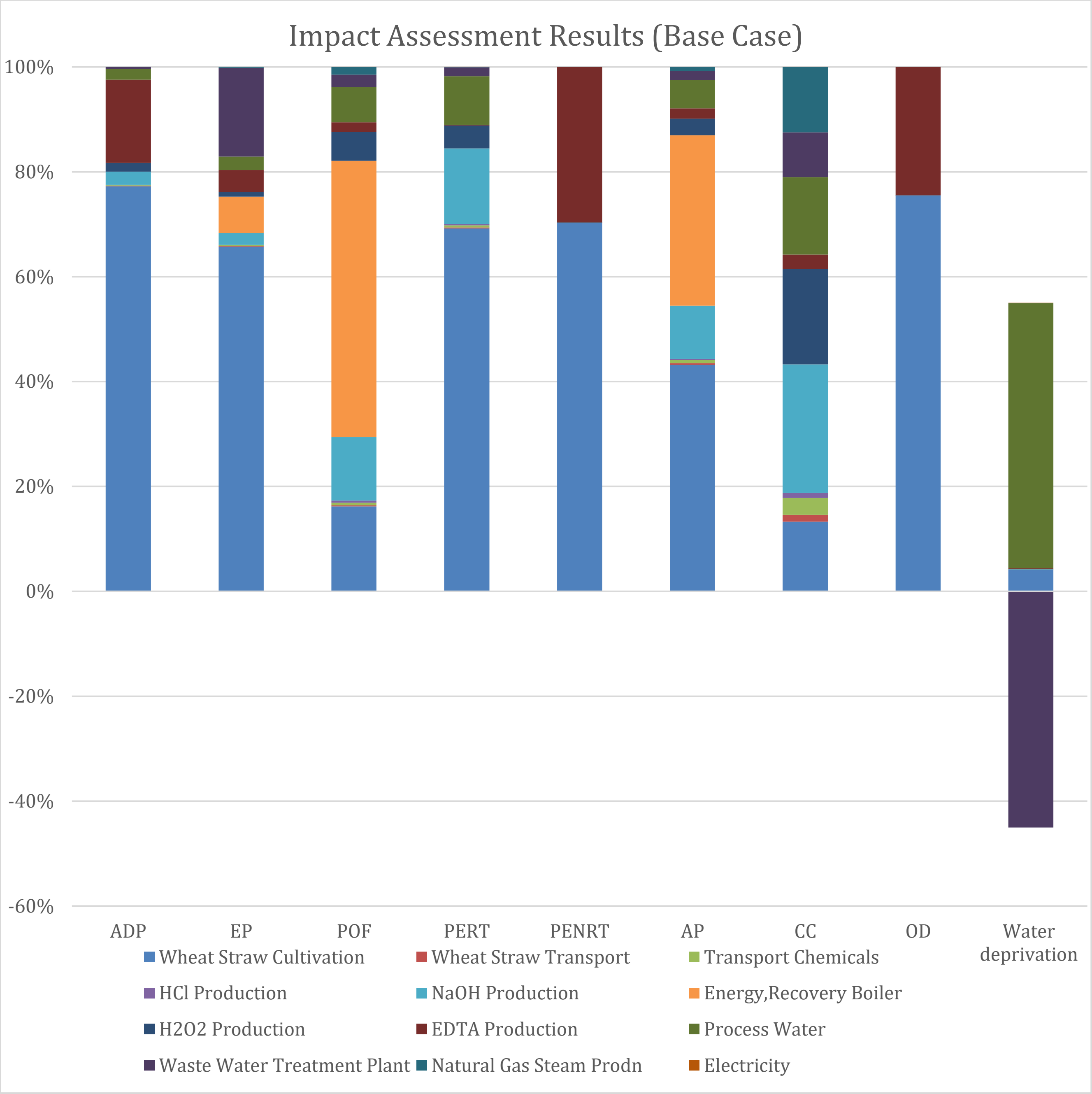

Figure 4. 1: Relative contribution of the different processes to indicators studied for the base case. ADP – Abiotic Depletion Potential, non fossil resource. POF – Photochemical Oxidant Formation. EP – Eutrophication Potential. PERT – Primary energy renewable resources. PENRT – Primary Energy non renewable resources. AP – Acidification Potential. CC – Climate Change. ODP – Ozone Depletion Potential.

From the graph above, a few interesting observations can be made. Wheat cultivation dominates highest contribution to 6 out of the 9 indicators studied, while also significantly contributing to the rest. The production of chemicals such as sodium hydroxide and EDTA have significant contributions to energy use, abiotic depletion potential, acidification potential and ozone depletion potential. Recovery boiler operations have highest contribution to photo chemical oxidant formation potential, while also significantly contributing to acidification potential. Transport activities have insignificant contributions to the overall impacts studied. Water deprivation is completely dominated with the use of process water in operations, however, the wastewater treatment plant releases cleaned water back to water bodies and hence has a negative value.

The reason for wheat cultivation's large impact is mainly due to the use of fertilizers and chemicals that are used as pesticides during its cultivation. The high contribution towards ADP is because of the impacts arising from the use of ammonium nitrate, inorganic fertilizers, and phosphorus fertilizers (Ecoinvent 3.8, accessed 15th May, 2023). The same can be said for its contribution to EP, it is also due to the release of nitrogen, ammonia and phosphates into fresh water. The release of ammonia emissions to air is what contributes to AP while organic compounds most probably emitted from the use of pesticides contribute to ODP. The use of energy is also high. This is because around 2MJ of energy from biomass are used per kg of wheat straw produced, along with some crude oil and natural gas (Ecoinvent 3.8, accessed 15th May, 2023).

The production of sodium hydroxide has significant contributions to photo chemical oxidant formation potential and acidification potential is due to the emissions of nitrogen, sulphur dioxides and ammonia during production. Production of sodium hydroxide also consumes a significant amount of renewable energy. This is due to the high energy required for the electrolysis of brine, which produces sodium hydroxide. Similarly, the use of different chemicals in EDTA production such as formaldehyde and sodium cyanide explain the significant contribution to abiotic depletion potential (Ecoinvent 3.8, accessed May 15th, 2023). A closer look into the impacts found that the reason for high contribution of the EDTA production towards ozone depletion potential is due to the release of halogenated compounds to air.

The contribution by the energy recovery process to POF and AP are also due to the release of nitrogen dioxide and sulphur dioxide to air. The burning of black liquor usually consists of lignin and some amount of sulphur is present in lignin. Burning with air implies the release of some nitrogen dioxides as well.

Process water used contributes the highest to water deprivation and it is because of the high-water demand of the processes. Most of the chemicals are highly diluted as per data provided from the simulation results. Process water contributes to other impacts as well and this because the process modelled includes the purification of water by an ion exchanger. This could explain the contributions to photo chemical oxidant formation potential and acidification potential while the use of energy in the ion exchange process explains the use of renewable energy.

4.1.1 Climate change impact

Since climate change is of high relevance a closer look into the individual contributions is shown below in Figure 4.2. From Table 4.1 above the total climate impact for producing 1 tonne of dissolving pulp from wheat straw is 760 kg CO2 eq. Sodium hydroxide and hydrogen peroxide production contribute mostly to climate change impact. The production of these chemicals has significant emissions of greenhouse gases to air. These along with the use of process water, wheat cultivation and steam from natural gas contribute to 80% of the climate change impact.

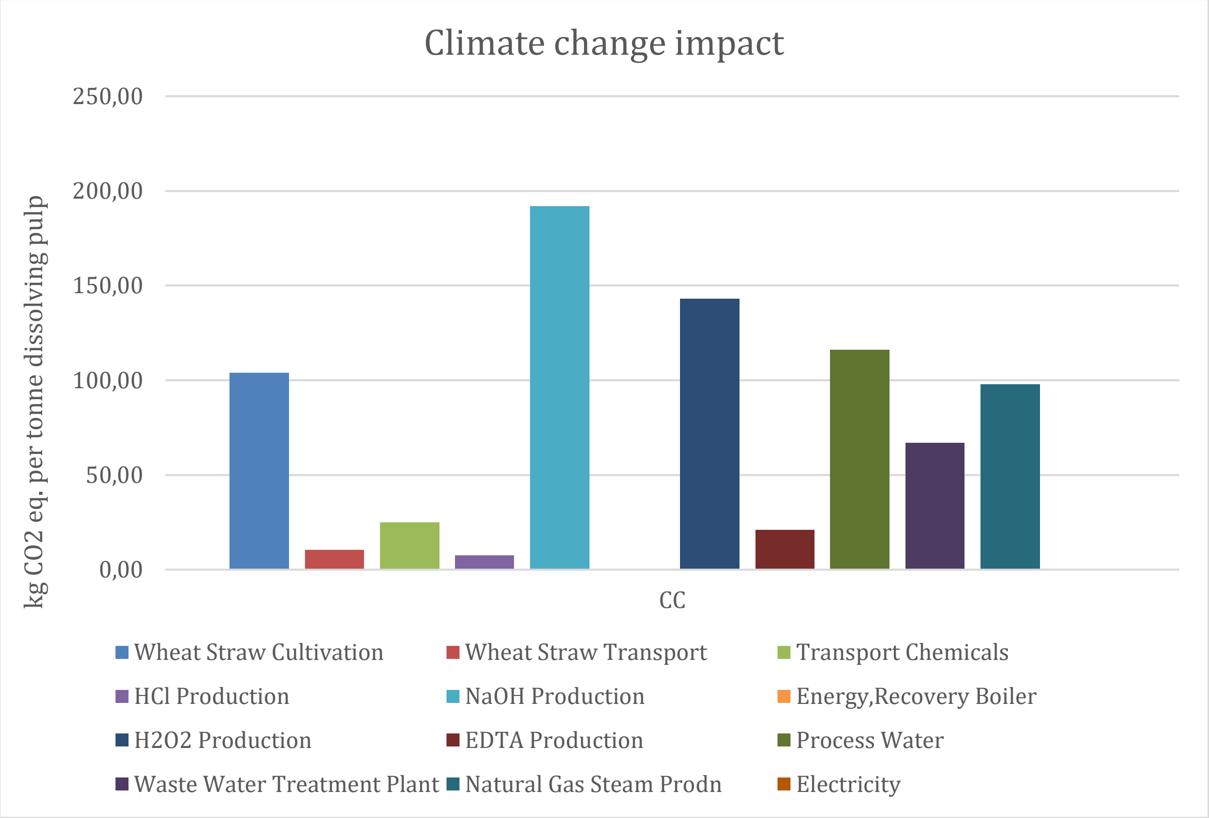

Figure 4.2: Contribution of different processes to the climate change impact indicator (base Case)

From the graph above, sodium hydroxide and hydrogen peroxide production contribute mostly to climate change impact. The production of these chemicals has significant emissions of greenhouse gases to air. These along with the use of process water, wheat cultivation and steam from natural gas contribute to 80% of the climate change impact.

Taking a closer look into sodium hydroxide production, it is most likely that the electricity use is what contributes to huge carbon emissions and thus to climate change impact. The data set used in the model is a European average and hence average electricity use in Europe is considered. The share of fossil fuels in the European grid mix is about 42% (Eurostat,2023). A higher share of renewables in the grid mix could lower the climate change impact of sodium hydroxide production. It should also be pointed out that the climate change impact presented in Figure 4.2 are after 70% of the sodium hydroxide has been recovered within the production process and actions could be taken to minimize the loss of chemicals.

When further studying different production methods for sodium hydroxide, there is evidence for a more sustainable way of producing sodium hydroxide via the oxygen depleting cathode (ODC) method as cited by (Garcia-Herrero et al., 2017). In the future it could be expected that such a process might be implemented throughout and so further reduce impact on the studied system.

Hydrogen peroxide is widely produced via the anthraquinone process which requires hydrogen as a key compound. The production of hydrogen in the data set used, is modelled via steam cracking which most likely uses steam produced from natural gas. Steam produced from biomass could lower climate change impact. An important factor to consider then is deciding on where to source these chemicals from. The high use of electricity and energy demands for these chemicals imply that the energy mixes of different geographies can affect the environmental performances of the foreground system as well.

Additionally, the wheat cultivation process contributes to 35% of the climate change impact and this arises from the release of dinitrogen oxides, the use of fertilizers and other farming operations (Ecoinvent 3.8, accessed May 15th, 2023).

The process water data-set used in this study undergoes a purification step as mentioned before and this is likely why it contributes to the climate change impact.

4.1.2 Sensitivity Analysis – steam from biomass

Most impact arises from the processes in the background system and not much can be done to change it directly from the perspective of the plant. However, sensitivity analysis could be used to study how different choices affect the environmental performance of the system. In this sensitivity analysis the effects of changing steam production from natural gas to biomass was studied and the results are shown below in Table 4.2.

Table 4.2: Impact Assessment results for one tonne of dissolving pulp, steam from biomass compared to base case

Impact Category	Units	Base case (steam from natural gas)	Biomass scenario (steam from biomass)	% Change
Abiotic Depletion Potential, non -fossil resources	kg Sb eq.	0.0014	0.0014	0
Eutrophication Potential	kg Phosphate eq.	2.5	2.6	+4
Photochemical Oxidant Formation Potential	kg NMVOC eq.	2.6	2.7	+4
Total use of Renewable Primary Energy	MJ	8600	10,200	+20
Total use of Non-Renewable Primary energy	MJ	1300	1300	0
Acidification Potential	moles H^+ eq.	4.5	4.6	+2
Climate Change	kg CO_2 eq.	780	694	-9
Ozone Depletion Potential	kg CFC-11 eq.	1.4E-05	1.4E-05	0
Water Deprivation	m^3 world eq.	35	35	0

From the table above, it is observed that producing steam from biomass lowers climate impact by roughly 9%. However, it does cause other impact categories like eutrophication potential, photo chemical oxidant formation potential and acidification potential to increase slightly. One important aspect to mention is that - there are biogenic carbon dioxide emissions from burning biomass for steam. The emissions are however are not accounted for since the amount of carbon dioxide emissions are balanced with the uptake of carbon dioxide during the growth of the biomass via photosynthesis.

4.1.3 Sensitivity Analysis – recycling water

Another sensitivity analysis studied was performed to investigate how recycling of the process water would affect the environmental performance of the system. From the data gathered, close to 97 tons of water per tonne of pulp is used in the system. It was assumed that 60% of water used can be recycled in pulping plants without loss in quality (Alexandersson,2003).With this assumption, the water demand reduces to 41 tons per tonne dissolved pulp. The results are shown in Table 4.3 below.

Table 4.3: Impact Assessment results for one tonne of dissolving pulp, recycling water compared to the base case

Impact Category	Units	Base case (No recycling of water)	Recycling Scenario (Recycling 60% of water)	% Change
Abiotic Depletion Potential, non -fossil resources	kg Sb eq.	0.0014	0.0014	0
Eutrophication Potential	kg Phosphate eq.	2.55	2.53	-1
Photochemical Oxidant Formation	Kg NMVOC eq.	2.63	2.57	-2
Total use of Renewable Primary Energy	MJ	8600	8300	-3
Total use of Non-Renewable Primary energy	MJ	1300	1300	0
Acidification Potential	Moles H^+ eq.	4.5	4.3	-3
Climate Change	Kg CO_2 eq.	780	739	-5
Ozone Depletion Potential	Kg CFC-11 eq.	1.4E-05	1.4E-05	0
Water Deprivation	m^3 world eq.	35	17	-51

Recycling water within the plant shows some interesting results. Overall, it reduces the environmental performance in most indicators. The climate change impact is reduced by 5% from the base case whereas water deprivation is reduced by 51% which is the highest effect by far. This is logical as reducing water demand will significantly reduce its overall deprivation.

4.1.4 Sensitivity Analysis – steam from biomass and recycling of water

From the perspective of climate change impact using steam from biomass and recycling water are both good and hence implementing both these cases together should give the maximum possible reduction in climate change impact. The overall changes in impact categories and indicators for implementing both steps simultaneously are shown in Table 4. 4 below.

Table 4. 4: Impact Assessment results for one tonne of dissolving pulp, steam from biomass and recycling water compared to base case

Impact Category	Units	Base Case	Biomass and recycling 60% water scenario	% Change
Abiotic Depletion Potential, non -fossil resources	kg Sb eq.	0.0014	0.0014	0
Eutrophication Potential	kg Phosphate eq.	2.55	2.58	1.8
Photochemical Oxidant Formation Potential	kg NMVOC eq.	2.63	2.70	2.6
Total use of Renewable Primary Energy	MJ	8612	9961	15.6
Total use of Non-Renewable Primary energy	MJ	1295	1295	0
Acidification Potential	moles H^+ eq.	4.5	4.56	1.3
Climate Change	kg CO_2 eq.	780	650	-16.7
Ozone Depletion Potential	kg CFC-11 eq.	1.36E-05	1.36E-05	0
Water Deprivation	m^3 world eq.	35	17	-51

It can be observed that implementing both scenarios reduce climate change impact by approximately 17% although it does cause other impacts to increase slightly. The energy use increases, but it can be argued that is the share of renewables that increases. Water deprivation too improves due to recycling which is advantageous.

4.1.5 Sensitivity analysis – no burden on wheat straw

Given that wheat cultivation dominates the contribution to most impacts, it was decided to see how the environmental performance is affected if no environmental burden is allocated to the raw material. It can be argued that since wheat is the main product during wheat cultivation, all environmental burden must be allocated to it and none to its by-products. This is a common method of allocation followed in LCA practice, known as the cut-off allocation method. The results of this sensitivity analysis are shown in Table 4. 5 below and relevant contributions to each indicator in Figure 4.3.

Table 4. 5: Impact assessment results for one tonne of dissolving pulp with no environmental burden on wheat straw compared to base case

Impact Category	Units	Total Amount (Base Case)	Total Amount (No Burden on Wheat Straw)	% Change
Abiotic Depletion Potential, non -fossil resources	kg Sb eq.	0.0014	0.0003	-70
Eutrophication Potential	kg Phosphate eq.	2.55	0.87	-65
Photochemical Oxidant Formation	kg NMVOC eq.	2.63	2.2	-16
Total use of Renewable Primary Energy	MJ	8612	2650	-20
Total use of Non-Renewable Primary energy	MJ	1295	385	-70
Acidification Potential	moles H^+ eq.	4.5	2.50	-55
Climate Change	kg CO_2 eq.	780	679	-13
Ozone Depletion Potential	kg CFC-11 eq.	1.36E-05	3.3E-06	-70
Water Deprivation	m^3 world eq.	35	20	-43

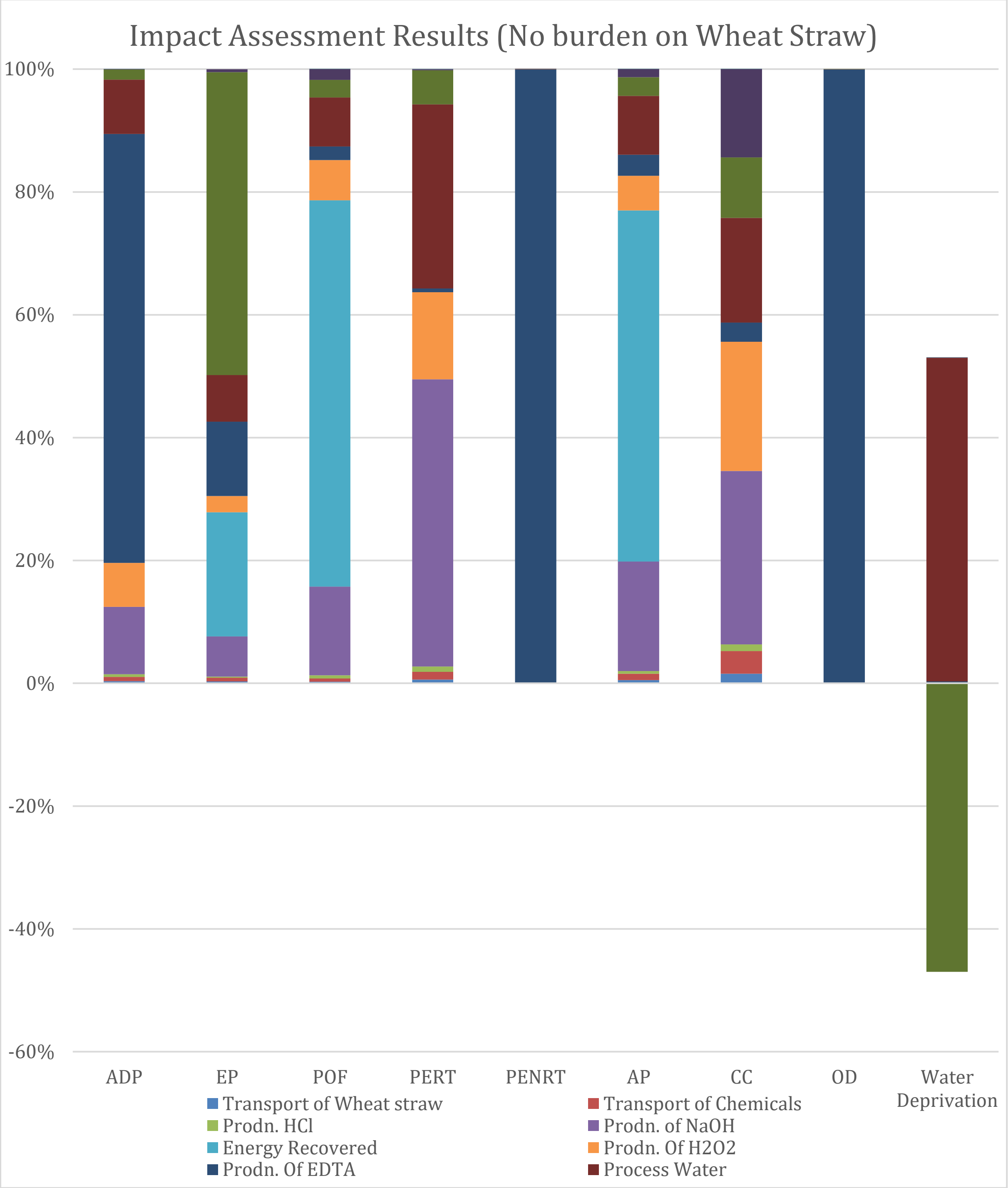

Figure 4.3: Contribution of different processes to the different impacts with no burden associated with wheat straw

From Table 4. 5, the exclusion of wheat straw burden drastically affects the environmental performance of the system and it further strengthens the need to include all relevant background processes involved in the system to get a precise understanding of the environmental impacts. It is also important since wheat cultivation has a huge impact on the system, uncertainty in data must be reduced. The data-set used was for the cultivation practices in Switzerland which were assumed to be the same as in Sweden. It would be wise to further look at local wheat cultivation data in Sweden and study how environmental performances are affected. It also highlights the importance of choice in allocation method. The Ecoinvent data-set allocates 95% of the burden to wheat and 5% to wheat straw. There could be higher economic value for wheat straw in the future which might call for an economic allocation procedure which can also affects the environmental impact studied.

Excluding wheat straw environmental burden sheds more light into the other processes. As can be seen in Figure 4.3 the production of sodium hydroxide and EDTA dominate the contribution to most indicators once again highlighting importance of considering where to source them from for the reasons mentioned in the section 4.1.4.

4.2 Comparison of dissolving pulp from wheat straw with wood

As mentioned earlier dissolving pulp is commonly made from wood and hence it would make sense to compare the environmental performances of producing pulp from wheat straw to that of wood. This section presents the results of the dissolving pulp from wood (based on data from Domsjö Farbiker AB). This will be the benchmark case and more information on the modelling of the benchmark can be found in Appendix B.

For the dissolving pulp from wood, the refinery produces other by-products such as ethanol and lignin. It was decided to allocate the environmental burden between dissolving pulp, ethanol, and lignin first by mass allocation and economic allocation methods, to get a range for which environmental impacts could vary. The results are shown in Table 4.6 below with results from the base case of producing dissolving pulp from wheat straw. All impacts values are for 1 tonne of dissolving pulp produced.

Table 4.6: Impact Assessment results for one tonne of dissolving pulp from wheat straw compared to the benchmark case. ADP – Abiotic Depletion Potential, non fossil resource. POF – Photochemical Oxidant Formation. EP – Eutrophication Potential. PERT – Primary energy renewable resources. PENRT – Primary Energy non renewable resources. AP – Acidification Potential. CC – Climate Change. ODP – Ozone Depletion Potential.

Impact Category	DP from wood (mass Allocation)	DP from wood (economic allocation)	DP from wheat straw (base case)
ADP, non -fossil resources (kg Sb eq.)	0.00033	0.00039	**0.0014**
EP (kg Phosphate eq.)	1.7	2.1	**2.55**
POF (kg NMVOC eq.)	3.7	3.9	**2.63**
PERT (MJ)	71480	83560	**8612**
PENRT (MJ)	10035	11731	**1295.5**
AP (Mole H^+ eq.)	5.2	6.1	**4.5**
CC (kg CO_2 eq.)	415	486	**780**
ODP (kg CFC-11 eq.)	1.6E-05	1.8E-05	**1.4E-05**
Water Deprivation (m^3 world equiv.)	1.3	1.5	**35**

The fields marked in red and green indicate if the base case performs better or worse when compared to the benchmark results. From the table above, pulp made from wheat straw has a better performance in total use of renewable and non-renewable energy, photochemical oxidation formation, acidification potential and ozone depletion. Whereas its climate change impact, water deprivation and abiotic depletion impacts are much larger than the base case. The eutrophication potential is only slightly higher in the base case when compared to the benchmark.

Figure 4. 4 below shows the contribution of the different processes in the benchmark case to the different indicators. The results are irrespective of the allocation procedure used since the relative contributions are shown. The contributions to the benchmark indicators mainly arise from plant related operations, forestry operations and production of chemicals.

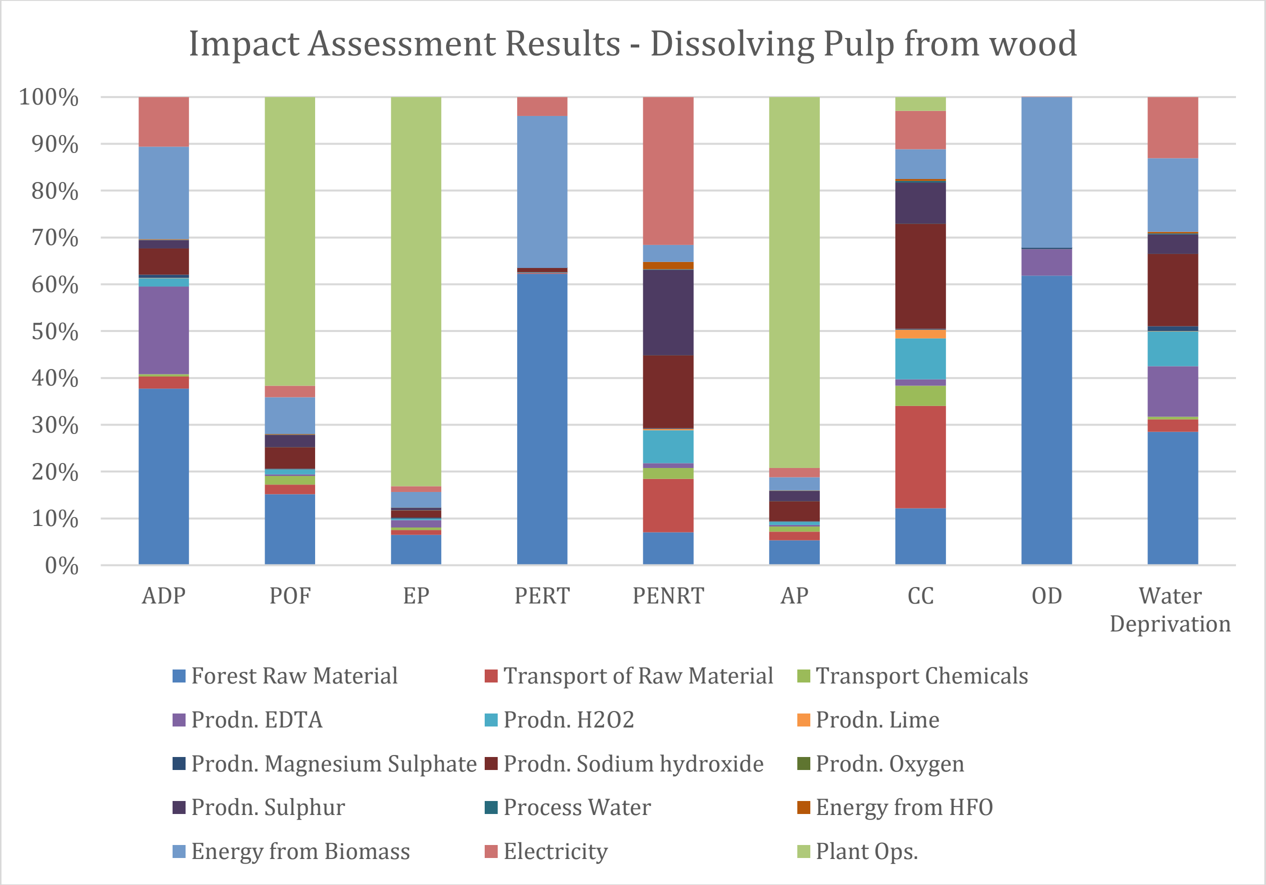

Figure 4. 4: Contribution of different processes to the impacts for the benchmark

The reason as to why wheat straw-based pulp performs better than the benchmark in POF and AP is that most of the impact in the benchmark arises from emissions in the plant which are higher when compared to emissions in the recovery boiler for wheat straw-based pulp. The benchmark operations have significantly higher emissions of nitrogen oxide and sulphur oxide gases as can be seen when comparing Table 3.3 with Table B. 4 .

A reason for this could also be because in the benchmark case, sulphurous acid is a main compound that is used for the cooking of wood chips and hence higher emissions of sulphur can be rightly expected, explaining the higher results. The data for emissions for the recovery boiler in the wheat straw case were estimated from literature, whereas for the benchmark local data has been used. The uncertainty in data could affect the results of these indicators.

The share of non-renewable energy is higher for the benchmark as the use of electricity is high and is the largest contributor to the indicator in the benchmark. Along with electricity consumption, the chemicals produced too contribute to PENRT in the benchmark case. The use of sodium hydroxide and hydrogen peroxide is much higher in the benchmark case than compared to the wheat straw case. The wheat straw-based pulp uses lesser chemicals as they are extremely diluted as per data from simulation results. The electricity use in wheat straw-based pulp has been estimated form literature as well and uncertainty could affect the results as well.
Looking into renewable energy use, both benchmark and the wheat straw case have major shares of contribution in raw material cultivation operations, but the energy use in forestry is higher than that for wheat cultivation.

Similar trends in OD can be observed in the benchmark and wheat straw-based case. Highest share comes from the cultivation of raw materials. The reason for this is due to the influence of halogenated compounds. However, when examining the datasets used, there is no direct use of halogenated compounds in the processes modelled. This could mean that there are traces of halogenated compounds used further upstream in the processes studied.

EP is higher in the wheat straw case as most emissions arise from cultivation of wheat as compared to emissions from the plant in the benchmark case.
As discussed earlier, wheat cultivation uses fertilizers and other compounds that directly affect eutrophication potential.

Water Deprivation is significantly lower in the benchmark case as there is a huge difference in the total water demand comparing both systems. A well-established plant in operation would have significant measures in place to efficiently use and re-circulate water within its operations. The data used for the wheat straw-based pulp case has estimated values of water and actual operations could use lesser amounts of water.

Evaluating from a climate change impact perspective the benchmark performs much better. However, these are also results based on allocation and hence it will always have a lower value than the wheat straw-based pulp. It is interesting to note that the unallocated results of the benchmark case have a climate change impact value of 645 kg CO_2 which is very close to the sensitivity analysis results for the wheat straw case in implementing recycling of water and using steam from biomass (see Table 4. 4). Another reason is also that wheat cultivation impacts are higher than wood and so the climate change impact is higher for wheat-based pulp.

5 CONCLUSION

This thesis set out to study the potential environmental impacts of producing dissolving pulp from wheat straw as raw material, using life cycle assessment.
Three research questions were defined in the goal and scope step of the assessment and the results from assessment conclude that: –

- The cultivation of wheat has the highest impact across most indicators due to the use of chemicals and fertilizers during cultivation. The production of chemicals also has significant contributions to the environmental impacts.
- In the foreground system, emissions from energy recovery and the high use of process water contribute to the different indicators studied.
- From a climate change impact perspective, the highest impacts arise from production of sodium hydroxide and hydrogen peroxide. The importance of why and where to source these chemicals from were also highlighted.
- Sensitivity analysis were conducted to see how impacts would change to varying the source of energy and recycling water used within the system. The results show that using biomass and recycling of water reduces climate change impact by 17% from the base case and water deprivation by 50%. However, other indicators perform slightly worse.
- When comparing with the benchmark case of wood-based pulp, pulp from wheat straw uses significantly lesser energy and has lesser eutrophication and acidification impacts. However, from a climate change perspective wheat straw pulp has a higher climate change impact. Same is the case for water deprivation as well.

There were a lot of significant assumptions that could affect the results and conclusions presented such as estimating emission and energy data from literature. The uncertainties for these have not been accounted for in this study and should be included in further research. The importance of wheat cultivation implies that primary data from cultivation activities in Sweden should give better insight into the impacts of producing dissolving pulp from wheat straw in Sweden. The benchmark case has production of by-products which too can be produced from wheat straw as raw material. Future research could also investigate simulation data for these and conducting LCA. The influence of background systems implies that future potential scenarios of how chemicals such as sodium hydroxide and hydrogen peroxide will be produced would help understand environmental impacts better.

The data used for the LCA study were those of simulation results. In an actual industrial scale production, one would have accurate and better data which would give better results with less uncertainty. The high-water demand and dilution of chemicals would be much different in an actual plant thereby affecting the results of the LCA study. The energy recovered from black liquor should be able to meet steam demand and some electricity demand as seen in literature (González-García et al., 2011). The energy calculations for black liquor done in this study does not do so and this is a limitation that can affect environmental impacts. Moreover, the electricity used in a plant would be much larger than what was assumed thereby affecting results. It is also interesting to note that no by products were considered or modelled in this study. Most industries have by-products produced that are sold or used elsewhere. The environmental performance would also be affected in that case as the notorious issue of allocation would then have to be considered. The soda cooking method is only one process route that is studied. Further research should consider which process route is the best comparing kraft process and sulphite process. There is also research on other cooking methods that use organic solvents and other alkaline compounds for pulping (Jahan et al., 2021). These could also be studied further in terms of their environmental impacts and performance. The process simulation is only at a preliminary stage and further optimization and improvements need to be studied which can also change the results presented here. One main issue in this system was the high use of water, which needs to be optimized. The recovery boiler too is a critical step in the entire process which needs further optimization. Operational issues such as build up of silica and its handling must be studied further.

The results presented only tell where and how much environmental impacts are caused. Decisions on whether to produce dissolving pulp from wheat straw will depend of other economic factors and value judgements of different stakeholders involved. The need however is clear that if indeed a bioeconomy transition as forecasted occurs, then wood and forestry alone cannot meet these demands and hence other alternatives should be studied and further research still needs to be carried out.

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Appendix A: Description of Impact Categories

1. Abiotic Depletion Potential, non-fossil resources

According to Van Oers et al. (2020) the abiotic depletion potential of resource is the ratio of annual production to the square of ultimate reserves, divided by the same for a reference element, which in most cases is antimony.

2. Eutrophication Potential

Eutrophication potential gives insight into how much nutrients released into the ecosystem can change its biological productivity. Most aquatic systems lack nutrients such as nitrogen and phosphorous. The release of these nutrients can cause micro-organisms to consume oxygen and lower levels of oxygen lead to loss of other species. Emissions of nitrogen oxides and phosphates contribute to this impact category mainly It is expressed usually in kg phosphate equivalent (Baumann & Tillman, 2004).

3. Acidification Potential

Acidification Potential shows what is the maximum possible acidification a substance can cause. It is measured as the ability of a substance to form H+ ions. Pollutants like sulphur dioxide, nitrogen oxides and ammonia have very high acidification potentials. These pollutants in the atmosphere can turn acidic and in turn affect soil and other water bodies when deposited by acid rain or fog for instance (Baumann & Tillman, 2004).

4. Total use of renewable primary energy resources

This indicator tells how much renewable energy is used within a system. The use of total primary energy resources according to the European standards EN15804 is a sum of renewable primary energy as carrier and renewable primary energy resources as material utilization (EPD International, n.d.).

5. Total use of non – renewable primary energy resources

This indicator tells how much non-renewable energy is used within a system. The use of total primary energy resources according to the European standards EN15804 is a sum of non-renewable primary energy as carrier and non-renewable primary energy resources as material utilization (EPD International, n.d.).

6. Photochemical Oxidant Formation

Pollutants like nitrogen oxides and hydrocarbons in the presence of sunlight form secondary pollutants known as photo oxidants. These cause the formation of photochemical smog also knows as summer smog that can cause damage to human health and vegetation. Ozone is an important photo oxidant and the photochemical oxidant formation calculates how much ozone can be produced photo chemically by a substance (Baumann & Tillman, 2004).

7. Climate Change, total

This impact category studies the global warming potential of greenhouse gases. All green house gases have the ability to absorb infrared radiation and heat the atmosphere, known as radiative forcing. The global warming potential (GWP) of a substance is defined as the ratio of increase in infrared radiation by a substance to the increased infrared radiation of 1 kg of carbon dioxide. GWP is expressed in kg CO2 eq. Apart from CO2 Gases such as methane, nitrogen oxides and Chlorofluorocarbons also contribute to global warming. The GWP can be calculated across different time horizons as different green house gases have varied life times in the atmosphere. The most common time span measured is GWP -100 years, which was also the basis for this study (Baumann & Tillman, 2004).

8. Ozone Depletion

Ozone Depletion potential is the change in stratospheric ozone in the steady-state due to emissions relative to that of CFC-11. The ozone layer is important as it prevents harmful ultraviolet radiation from the sun to enter the earth's atmosphere. The presence of halogenated compounds due to emissions slowly start depleting the ozone layer, causing damage to human life and other animal species (Baumann & Tillman, 2004).

9. Water Deprivation, Available Water Remaining (AWARE) method

The water deprivation calculated by the AWARE method tells how much water is deprived in a region or ecosystem. It is calculated as the inverse of the difference between available water per area and the demand of water per area. The characterisation factor obtained can range from 0.1 -100. An important note in the results from GaBi software is that un regionalized flows have a world average characterization factor of 43, which is unrepresentative of Sweden. All such flows were multiplied with a Swedish Characterisation factor of 1.694 as per data provided by WULCA (2021).

Appendix B: Life Cycle Analysis of Benchmark – Dissolving Pulp from wood

This section describes the LCA conducted for the benchmark. All data necessary were compiled from the environmental reports published by Domsjö Fabriker AB for the years 2019, 2020 and 202 representative of a general pulping plant in Sweden (Fabriker, 2019, 2020, 2021). From the reports it was difficult to assess the electricity used in each of the years and data from (Klugman et al., 2019) was assumed to be the same throughout all the years.
The functional unit was 1 tonne of dissolving pulp produced and the impact results can be easily compared to that of the pulp produced by wheat straw.

Domsjö Fabriker Operations
Domsjö Fabriker is a bio refinery located in Örnsköldsvik, Sweden which can produce up to 255,000 tons of pulp. The refinery also produces by-products ethanol and lignin. Most of the cellulose is used for textile fibre production while lignin is exported. Ethanol is sold to SEKAB and is used in biofuels or to produce other chemicals. Raw material used in the refinery is spruce and pine wood. The process used to produce dissolving pulp is the sodium-based sulphite process where it is carried out in two stages to have minimum lignin in the pulp. The cooked pulp is then bleached in a two-stage bleaching process to produce dissolving pulp of 91% - 92% cellulose which is further dried and sent for storage. Meanwhile the black liquor produced from the cooking process and bleaching steps are ctollected evaporated and sent for production of ethanol. The collected process liquid also is used in two recovery boilers that produce high pressure steam which is used for meeting some of the electricity demand. The effluents from the boiler are sent for chemical recovery, thereby recycling sodium and sulphur. Part of the stream that is sent for ethanol production is diverted for lignin production as well where it is stored mostly as dry powder (Fabriker, 2021)

Assumptions

Assumptions made for modelling the system for the benchmark is given below –

- No background processes existed for production of Sulphur Dioxide as raw material. The amount of Sulphur needed was calculated by stoichiometry and was added to total sulphur needed.
- The density of softwood was taken as 420 kg/m^3 fub (100% dry content)
- Energy content for Heavy Fuel Oil was assumed to 40.4 MJ/kg and that of biomass 16 MJ/kg.
- Transport distance for raw material was considered to be 1000 kms by truck
- Transport distance for chemicals was assumed to be 15000 kms by truck and 200km by ship.

GaBi Process Settings

The settings for the different flows and processes used are presented below.

Table B. 1: Process settings in GaBi for benchmark

Inflow	Process setting
Soft wood	Soft wood forestry, pine, sustainable forest management (ecoinvent 3.8)
EDTA	RER: EDTA production (ecoinvent 3.7.1)
Calcium oxide	DE: Lime (CaO, finelime) (thinkstep)
Oxygen	EU-28: Oxygen gaseous (thinkstep)
Hydrogen peroxide	DE: Hydrogen peroxide (100%), steam cracking (thinkstep)
Electricity	SE: Electricity grid mix 1kV-60kV (thinkstep)
Heavy fuel oil	EU-28: Heavy fuel oil at refinery (1 %wt S) (thinkstep)
Magneasium sulphate	RER: Magnesium Sulphate production (ecoinvent 3.7)
Sulphur	EU-28: Sulphur (elemental) at refinery (thinkstep)
Sodium hydroxide	EU-28: Sodium hydroxide (100%) (thinkstep)
Process water	SE: Tap water from ground water (thinkstep)

Table B. 2: Process Settings in GaBi for raw material transport for benchmark

Process setting	6% RME
Vehicle type	Truck Euro 6 , 34-40t gross weight. 27t payload
Load factor	0.85
Distance	1000 kms

Table B. 3: Process Settings in GaBi for transport of chemicals for benchmark

Process setting	6% RME
Mode of transport – truck	Truck Euro 6 , 34-40t gross weight. 27t payload
Load factor	0.85
Distance	1000 kms
Mode of transport - ship	Ro-ro-ship, 1200-10000 dry weight ton pay load capacity
Distance	200 kms

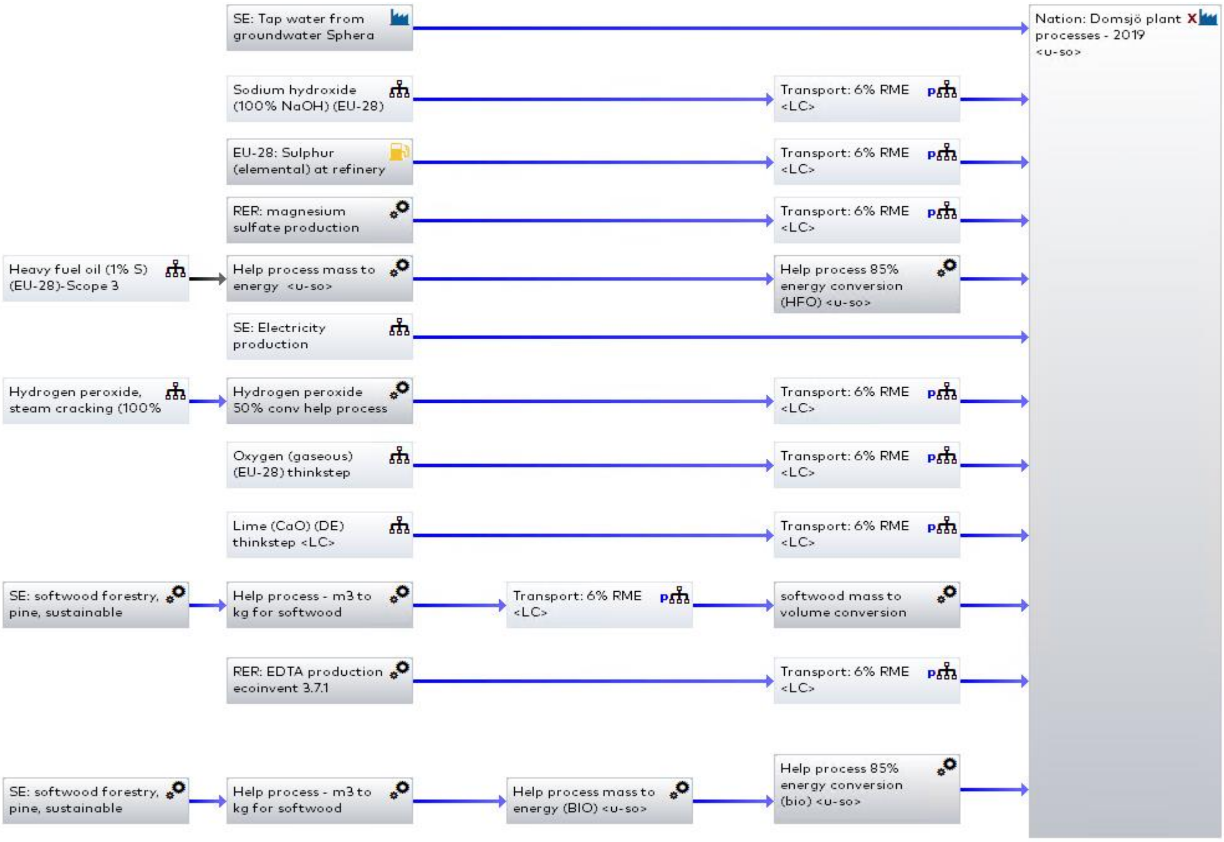

Figure B.1: LCA model for the benchmark in GaBi for the year 2019

Life Cycle Inventory Data

The inventory data needed for the years 2019,2020 and 2021 are presented below.

Table B. 4: Life Cycle Inventory data for benchmark case

Domsjö Fabriker AB				
Year	2019	2020	2021	
Input				
Material	**Amount**			**Units**
Pulp wood Conifer	6.7	6.7	7.3	m^3/ tonne DP
Lime	8.9	11.2	10.1	kg/ tonne DP
Complexing Agent	1.7	2.1	2.2	kg/ tonne DP
Magnesium Sulphate	6.6	5.7	5.7	kg/ tonne DP
Sodium hydroxide	163	162	179	kg/ tonne DP
Oxygen	2.87	2.67	2.91	kg/ tonne DP
Hydrogen Peroxide	71	70	67	kg/ tonne DP
Sulphur	33	32	35	kg/ tonne DP
Sulphur Di oxide	98	95	114	kg/ tonne DP
Water	28.4	26	25.2	m^3/ tonne DP
Steam from biomass	19330	20611	21621	MJ/ tonne DP
Steam from fuels	181	147	232	MJ/ tonne DP
Electricity	4325	4325	4325	MJ/ tonne DP
Output				
Dissolving pulp	1	1	1	tonne DP
Bark	524	512	496	kg/ tonne DP
Ethanol	91	83	68	kg/ tonne DP
Lignin	459	416	534	kg/ tonne DP
Biogas	6	5.9	10.6	kg/ tonne DP
Bio resin	22	16	12	kg/ tonne DP
Carbon di oxide	6.7	16.7	8.4	kg/ tonne DP
Emissions to air				
Nitrous oxides	2.5	3.1	3.4	kg/ tonne DP
Sulphur Di oxide	3.7	3.1	2.7	kg/ tonne DP
Particulate Matter	0.89	0.93	1.01	kg/ tonne DP
Carbon di oxide (biogenic)	2780	2927	2623	kg/ tonne DP
Carbon dioxide fossil	18.1	15.4	23.1	kg/ tonne DP
Emissions to water				
Chemical Oxygen Demand	78	75	81.2	kg/ tonne DP
Phosphorous	0.08	0.11	0.12	kg/ tonne DP
Nitrogen	0.66	0.75	0.73	kg/ tonne DP
Waste				
Non-hazardous waste	62.3	60.2	53.5	kg/ tonne DP
Hazardous waste	0.55	1.38	1.79	kg/ tonne DP

Life Cycle Impact Assessment – Results

The same set of indicators in Table 3.1 were also used to in the benchmark LCA. The average results of all years (unallocated) were considered and is shown in Table B. 5 below. The interpretation of these results can be referred to in section 4.2

Table B. 5: Average results of environmental indicators studied for benchmark case (unallocated).

ADP – Abiotic Depletion Potential, non fossil resource. POF – Photochemical Oxidant Formationl. EP – Eutrophication Potential. PERT – Primary energy renewable resources. PENRT – Primary Energy non renewable resources. AP – Acidification Potential. CC – Climate Change. OD – Ozone Depletion.

Activity	Indicators Average Values								
	ADP (kg Sb eq.)	POF (kg NMVOC eq.)	EP (kg Phosphate eq.)	PERT (MJ)	PENRT (MJ)	AP (Mole of H+ eq.)	CC (kg CO2 eq.)	OD (kg CFC-11 eq.)	Water Deprivation (m^3 world eq.)
Forest Raw Material	1,96E-04	8,01E-01	1,77E-01	6,90E+04	1,09E+03	4,29E-01	7,84E+01	1,53E-05	5,88E-01
Transport of Raw Material	1,34E-05	1,08E-01	2,88E-02	1,86E+02	1,78E+03	1,49E-01	1,41E+02	2,26E-14	5,53E-02
Transport Chemicals	2,48E-06	9,72E-02	1,49E-02	3,31E+01	3,56E+02	8,36E-02	2,79E+01	1,92E-13	1,09E-02
Prodn. EDTA	9,72E-05	1,97E-02	4,39E-02	6,45E+00	1,60E+02	3,15E-02	8,57E+00	1,39E-06	2,23E-01
Prodn. H2O2	9,46E-06	5,55E-02	8,84E-03	1,37E+02	1,10E+03	5,22E-02	5,66E+01	2,90E-10	1,55E-01
Prodn. Lime	3,30E-07	2,93E-03	4,42E-04	6,05E+00	3,56E+01	2,66E-03	1,21E+01	1,27E-11	6,67E-04
Prodn. Magnesium Sulphate	3,38E-06	3,85E-03	4,50E-03	4,23E+00	3,06E+01	7,98E-03	1,34E+00	7,01E-08	2,21E-02
Prodn. Sodium hydroxide	2,92E-05	2,42E-01	4,30E-02	9,36E+02	2,42E+03	3,39E-01	1,44E+02	1,36E-09	3,18E-01
Prodn. Oxygen	7,55E-08	3,46E-04	5,98E-05	2,62E+00	4,71E+00	5,70E-04	2,62E-01	3,80E-12	4,70E-04
Prodn. Sulphur	9,13E-06	1,38E-01	1,31E-02	3,53E+01	2,83E+03	1,78E-01	5,69E+01	4,83E-11	8,60E-02
Process Water	2,30E-07	2,84E-03	2,57E-03	5,37E+00	2,94E+01	3,32E-03	2,08E+00	7,00E-12	4,22E-03
Energy from HFO	7,28E-07	7,93E-03	7,19E-04	9,42E-01	2,40E+02	8,83E-03	2,66E+00	1,14E-12	7,08E-03
Energy from Biomass	1,02E-04	4,17E-01	9,24E-02	3,60E+04	5,69E+02	2,23E-01	4,08E+01	7,96E-06	3,24E-01
Electricity	5,51E-05	1,29E-01	3,20E-02	4,47E+03	4,91E+03	1,61E-01	5,32E+01	5,68E-10	2,70E-01
Plant Ops.	0,00E+00	3,26E+00	2,28E+00	0,00E+00	0,00E+00	6,37E+00	1,89E+01	0,00E+00	0,00E+00
Total	5,19E-04	5,28E+00	2,75E+00	1,11E+05	1,56E+04	8,04E+00	6,45E+02	2,47E-05	2,06E+00

Allocation procedure

The results presented above are for all the products produced within the refinery. Since we're only interested in the environmental burden of dissolving pulp, there needs to be a partitioning of burdens between the different products. The main products were assumed to be dissolving pulp, ethanol, and lignin. The environmental burdens were then allocated based on mass and economic value. The price data as per González-García et al., (2011) were used for economic allocation. The allocation for each year was done and the average values were taken as allocation keys. The results for the total impact for each category can be referred to in Table 4.6 in section 4.2

Table B.6: Prices for products from Domsjö Fabriker, adapted from (González-García et al., 2011)

Product	Price ($/tonne)
Dissolving pulp	700
Lignin	400
Ethanol	500

$$Mass\ allocation\ factor = \frac{mass\ of\ product}{\Sigma\, mass\ of\ all\ products} \qquad (2)$$

$$Economic\ Allocation\ factor = \frac{price\ of\ product * mass\ of\ product}{\Sigma\, price * mass\ for\ all\ products} \qquad (3)$$

Table B. 7: Mass and economic allocation factors for dissolving pulp, lignin, and ethanol

Product	Mass allocation Factor	Economic allocation Factor
Dissolving pulp	0.64	0.75
Lignin	0.3	0.2
Ethanol	0.05	0.04

Appendix C: Life Cycle Inventory Assessment of dissolving pulp from wheat straw

Table C. 1: Life cycle inventory data for dissolving pulp from wheat straw

Process - Acid Prehydrolysis				
Inputs				
Material	Amount	Units	Amount Normalised	Units
Wheat straw (89% dry)	112908.60	tons/yr	2.48	ton/f.u
Hydrochloric Acid (0.125%)	1200301.20	tons/yr	26.34	ton/f.u
Energy			6.09	MJ/f.u
Outputs				
Material	Amount	Units	Amount Normalised	Units
Treated Wheat straw	501915.12	tons/yr	11.01	ton/f.u
Waste stream	811293.84	tons/yr	17.80	ton/f.u
Process - Soda Cooking				
Inputs				
Material	Amount	Units	Amount Normalised	Units
Treated Wheat Straw	501915.12	tons/yr	11.01	ton/f.u
Sodium Hydroxide (7.4%)	457770.6	tons/yr	10.04	ton/f.u
Energy			3.76	MJ/f.u
Outputs				
Material	Amount	Units	Amount Normalised	Units
Cooked pulp	350624.4	tons/yr	7.69	ton/f.u
Black Liquor	609060.48	tons/yr	13.36	ton/f.u
Process - Washing 1				
Inputs				
Material	Amount	Units	Amount Normalised	Units
Cooked Pulp	350624.4	tons/yr	7.69	ton/f.u
Process Water	445200	tons/yr	9.76	ton/f.u
Outputs				
Material	Amount	Units	Amount Normalised	Units
Washed Pulp	304629.36	tons/yr	6.68	ton/f.u
Waste stream	491195.04	tons/yr	10.77	ton/f.u
Process - Hydrogen Peroxide Bleaching with EDTA				
Inputs				
Material	Amount	Units	Amount Normalised	Units
Washed Pulp	304629.36	tons/yr	6.68	ton/f.u
Hydrogen Peroxide (0.62%)	351190.56	tons/yr	7.70	ton/f.u
Hydrogen Peroxide (0.37%)	436535.4	tons/yr	9.57	ton/f.u
EDTA	701505	tons/yr	15.39	ton/f.u
Electricity for all pumps			0.01	MJ/f.u
Energy			0.19	MJ/f.u
Outputs				
Material	Amount	Units	Amount Normalised	Units
Bleached Pulp	917540.4	tons/yr	20.13	ton/f.u
Waste stream	878178	tons/yr	19.27	ton/f.u
Process - Washing 2				
Inputs				
Material	Amount	Units	Amount Normalised	Units
Bleached Pulp	917540.4	tons/yr	20.13	ton/f.u
Process Water	1310400	tons/yr	28.75	ton/f.u
Outputs				
Material	Amount	Units	Amount Normalised	Units
Washed pulp to drying	291043.2	tons/yr	6.38	ton/f.u
Waste stream	1936897.2	tons/yr	42.50	ton/f.u
Process - Drying				
Inputs				
Material	Amount	Units	Amount Normalised	Units
Washed pulp to drying	291043.2	tons/yr	6.38	ton/f.u
Energy			5487.50	MJ/f.u
Outputs				
Material	Amount	Units	Amount Normalised	Units
Dissolving Pulp (93% dry)	45568.32	tons/yr	1	ton/f.u

Waste Water	205987.32	tons/yr	4.52	ton/f.u
Vapour	38652.6	tons/yr	0.84	ton/f.u

Appendix D: Process settings for dissolving pulp to wheat straw in GaBi

Table D. 1: Process settings in GaBi for the different flows, dissolving pulp from wheat straw

Inflow	Process setting
Wheat straw	CH: wheat production, Swiss integrated production, extensive (ecoinvent 3.8)
EDTA	RER: EDTA production (ecoinvent 3.7.1)
Hydrochloric acid	DE: Hydrochloric acid mix (100%) (thinkstep)
Hydrogen peroxide	DE: Hydrogen peroxide (100%), steam cracking (thinkstep)
Electricity	SE: Electricity grid mix 1kV-60kV (thinkstep)
Process steam	SE: Process steam from natural gas 90% (thinkstep)
Sodium hydroxide	EU-28: Sodium hydroxide (caustic soda) mix (100%) (thinkstep)
Process water	EU-28: Process Water from surface water (thinkstep)
Wastewater treatment plant	EU-28: Municipal waste water treatment (sludge treatment mix)
Process steam (sensitivity analysis)	SE: Process steam from biomass (solid) 90% Sphera

Table D. 2: Process settings for transport of wheat straw in GaBi

Process setting	Diesel MK1 (Red-diesel 2022: 36.3% bio fuel (6% RME and 30.3% HVO))
Vehicle Type	Truck Euro 6 , 34-40t gross weight. 27t payload
Load Factor	0.85
Distance	120 kms

Table D. 3: Process setting for transport of chemicals in GaBi

Process setting	6% RME
Mode of transport – truck	Truck Euro 6 , 34-40t gross weight. 27t payload
Load factor	0.85
Distance	1500 kms
Distance	200 kms

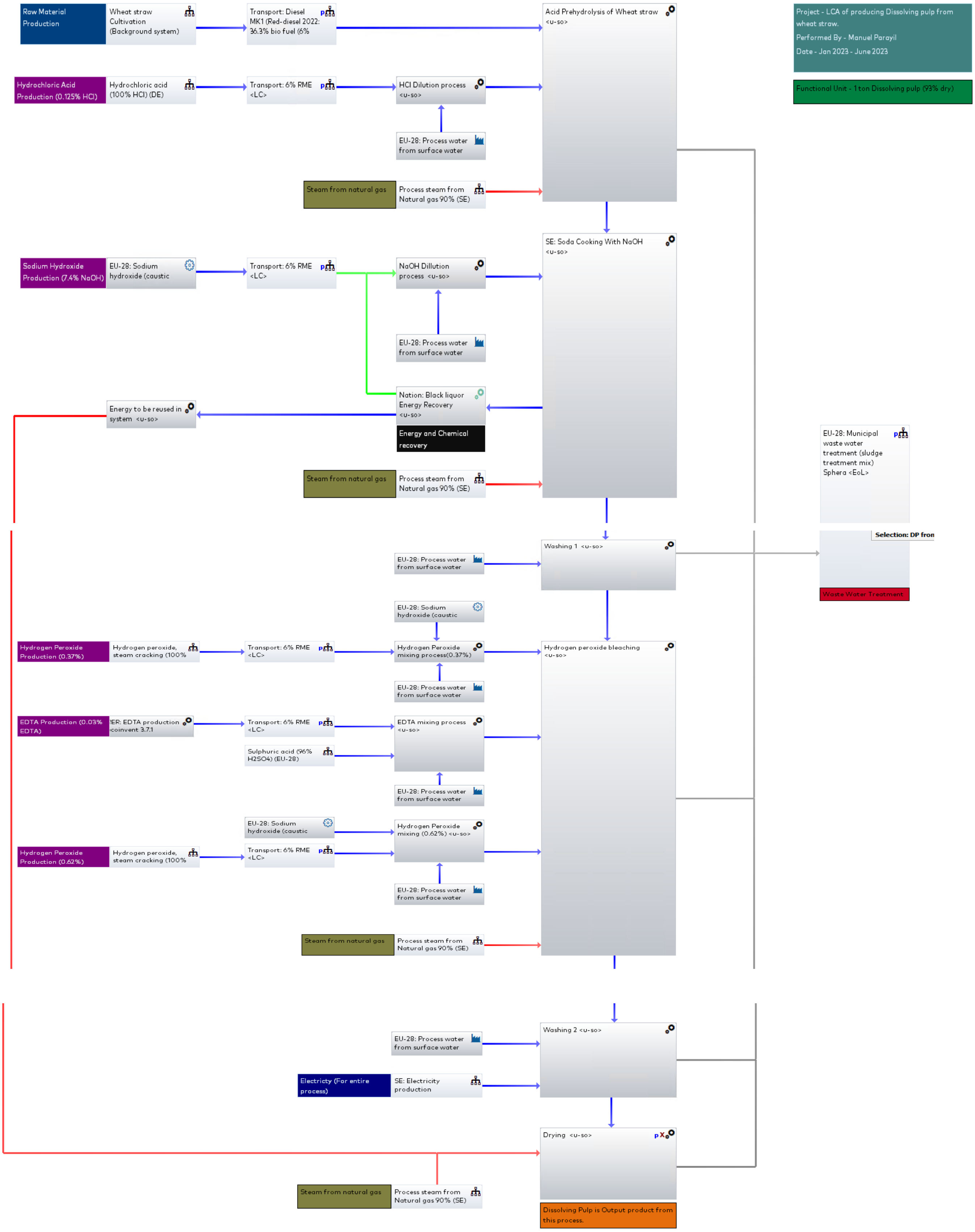

Figure D.1: LCA model for dissolving pulp from wheat straw in GaBi

Appendix E: Additional LCA results of dissolving pulp from wheat straw

Table E. 1: Impact assessment results of individual processes in dissolving pulp from wheat straw (base case)

Activity	**Impact Categories**								
	ADP	**EP**	**POF**	**PERT**	**PENRT**	**AP**	**CC**	**OD**	**Water deprivation**
Wheat Straw Cultivation	1,13E-03	1,68E+00	4,28E-01	5,96E+03	9,11E+02	1,93E+00	1,04E+02	1,03E-05	1,46E+01
Wheat Straw Transport	1,08E-06	2,67E-03	5,39E-03	1,63E+01	1,73E-02	1,32E-02	1,05E+01	1,94E-15	1,27E-03
Transport Chemicals	2,38E-06	5,14E-03	1,20E-02	3,33E+01	3,35E-02	2,65E-02	2,51E+01	4,03E-15	9,91E-04
HCl Production	1,48E-06	1,67E-03	1,08E-02	2,25E+01	5,41E-03	1,01E-02	7,43E+00	4,77E-11	-2,03E-02
NaOH Production	3,66E-05	5,72E-02	3,20E-01	1,24E+03	1,78E-01	4,52E-01	1,92E+02	1,80E-09	3,52E-01
Energy,Recovery Boiler	0,00E+00	1,77E-01	1,39E+00	0,00E+00	0,00E+00	1,45E+00	0,00E+00	0,00E+00	0,00E+00
H2O2 Production	2,39E-05	2,34E-02	1,45E-01	3,76E+02	8,46E-02	1,43E-01	1,43E+02	7,67E-10	6,07E-02
EDTA Production	2,33E-04	1,06E-01	4,88E-02	1,63E+01	3,84E+02	8,59E-02	2,10E+01	3,34E-06	5,42E-01
Process Water	2,95E-05	6,65E-02	1,77E-01	7,95E+02	1,45E-01	2,43E-01	1,16E+02	1,38E-09	1,80E+02
Waste Water Treatment Plant	5,56E-06	4,32E-01	6,29E-02	1,48E+02	2,66E-02	7,70E-02	6,68E+01	2,80E-10	-1,60E+02
Natural Gas Steam Prodn	2,21E-07	4,46E-03	3,89E-02	4,61E+00	2,22E-04	3,39E-02	9,78E+01	3,62E-13	7,06E-03
Electricity	1,62E-10	1,18E-07	4,57E-07	1,65E-02	6,57E-07	5,96E-07	1,97E-04	2,10E-15	8,68E-04

Table E. 2: Impact assessment results for individual processes when considering steam from biomass

Activity	Impact Categories								
	ADP	EP	POF	PERT	PENRT	AP	CC	OD	Water deprivation
Wheat Straw Cultivation	1,13E-03	1,68E+00	4,28E-01	5,96E+03	9,11E+02	1,93E+00	1,04E+02	1,03E-05	1,46E+01
Wheat Straw Transport	1,08E-06	2,67E-03	5,39E-03	1,63E+01	1,73E-02	1,32E-02	1,05E+01	1,94E-15	1,27E-03
Transport Chemicals	2,38E-06	5,14E-03	1,20E-02	3,33E+01	3,35E-02	2,65E-02	2,51E+01	4,03E-15	9,91E-04
HCl Production	1,48E-06	1,67E-03	1,08E-02	2,25E+01	5,41E-03	1,01E-02	7,43E+00	4,77E-11	-2,03E-02
NaOH Production	3,66E-05	5,72E-02	3,20E-01	1,24E+03	1,78E-01	4,52E-01	1,92E+02	1,80E-09	3,52E-01
Energy, Recovery Boiler	0,00E+00	1,77E-01	1,39E+00	0,00E+00	0,00E+00	1,45E+00	0,00E+00	0,00E+00	0,00E+00
H2O2 Production	2,39E-05	2,34E-02	1,45E-01	3,76E+02	8,46E-02	1,43E-01	1,43E+02	7,67E-10	6,07E-02
EDTA Production	2,33E-04	1,06E-01	4,88E-02	1,63E+01	3,84E+02	8,59E-02	2,10E+01	3,34E-06	5,42E-01
Process Water	2,95E-05	6,65E-02	1,77E-01	7,95E+02	1,45E-01	2,43E-01	1,16E+02	1,38E-09	1,80E+02
Waste Water Treatment Plant	5,56E-06	4,32E-01	6,29E-02	1,48E+02	2,66E-02	7,70E-02	6,68E+01	2,80E-10	-1,60E+02
Electricity	1,62E-10	1,18E-07	4,57E-07	1,65E-02	6,57E-07	5,96E-07	1,97E-04	2,10E-15	9,76E-07
Steam biomass	1,11E-05	5,71E-02	1,66E-01	1,66E+03	3,63E-01	2,19E-01	8,43E+00	5,11E-14	1,92E-02

Table E. 3: Impact assessment result for all processes when considering no environmental burden on wheat straw

Activity	Impact Categories								
	ADP	EP	POF	PERT	PENRT	AP	CC	OD	Water Deprivation
Transport of Wheat straw	1,08E-06	2,67E-03	5,39E-03	1,63E+01	1,73E-02	1,32E-02	1,05E+01	1,94E-15	1,27E-03
Transport of Chemicals	2,38E-06	5,14E-03	1,20E-02	3,33E+01	3,35E-02	2,65E-02	2,51E+01	4,03E-15	9,91E-04
Prodn. HCl	1,48E-06	1,67E-03	1,08E-02	2,25E+01	5,41E-03	1,01E-02	7,43E+00	4,77E-11	-2,03E-02
Prodn. of NaOH	3,66E-05	5,72E-02	3,20E-01	1,24E+03	1,78E-01	4,52E-01	1,92E+02	1,80E-09	3,52E-01
Energy Recovered	0,00E+00	1,77E-01	1,39E+00	0,00E+00	0,00E+00	1,45E+00	0,00E+00	0,00E+00	0,00E+00
Prodn. Of H2O2	2,39E-05	2,34E-02	1,45E-01	3,76E+02	8,46E-02	1,43E-01	1,43E+02	7,67E-10	6,07E-02
Prodn. Of EDTA	2,33E-04	1,06E-01	4,88E-02	1,63E+01	3,84E+02	8,59E-02	2,10E+01	3,34E-06	5,42E-01
Process Water	2,95E-05	6,65E-02	1,77E-01	7,95E+02	1,45E-01	2,43E-01	1,16E+02	1,38E-09	1,80E+02
Waste Water treatment Plant	5,56E-06	4,32E-01	6,29E-02	1,48E+02	2,66E-02	7,70E-02	6,68E+01	2,80E-10	-1,60E+02
Steam Natural Gas	2,21E-07	4,46E-03	3,89E-02	4,61E+00	2,22E-04	3,39E-02	9,78E+01	3,62E-13	7,06E-03
Electricity	1,62E-10	1,18E-07	4,57E-07	1,65E-02	6,57E-07	5,96E-07	1,97E-04	2,10E-15	8,68E-04

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