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Life Cycle Assessment of Gasification-based Fischer-Tropsch Bio Jet Fuel production

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In cooperation with Bioshare AB

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Table of contents

Summary

Jet-fuels need to be produced from renewable resources for meeting set sustainability goals. Currently, only a small amount of the jet fuels used originates from renewables with fossil resources as the main raw material supply, for which the aviation industry and society are seeking alternative solutions.

Bioshare AB has, together with SIVL, commissioned IVL Swedish Environmental Institute to conduct a life cycle assessment (LCA) of the production of Fischer Tropsch (FT) – fuel from a gasification-based production process of biofuels in an existing combined heat and power plant. Thus, the production produces three products; heat, electricity and FT-fuel. This multifunctionality has been handled through system expansion.

This study considers all in- and outputs from the production process, without separating potential environmental impact from each unit operation. The functional unit is set to 1 MJ FT-fuel produced and the studied environmental impacts are Global Warming Potential, GWP (excl. biogenic carbon), Eutrophication and Acidification potential. The load is assumed to be medium and the electricity source is Swedish grid mix.

The result from this study showed that based on the defined system boundaries and assumptions, the transports to and from the production facility contribute the most to GWP, followed by biomass production and the electricity consumption. The highest contribution to the result for eutrophication and acidification potential originates from the consumption of scrubber oil for gas purification. However, these results are sensitive for the biofuel used and to some extent also for the assumed load scenario.

Sammanfattning

Flygbränslen behöver gå från fossila resurser till förnyelsebara alternativ för att vi ska nå uppsatta hållbarhetsmål. På dagens marknad består flygbränslen främst av fossilt jet-bränsle alternativt biobränsle och det efterfrågas alternativa lösningar.

Bioshare AB har tillsammans med samfinansierad forskning från IVL Svenska Miljöinstitutet genomfört en livscykelanalys (LCA) på produktion av bioflygbränsle från en förgasningsbaserad process av biomassa i en befintlig fjärrvärmeanläggning. Således har produktionen tre produkter; värme, el och Fischer Tropsch (FT) bränsle. Multifunktionaliteten av de tre produkterna hanterades genom systemexpansion.

Studien har tagit hänsyn till alla in- och utflöden från produktionsprocessen, utan beaktande av varje delprocess potentiella miljöpåverkan. Funktionell enhet är 1 MJ producerad FT-bränsle och de studerade miljöpåverkanskategorierna är påverkan på klimatförändringar (utan biogen koldioxid), försurning och övergödning. Lastfallet antogs vara medium och elektricitetskonsumtionen svensk elektricitetsmix.

Resultatet av denna studie visar att transporter till och från produktionsanläggningen har störst påverkan på klimatförändringar, därefter bidrar produktion av biomassa och elkonsumtion mest. Störst potentiell påverkan på försurning och övergödning kommer från användning av skrubberolja för gasrening. Resultatet av studien är dock känsligt för val av processer för modellering av biobränsle och i viss utsträckning vilken last som beaktas.

1 Introduction

This aim of the present study is to carry out a Life Cycle Assessment (LCA) of a renewable jet fuel produced through biomass gasification and subsequent Fischer-Tropsch synthesis. The technical concept is based on a gasifier of steam-blown indirect fluidized bed type which is integrated with existing fluid bed boiler at a combined heat and power (CHP) plant. The gas formed is purified and converted into Fischer-Tropsch (FT) fuel with focus on aviation fuel fractions.

The study is linked to a project on CHP-integrated jet fuel production funded by Energiforsk and led by Bioshare. The project builds on previous research and industrial development projects. The aim is to obtain a process which can produce about 15,000 tonnes of FT fuel per year on commercial grounds. The concept is based on a modification of fluid bed boilers to enable flexible co-production of bio-aviation fuels with existing cogeneration of heat and electricity.

Focusing on current profitability through synergies and utilization of existing infrastructure, the project has high relevance for many combustion plants in the industrial and district heating sectors. Moreover, the results from the study at hand will be integrated into the project “Large scale Bio-Electro-Jet fuel production integration at CHP-plant in Östersund, Sweden”, funded by the Swedish Energy Agency and led by IVL Swedish Environmental Research Institute (IVL), where the potential environmental impact from manufacturing of three different jet fuels namely: gasification based bio-jet fuel, bio electro jet fuel and conventional, petroleum-based jet fuel, will be compared.

This project has been performed by IVL on commission of Bioshare. Contact person in Bioshare was Christer Gustavsson. The study was reviewed by Sofia Poulikidou, IVL.

1.1 About this report

The report presents the main findings of this LCA study and consists of two parts. The main part of the report includes a summary about the LCA methodology, system specifications, assumptions and main findings. The report also contains several appendices that deepen the knowledge of the modelling choices and system boundaries of the LCA. The information in the appendix is mainly targeted towards LCA practitioners and included for the purpose of review, reproducibility and transparency of data.

2 Method

The environmental impact of FT-crude production is assessed using life cycle assessment (LCA). LCA is a widely used and accepted method for investigating the environmental performance of various products and systems throughout their whole life cycle. This includes evaluating energy and resource consumption as well as emissions, from all life cycle stages including; material production, manufacturing, use and maintenance, and end-of-life. A schematic overview of a life cycle is shown in Figure 1.

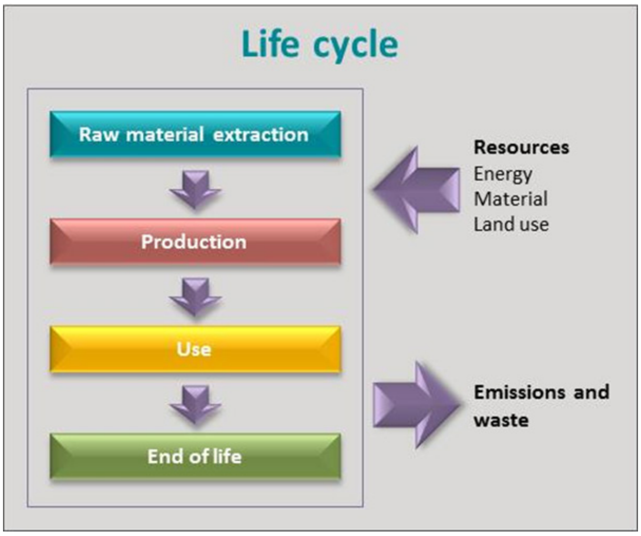

Figure 1. Illustration of the LCA system.

The LCA in this report is performed in accordance with ISO 14040:2006 (ISO 14040, 2006) and ISO 14044:2006 standards (ISO 14044, 2006). LCA consists of four main stages namely: the goal and scope definition, inventory analysis, impact assessment and results interpretation (see Figure 15, Appendix A). For additional information on how an LCA is performed and what parts it contains, see Appendix A.

3 Goal and scope definition

A clearly defined goal and scope is crucial in order to fully understand the LCA and the associated results. Together with the functional unit, which is a reference unit to which the inputs and outputs of the LCA are related to, the scope is what defines the boundaries and circumstances under which the LCA and respective results are valid.

The goal and scope of the present study are summarised below together with the brief description of the studied product.

3.1 Goal of this study

The goal of the study is to evaluate the potential environmental impact from manufacturing of a bio jet fuel produced through biomass gasification and Fischer-Tropsch synthesis, integrated at an existing CHP plant. The study adopts a life cycle perspective i.e. including the stages of raw material extraction, fuel production as well as associated transports. However, the system boundary of the study is set to manufacturing of FT crude i.e. before separation and final conversion to different fuel fractions.

3.2 Scope

3.2.1 Type of LCA

There are two types of LCA: attributional and consequential. The processes included in an attributional LCA are those that contribute directly to the life cycle environmental impact of the product or service studied. The processes included in a consequential LCA take into account a wider perspective and also include indirect effects (Erlandsson, et al., 2014). Attributional LCA uses average data that reflect the actual physical flows, while consequential LCA usually uses marginal data that reflect the effects of small changes (Finnveden, et al., 2009).

The present study applies the attributional LCA approach and considers the life cycle of the manufacturing of FT-crude from cradle to gate. Attributional LCA was chosen because this study aims to evaluate the potential environmental impacts from an existing production process, rather than studying consequences of a change in the manufacturing process. In addition, this study does not focus on supplying alternative suggestions in the production process of FT-crude, which often is the case for using a consequential approach.

3.2.2 Functional unit

The functional unit in LCAs represents the reference value in which all inputs and outputs of the studied system relate to. The desired function of the studied process is to produce FT-crude i.e. an intermediate product before the conversion to bio jet fuel.

The **chosen functional unit is therefore: 1 MJ FT-crude produced.**

The amount of resources, materials and electricity needed are all related to this function.

However, the same facility also produces district heating and electricity as co-products which implies that the studied product system or process has more than one function; e.g. combustion of biomass generates both heat, electricity and FT-crude. Multifunctionality has been handled through system expansion.

3.2.3 Product system specifications

The study assesses the environmental performance of FT-crude, a fuel that is produced through biomass gasification followed by Fischer-Tropsch synthesis. In this study, the system boundary is set from cradle to gate, as shown in Figure 2 excluding the process of separation and conversion to jet fuel fractions as well as fuel distribution and use.

All upstream activities including biomass production and transport to the gasification facility are included.

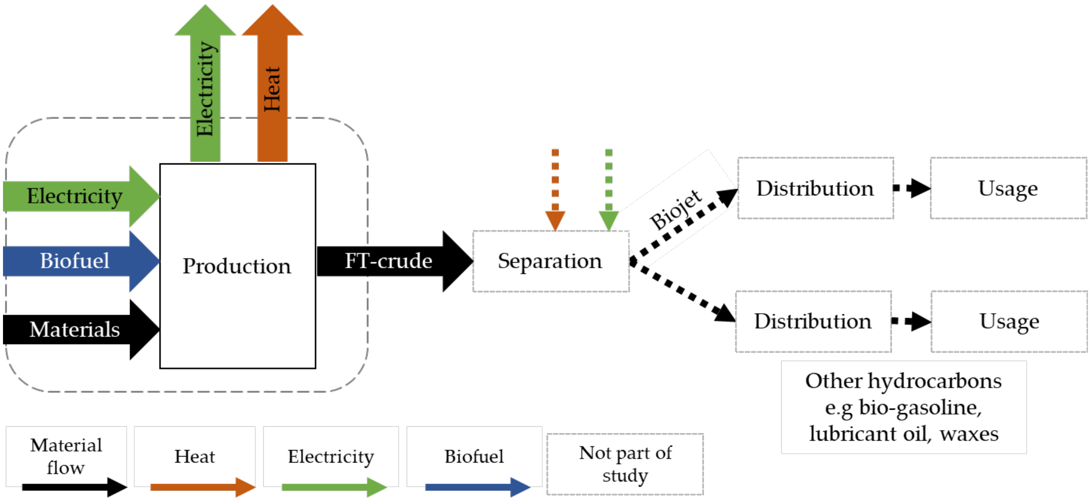

Figure 2. The system boundary of this study.

A mid-load scenario has been assessed and presented as "base case" in this analysis. The level of load assessed reflects the amount of input material, resource and energy consumption, as well as the output (i.e. FT-crude, district heating and electricity).

Data on biomass composition was obtained from Bioshare. Grot ("grenar och toppar", i.e. forest residues) in the biomass for the base case scenario is collected from the south of Sweden based data from Lindholm, Berg, & Hansson, 2010.

The site is assumed to operate 335 days per year and 24 hours per day, without any shutdowns or reduced production.

Additional load scenarios namely a low-load as well as a high- load scenario have been evaluated as sensitivity analysis (see section 6.2).

3.3 System boundaries, assumptions and limitations

The study approaches the manufacturing of FT-crude as a black box, i.e. does not consider all units separately, but rather evaluate all inputs and outputs from a larger perspective. Material and energy flows in the unit operations are included in the assessment. Balance of Plant (BOP) and transports of the final product are however excluded.

3.3.1 Geographical boundaries

In the base case, average Swedish data was used to model energy consumption and resource usage when possible. When Swedish data was not accessible, European data where preferred over global datasets.

3.3.2 Time boundaries

The study aims at describing the current situation, and therefore as recent data as possible has been collected.

3.3.3 Multifunctional processes

"Multifunctionality" implies that a studied product system or process has more than one function; in this case combustion of biomass generates both heat, electricity and FT-crude. Different ways to deal with multifunctionality exist such as system expansion or allocation (Curran, 2015).

During system expansion a credit is given for the product or products that are replaced by the by-product or material of interest. In other words, it means that the impact associated with the saved material and energy production are subtracted from the total life cycle impact.

Allocation refers to the process of dividing the potential environmental impacts to the outputs of the system, e.g. based on their share of total weight, energy content or economic revenue for the system.

Multifunctionality in this study has been handled through system expansion and substitution (ISO 14040, 2006).

In the "base case" average Swedish electricity is assumed to be replaced by the electricity produced in the CHP facility. The heat produced substitutes heat produced by combustion of biomass modelled using dataset from Thinkstep AG (2018).

3.3.4 Limitations

Conclusions regarding impacts from specific unit operations cannot be drawn, since the system is evaluated in terms of its total inputs and outputs without considering the internal unit processes.

3.4 Sensitivity analysis

Sensitivity analyses have been performed to investigate the influence of specific flows in the results of the study but also to deal with uncertainties in terms of inventory data and assumptions. The following scenarios are considered for sensitivity analysis in this study:

- Location of biomass production
- Inventory data regarding biomass, where biomass production from two different locations in Sweden was compared to two generic datasets from Wernet G et al., (2016).
- Additional load scenarios

3.5 Impact assessment

Life cycle impact assessment (LCIA) implies taking the inventory results for all flows (materials, resources, energy and emissions) and evaluating each material and emission's impact on different impact categories.

For this study, the selected impact categories are global warming potential (GWP) excluding biogenic carbon, eutrophication potential (EP) and acidification potential (AP), see Table 1.

Table 1. Environmental impact categories

Impact category	Category indicator	Reference
Global warming potential (GWP) excl. biogenic carbon	kg CO_2 equivalents	CML2001 - April 2016
Eutrophication potential (EP)	kg PO_4 equivalents	CML2001 - April 2016
Acidification potential (AP)	kg SO_2 equivalents	CML2001 - April 2016

The inclusion of these impact categories and hence the exclusion of other impact categories are motivated by the fact that the chosen impacts are more commonly used and less uncertain than e.g. Human toxicity and Ecotoxicity. This choice is also based on the ranking in ILCD on the robustness of the impact categories. The impact categories have also been selected due to their relevance for the studied products (and included materials). A detailed description of the impact categories and the mechanisms causing the impacts are described in Appendix A.

3.5.1 Biogenic carbon modelling

There are different ways of modelling the embedded biogenic carbon due to the carbon uptake during the growth of trees:

- Alternative 1: The carbon uptake in the material is not included. When the biogenic carbon in the material is released, for instance when incinerated, these biogenic CO_2 emissions should be considered not to contribute to global warming. This is the most common way to treat "short cycle carbon" in LCAs.
- Alternative 2: The carbon uptake in the material is accounted for in the production phase of the material, as a negative biogenic CO_2 flow contributing with a negative global warming.

> When the biogenic carbon in the material is released, for instance when incinerated, these biogenic CO_2 emissions contribute to the overall CO_2 emissions from the system (and accounted for separately from the fossil CO_2).

In this study, biogenic carbon was excluded from the results as the main product of the system will be used as a fuel, and the carbon embodied in the product will be released from its combustion. Therefore, alternative 1 was chosen.

4 Data collection

Information about site specific material and energy input flows as well as process emissions for manufacturing of FT-crude was retrieved through personal communication from the client, Bioshare. Additional data with regards to background system modelling have been retrieved from generic life cycle inventory (LCI) databases e.g. the LCI provided by Gabi (Thinkstep AG, 2018) or EcoInvent (Wernet et al., 2016) as well as scientific publications.

Details on the datasets used can be found in Appendix C.

The LCA study was modelled using the software Gabi (Thinkstep AG, 2018).

5 Life cycle inventory

In this part of the study, data and assumptions in relation to the life cycle model of FT-crude are presented.

5.1 Material, energy and resource flows

The material, energy and resource flows considered in the studied process include the biomass entering the boiler and gasifier, as well as electricity and chemicals as shown in Table 2.

Table 2. The material- and resource flows for FT-crude manufacturing.

		Mass flow kg wet	LHV MJ
Inputs	Biomass	0.368	3.34
	Scrubber oil (RME)		0.092
	Electricity consumed		0.426
	Amine	0.000010	
	Feed water	0.091	
	Guard bed for Cl	0.0000007	
	Guard bed for S	0.000007	
	N2	0.000017	
	Propane	0.00001	
	Sand	0	
Outputs	Process water	0.225	
	Ash	0.00013	
	Flue gas	1.146	
	FT-crude	0.023	1
	District heating produced		1.952
	Electricity produced		0.391

Biomass composition based on data from Bioshare is illustrated in Figure 3. The biomass consists of 66% grot, 15% wood and 14% bark. Since only 5% is excluded the remaining weight was divided between wood and bark, instead of modelling all other wood types. Thus, both wood and bark were set to 17% respectively.

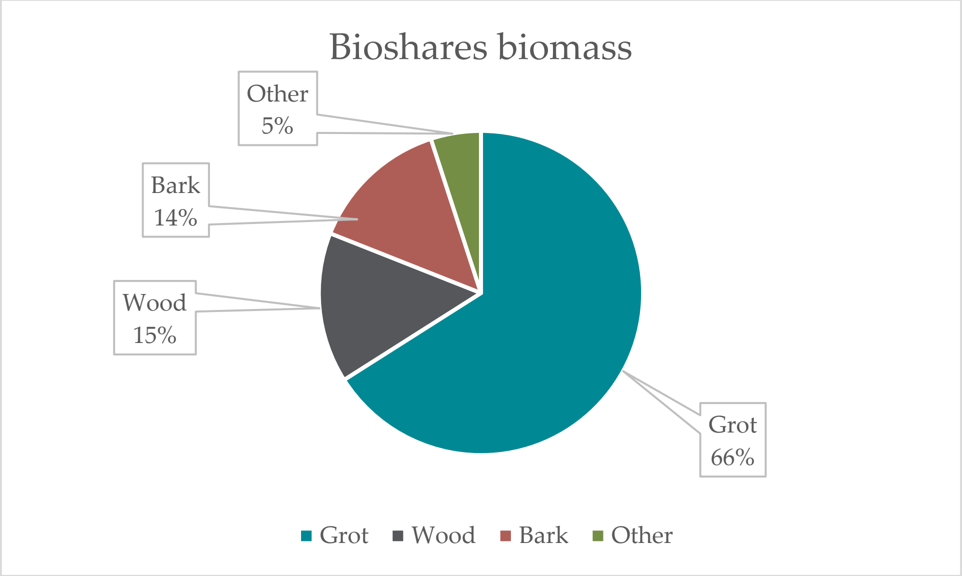

Figure 3. The biomass composition at Bioshare production facility.

Inventory data on grot was obtained from the study by Lindholm, Berg, & Hansson (2010) (see appendix C) since no generic dataset was available. Thus data from the article is assumed to be representative for the grot Bioshare is using. The southern latitude was chosen to represent the base case, while additioncal locations were considered in the sensitivity analysis.

The remaining biomass fractions were modelled based on data from Thinkstep and Ecoinvent, see Table 6, Appendix C.

For the electricity prodution, inventory data on the Swedish electricity mix were used.

Scrubber oil specifically Rape methyle ester (RME) is used in the production process for FT-crude to clean the producer gas (syngas). RME is modelled using data from Thinkstep AG (2018).

Chemicals were modelled based on generic data from European datasets when possible and Global datasets otherwise (see alsoTable 6, Appendix C).

5.1.1 Transport

Transports of biomass to the site, transports of ash from the production and internal transports are included in the study. The information is taken from Hjalmarsson (2011) and a budget for 2020´s production in the studied production system. The amount kg×km/FU was calculated by dividing the sum of kg×km with the yearly production time in seconds.

The transports were removed for modelling the potential impact from grot, since these are already included in the data obtained from Bioshare in the report by Hjalmarsson (2011).

The transports to and from the production facility were modelled using a Euro 5 truck and the internal transports were modelled based on diesel consumption. Details regarding the transports to and from the site are presented in Table 3 while the internal transport are presented in Table 4.

Table 3. Transports to and from the production facility.

Transport	Weight transported/year [tonne]	Transport Capacity [tonne/truck]	Average distance/transport [km]	Total amount of transports	Tonnekm/year	Yearly kgkm/FU
Forest Fuels	251333	32	15	7854	3769920	130

Table 4. Internal transports.

Transport	Reference case	Yearly consumption	Yearly consumption/FU
Amount and type of truck	1 truck, Volvo L150F		
Amount hours driven per year	2200	33 000 liters	0.000076 liters/FU
Fuel consumption liter/hour	15	33 000 liters	0.000076 liters/FU

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6 Results

This section presents the results of this LCA study for the three impact assessment categories selected namely: global warming potential (GWP), eutrophication potential (EP) and acidification potential (AP). The results are shown and discussed per functional unit as defined in section 3.2 i.e. "1 MJ of FT-crude produced". First, results for the base case are presented (section 6.1.), followed by the results from the additional scenarios/loads tested as sensitivity analysis (section 6.2).

6.1 The base case

In this chapter, a summary of the result for the base case for GWP, AP and EP is presented. Table 5 describes a summary of the result for the three studied categories.

Table 5. A summary of the result per 1 MJ FT-crude produced.

Category	Result
GWP, excl. biogenic carbon [kg CO_2 eq.]	0.009842
EP [kg Phosphate eq.]	-0.000037
AP [kg SO_2 eq.]	-0.000267

The negative number is a result from using system expansion, where the impact from the by-products are subtracted to the result. The result for AP and EP is, therefore, negative since this production facility produces much district heating in relation to the FT-crude production.

6.1.1 Global Warming Potential

Figure 4 represents the result for GWP, as a result of the different inputs or outputs of the system during the life cycle of FT-crude. As seen in Figure 4, transports to and from the production site contribute the most, followed by biomass production, electricity and material inputs.

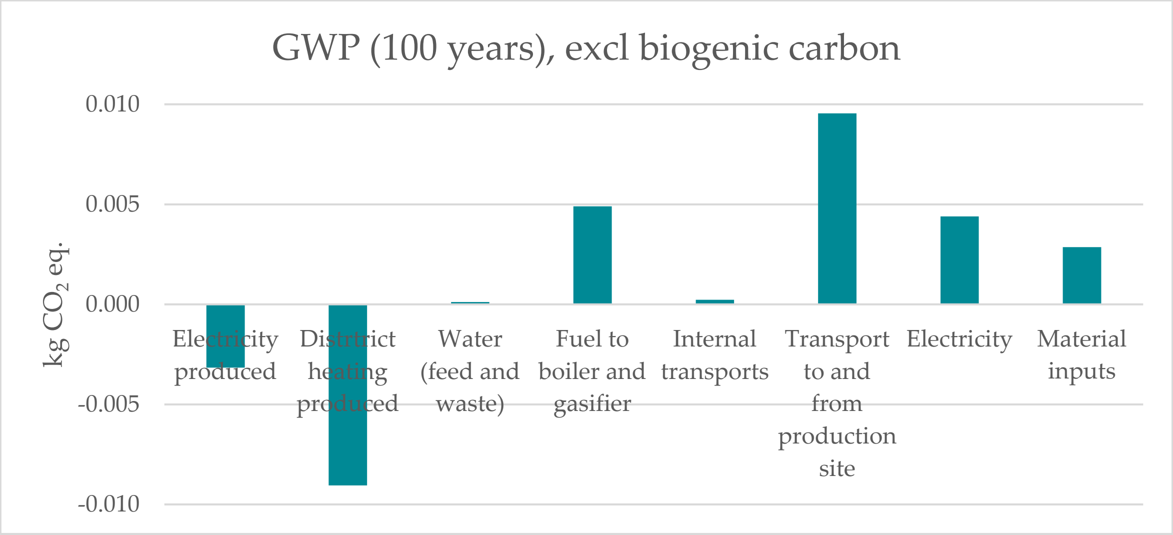

Figure 4. The potential impact to GWP, related to 1 MJ FT crude produced. In the graph, the material inputs consist of ash, alumina, MDEA, nitrogen, propane, sand, scrubber oil and zinc oxide.

The environmental impact from transports derives mainly from the combustion of fossil fuel and specifically diesel that is used in the vehicles performing the transport.

The biomass input considered in this study consists of 66% grot, 15% wood and 14% bark (although it is modelled as 17% wood and 17% bark). 50% of the GWP-contribution from biomass is derived from wood, see Figure 5.

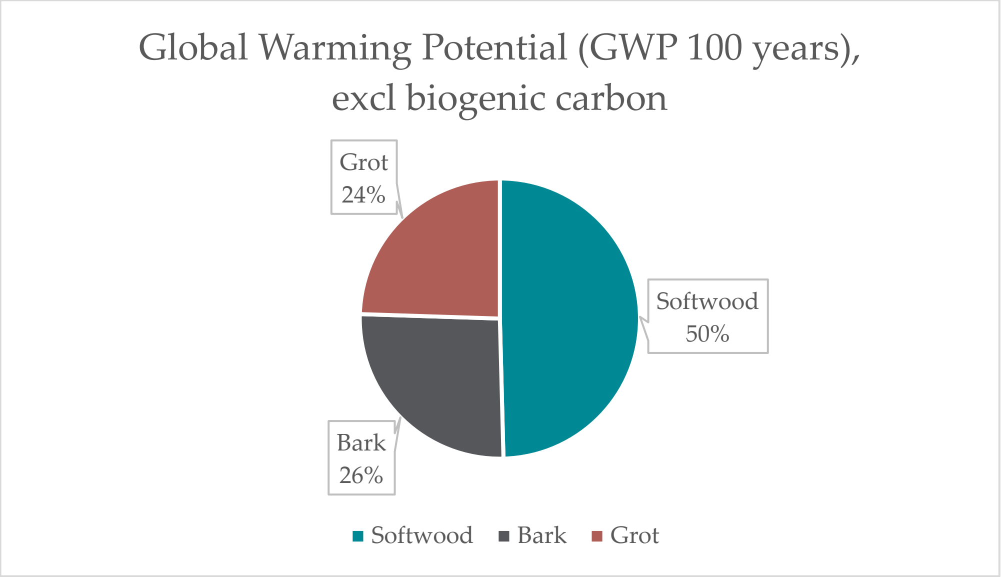

Figure 5. The elements in the fuel to the boiler and gasifier to GWP, related to 1 MJ FT-crude produced

The softwood dataset used in the study to model the wood fraction includes the activities such as splitting of wood, harvesting, sawing, tree seedling, and wood chipping as well as fuel combustion from the machines. High amount of CO_2 is emitted during combustion of diesel. As a result of this high contribution, the impact from biomass is further assessed in sensitivity analysis through a comparison between the datasets used.

6.1.2 Eutrophication Potential

The result in Figure 6 represents the quantified result on EP, the result shows the different inputs or outputs of the system during the life cycle of FT-crude. As seen in Figure 6, most of the impact on EP originate from the materials and chemicals used in the process. Transport, biomass input and electricity contribute to the impact at a lesser extent, while the impact from internal transports is negligible.

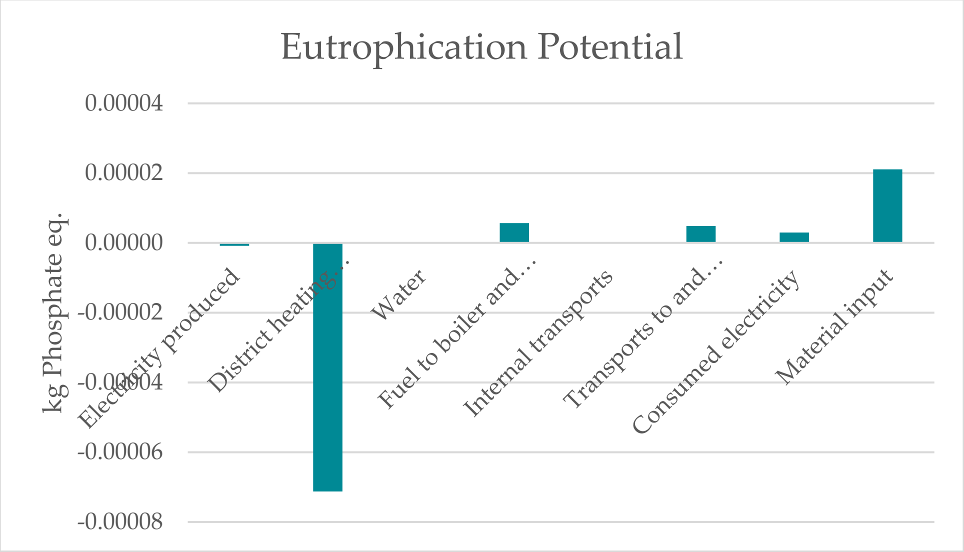

Figure 6. The potential impact to EP from 1 MJ FT crude produced. In the graph, the material inputs consist of ash, alumina, MDEA, nitrogen, propane, sand, scrubber oil and zinc oxide.

As seen in Figure 7, most of the EP-contribution from the materials originate from scrubber oil.

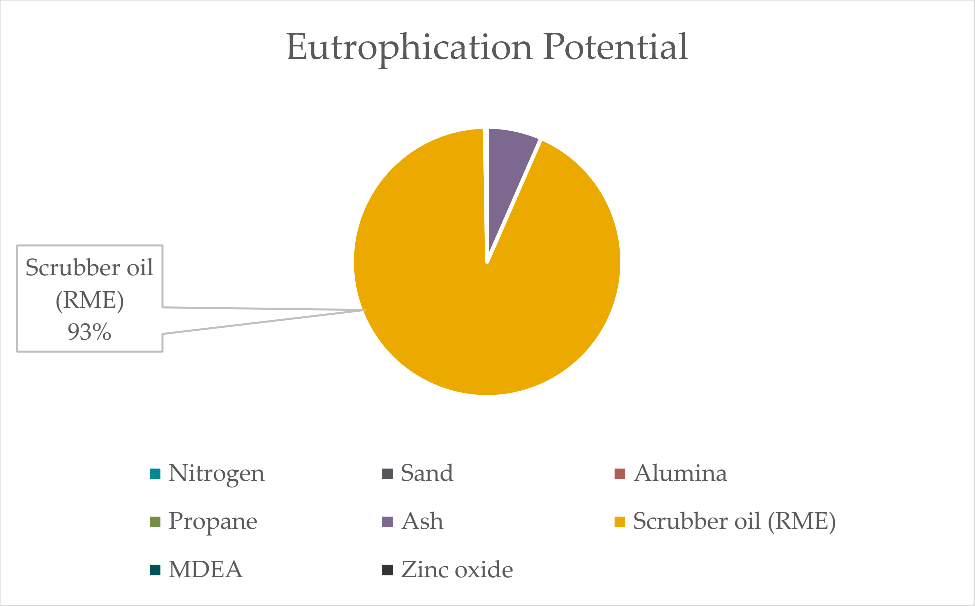

Figure 7. The relative contribution from the materials, related to 1 MJ FT-crude produced.

The high contribution to EP originates from the high amount of emissions of chemicals to water, from production of RME. The dataset is based on rapeseed cultivation and includes the use of fertilizers which impacts the results.

6.1.3 Acidification Potential

The result in Figure 8 depicts the quantified result for AP. The result shows the different inputs or outputs of the system during the life cycle of FT-crude. The input materials have the highest contribution to AP, see Figure 8, followed by transports, biomass and electricity consumed.

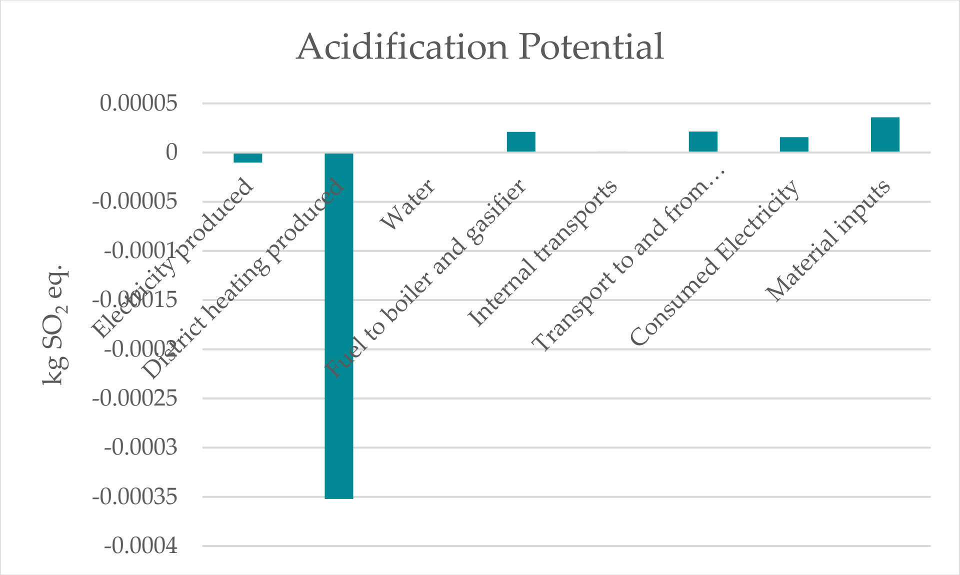

Figure 8. The potential impact to AP, related to 1 MJ FT-crude produced. In the graph, the material inputs consist of ash, alumina, MDEA, nitrogen, propane, sand, scrubber oil and zinc oxide.

As seen in Figure 9, the contribution from the materials used in the fuel production process originates from the scrubber oil.

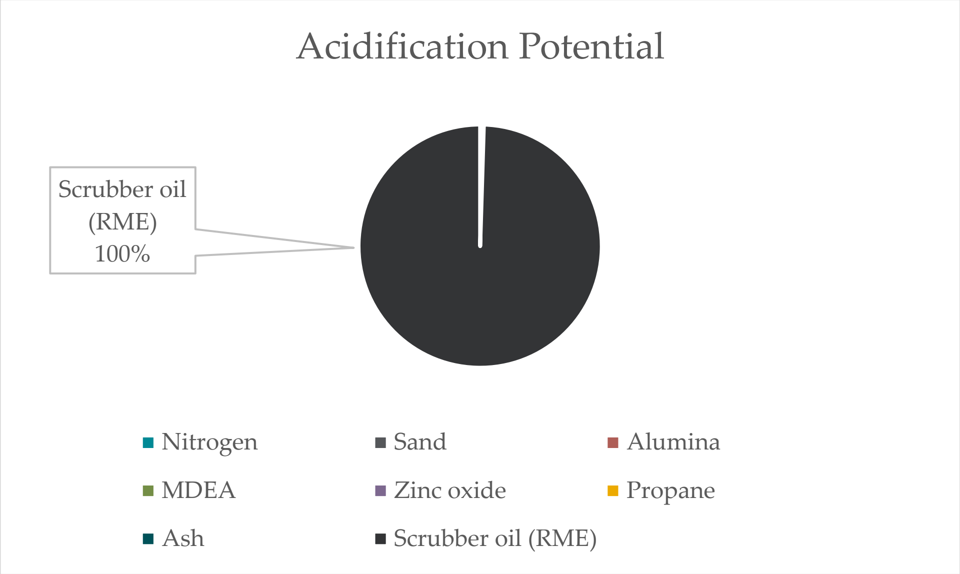

Figure 9. The relative contribution from the materials in the production process of 1 MJ FT-crude.

Table 2 describes the potential impact from the materials related to AP. RME accounts for the whole impact on AP, relatively the other materials. RME is a biofuel that has an intense cultivation process during production (Wernet G et al., 2016).

With regards to biomass composition, softwood has the largest contribution to AP compared to grot and bark, see Figure 10. As mentioned above, the biomass is modelled as 17% softwood, 17% bark and 66% grot.

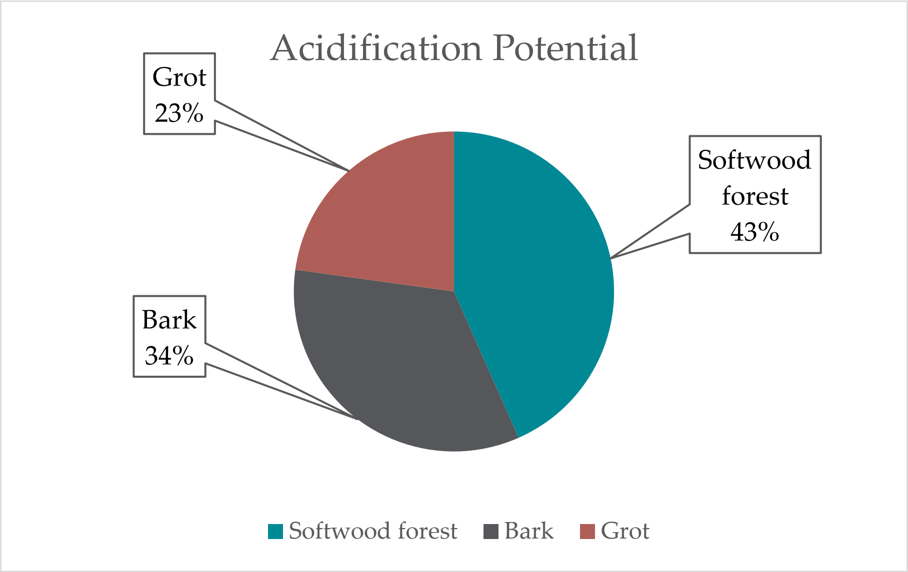

Figure 10. The elements in the biomass contribution to AP, related to 1 MJ FT-crude produced.

The contribution from softwood is associated with the production of the wood. The contribution to AP from grot is associated with the primary energy use (Lindholm, Berg, & Hansson, 2010).

6.2 Sensitivity analysis

It is important to include sensitivity analysis when a life cycle step has high impact on the result and data is uncertain. Two sensitivity analyzes have been carried out. The first analysis compares three different load scenarios for the production plant: low, mid and high load. The mid load was used for the base case. The second analysis compare the results from using different biomasses. A generic dataset for biomass was compared to Bioshare´s biomass composition and modelling of three different datasets for grot, because grot accounts for 66% of Bioshare´s biomass.

6.2.1 Biomass

The biomass that Bioshare uses was modelled according to the most frequently used composition, which is described in Figure 3. The modelling of grot for the base case was done with emission factors stated in the article from Lindholm, Berg, & Hansson (2010). In this article, two different emission factors were presented representing different geographic areas for grot collection in Sweden, i.e., north and south. The values differ to a large extent between the two areas. The base case was modelled using the emission factor representing southern Sweden.

The sensitivity analysis is divided into two steps. The first step is a comparison of grot from the two geographical areas. The second step was to replace the emission factors from the article from Lindholm, Berg, & Hansson (2010) with generic datasets from Thinkstep and Ecoinvent, respectively named "generic dataset 1" and "generic dataset 2". Generic dataset 1 is modelled with a different composition representing a global commonly used biofuel composition. Generic dataset 2 uses the biomass composition of Bioshare but employs an emission factor from Wernet G et al., (2016).

As seen in Figure 11, the generic dataset 2 has the highest impact on GWP. Grot from the south of Sweden has the lowest impact on GWP. The choice of biomass affects the overall environmental performance of FT-crude production.

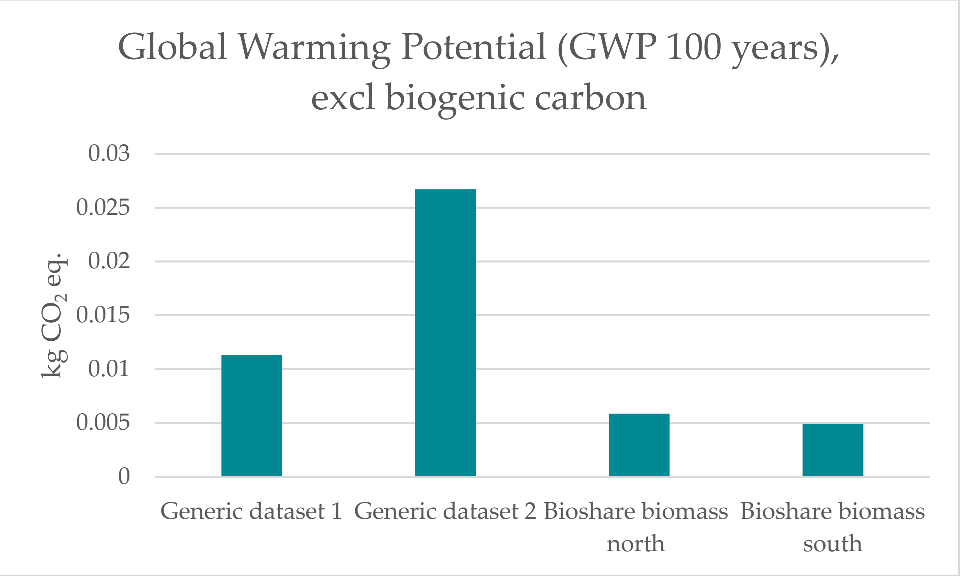

Figure 11. The result from a comparison between the different biomasses contribution on GWP. The result shows the impact from each biomass evaluated.

Grot from the north of Sweden has higher impact than from the south, because of less efficient production for deliver the same amount of material. According to the study by Lindholm, Berg, & Hansson (2010) the production of grot in southern Sweden had higher energy efficiency than in the north, such as less loading and unloading of transports and greater production of forest residues. The result for AP and EP has similar trends and can be found in Figure 16 and Figure 17, Appendix E.

6.2.2 Comparison between loads

In this chapter, the overall results for the FT-crude production are presented in three loads; low, mid and high. The differences among the load scenarios are related to the portion biomass consumed, volume flue gases generated plus the amount of district heating and electricity produced, see Table 7 and Table 8 in Appendix D, for a full description of the inputs related to each load scenario.

The mid load is chosen as the base case, but Bioshare requested to see the potential change between three different loads to evaluate the production of FT-crude in relation to GWP. The results in Figure 12 describe the potential environmental impacts from the comparison of the three cases related to GWP.

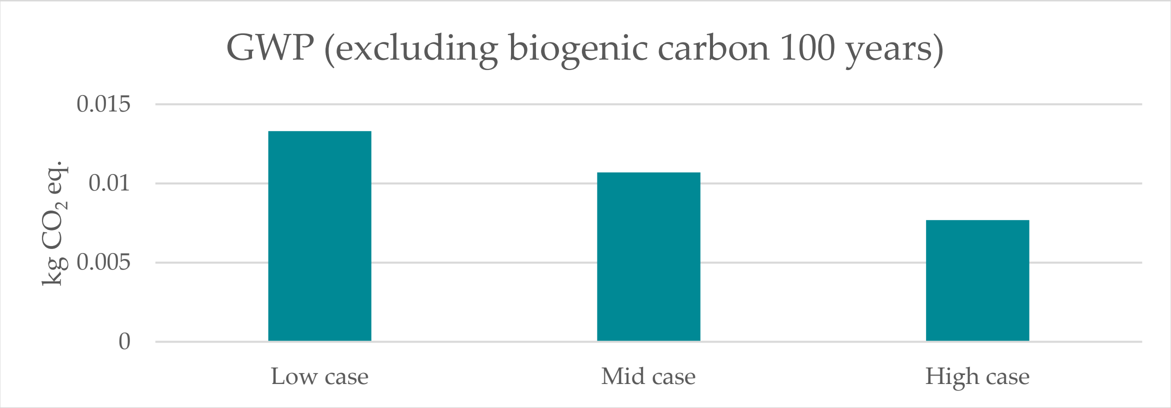

Figure 12. The results of the GWP per for 1 MJ FT-crude produced.

Figure 12 describes the potential impact to GWP from three different load scenarios. The differences among the scenarios are related to the amount of district heating and electricity produced, which in the low load scenario is smaller than in the high load scenario. However, the amount biomass consumed is also smaller in the low load scenario compared to the high load. The lower result from the high case load is related to the amount of by-product (district heating and electricity) produced, which is handled by system expansion i.e. the emissions connected to the saved energy has been given credits and subtracted from the result from the total life cycle. In this study, the produced district heating and electricity has been considered as avoided.

7 Interpretation

This aim of the present study was to make an LCA of a renewable jet fuel produced through biomass gasification and subsequent Fischer-Tropsch synthesis. The technical concept is based on a gasifier of steam-blown indirect fluidized bed type which is integrated with existing fluid bed boiler at a combined heat and power (CHP) plant. The gas formed is purified and converted into Fischer-Tropsch (FT) fuel (FT-crude) with focus on aviation fuel fractions.

The result from this study shows that the highest impact on GWP comes from the transport of biomass to the production facility. To minimize the impact from transport, using trucks with renewable fuel and transport shorter distances are preferred. In addition, the material inputs have the highest contribution to EP and AP, for producing 1 MJ of FT-crude. The scrubber oil has the highest impact from the materials, where the great amount of fertilizers used in cultivation process of the raw material for the oil (rape seed) is indicated to be the largest reason for the high impact. There are other possible options which could be considered for usage as scrubber oil. Hydrogenated Vegetable Oil (HVO) produced from renewable feed stocks with low environmental impact (beef tallow or raw tall oil) are both alternatives that could potentially greatly reduce this impact.

The raw material i.e. biomass has a considerable impact on the results too, for all selected categories. This contribution depends highly on the production of the wood, grot and bark where the transports and handling have high impact on the result. To minimize the potential impact on GWP and EP, biomass with as low contribution as possible is preferred. The environmental impact from the biomass originate from the handling and transportation, therefore, by choosing biomasses with minimal handling is preferred over biomass with, for example, much transports.

8 Conclusions and recommendations

Main conclusions and recommendations:

Conclusion 1: Reducing transports of biofuel to the production facility and transports related to the extraction of biomass would generate lower potential environmental impact.

Conclusion 2: Pick biomass with low environmental impact. Choosing which biomass to use based on its environmental performance would affect the environmental impact of FT-crude.

Conclusion 3: The load cases impact the result and the case with high load generates lower potential environmental impact of producing FT-crude.

The LCA in this project is modelled as a black box, i.e. not modelled per unit operation but instead considering all inputs and outputs from the production as a combined process. Thus, no conclusion can be made regarding unit operations as hotspots in the production process.

A final recommendation is to evaluate other possible scrubber oils, than RME, which would generate a better impact on AP and EP. In addition, possibilities to internally re-use for cleaning the producer gas (syn gas) or recycle the oil could also be evaluated to receive a better potential environmental impact compared to the use of virgin resources only.

8.1 Recommendations for future work

Future studies are recommended to add more detailed data on material inputs, resource use, energy consumption and waste generated. It would be preferred to model biomass input in greater detail to reflect the actual impact even better. In addition, future studies are recommended to include the unit operations of the production process for producing 1 MJ FT-crude, to conclude which operations that should be in focus to minimize the environmental impact overall. Moreover, a more detailed study on possible replacements and/or reusage strategies for the scrubber oil have the potential to generate knowledge that could be utilized to reduce the environmental impact of FT-crude even further. Finally, the data from this study will be further processed and integrated into the LCA-analysis work of the project "Large scale Bio-Electro-Jet fuel production integration at CHP-plant in Östersund, Sweden" to generate a comparison of three different jet-fuels and their respective environmental performance.

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Appendix A. Brief introduction to LCA

Environmental life cycle assessment (LCA) is the calculation and evaluation of the environmentally relevant inputs and outputs and the potential environmental impacts of the life cycle of a product, material or service (ISO 14040:2006 and 14044:2006).

Environmental inputs and outputs refer to demand for natural resources and to emissions and solid waste. The life cycle consists of the technical system of processes and transports used at/needed for raw material extraction, production, use and after use (waste management or recycling). LCA is sometimes called a "cradle-to-grave" assessment (Figure 14).

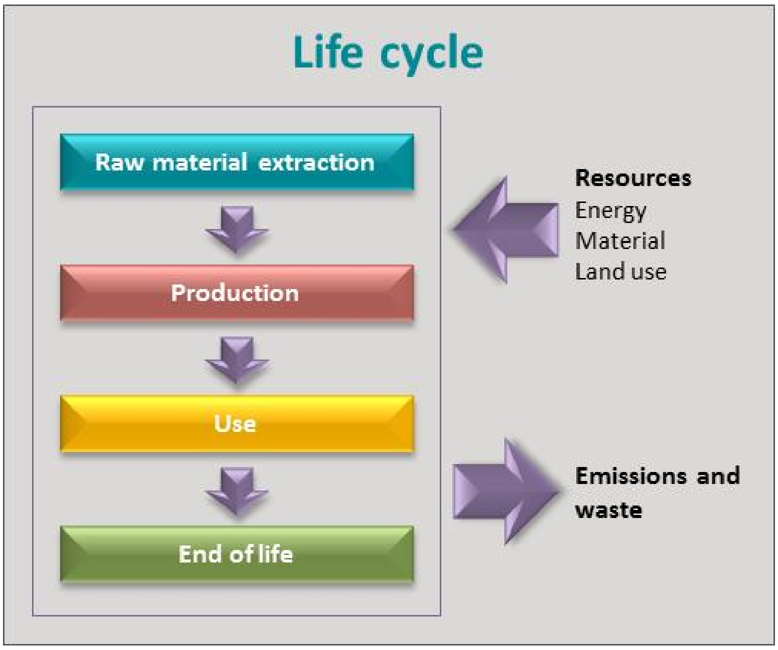

Figure 13. Illustration of the LCA system.

An LCA is divided into four phases. In accordance with the current terminology of the International Organization for Standardization (ISO), the phases are called goal and scope definition, inventory analysis, impact assessment, and interpretation (Figure 13).

An LCA can be used in many different ways, depending on how the goal and scope are defined. Product development, decision making, indicator identification and marketing are examples of areas where the information retrieved from an LCA may be valuable.

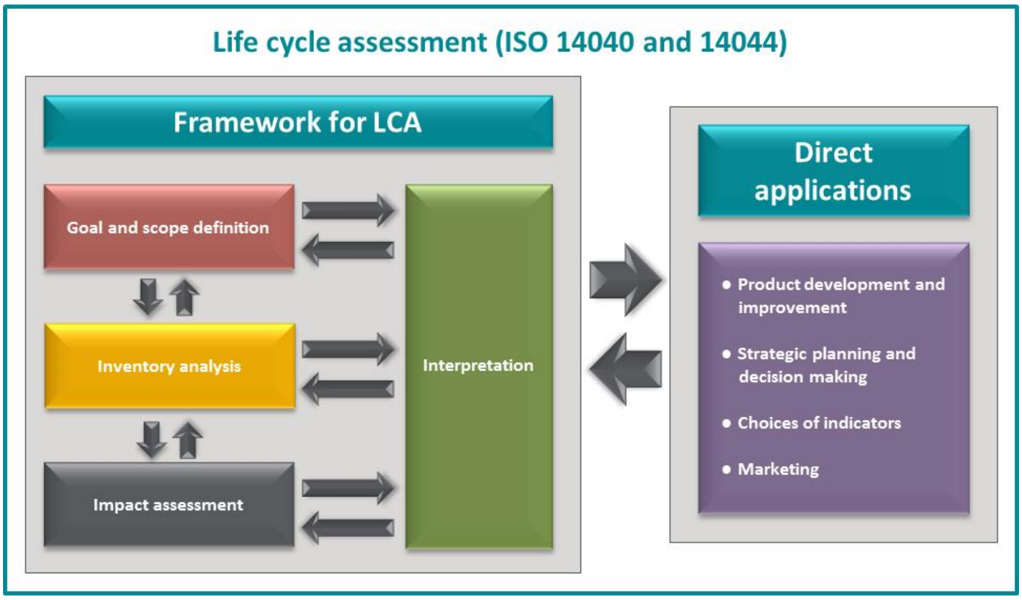

Figure 14. Illustration of the phases of an LCA.

Goal and Scope

In the first phase the purpose of the study is described. This description includes the intended application and audience, and the reasons for carrying out the study. Furthermore, the scope of the study is described. This includes a description of the limitations of the study, the functions of the systems investigated, the functional unit, the systems investigated, the system boundaries, the allocation approaches, the data requirements and data quality requirements, the key assumptions, the impact assessment method, the interpretation method, and the type of reporting.

Inventory analysis

In the inventory analysis, data are collected and interpreted, calculations are made and the inventory results are calculated and presented. Mass flows and environmental inputs and outputs are calculated and presented.

Impact assessment

In the life cycle impact assessment (LCIA), the production system is examined from an environmental perspective using category indicators. The LCIA also provides information for the interpretation phase.

For comparative assertions, there are four mandatory elements of LCIA:

Selection of impact categories, category indicators and models,

Assignment of the LCIA results (classification),

Calculation of category indicator results (characterization) and

Data quality analysis.

The following elements are optional:

Calculating the magnitude of category indicator results relative to a reference value (normalization),

Grouping and

Weighting.

Interpretation

The interpretation is the phase where the results are analysed in relation to the goal and scope definition, where conclusions are reached, the limitations of the results are presented and where recommendations are provided based on the findings of the preceding phases of the LCA.

An LCA is generally an iterative process. The impact assessment helps increasing the knowledge about what environmental inputs and outputs are important. This knowledge can be used in the collection of better data for those inputs and outputs in order to improve the inventory analysis.

The conclusions of the LCA should be compatible to the goals and quality of the study.

A.1 Category definition, classification and characterisation

For each impact category *i*, the reasons why the environmental impact is considered to be an environmental problem are described. The category indicator – the quantified representation of the environmental impact – is defined, and the mechanisms that are modelled in the characterisation are described in brief. The characterisation factor describes the potential contribution to the impact category *i* from the input or output of substance *j* per unit mass of *j*. The total contribution to the impact category from the life cycle, C_i, is calculated as:

$$C_i = \sum E_j \cdot W_{ij}$$

where E_j is the amount of the input or output of substance *j.*

Global warming

A global climate change is a problem for many reasons. One is that a higher average temperature in the seawater results in flooding of low-lying, often densely populated coastal areas. This effect is aggravated if part of the glacial ice cap in the Antarctic melts. Global warming is likely to result in changes in the weather pattern on a regional scale. These can include increased or reduced precipitation and/or increased frequency of storms. Such changes can have severe effects on natural ecosystems as well as for the food production.

Global warming is caused by increases in the atmospheric concentration of chemical substances that absorb infrared radiation. These substances reduce the energy flow from Earth in a way that is similar to the radiative functions of a glass greenhouse. The category indicator is the degree to which the substances emitted from the system investigated contribute to the increased radiative forcing. The characterisation factor stands for the extent to which an emitted mass unit of a given substance can absorb infrared radiation compared to a mass unit of CO_2. As the degree of persistence of these substances is different, their global warming potential (GWP) will depend on the time horizon considered, such as 20, 100 and 500 years. In this study, a time horizon of 100 years has been applied. The time scale 100 years is often chosen as a "surveyable" period in LCAs and discussions regarding global warming.

The characterisation of this environmental impact considers the substances that contribute directly to the greenhouse effect. The total contribution to the global warming potential from the life cycle is calculated as:

$$\mathrm{GWP} = \sum \mathrm{GWP}_j \cdot \mathrm{E}_j$$

where E_j is the amount of the output j and GWP_j the characterisation factor for this output. The characterisation factor is measured *in g* CO_2 *equivalents per g of the emitted substance*, and thus, the unit of the category indicator is *g* CO_2 *equivalents (g* CO_2 *eq.)*.

Acidification

Acidification stands for the decrease of the pH value in terrestrial and water systems. This is a problem, e.g., because it causes substances in the soil to dissolve and leak into the water systems. These substances include nutrients, which are needed by plants, as well as metals such as aluminium and mercury, which can have toxic effects in the aquatic ecosystems. Reduced pH in the water system also has direct, ecotoxic effects, reducing the number of species that can live in lakes, etc. Emission of acidifying substances also causes damage on human health, and on buildings, statues and other constructions.

The characterisation takes into account the substances that contribute to the acidification of the soil and of lakes. The category indicator is the ability of the emissions from the system investigated to release H^+ ions. The acidification potential is the ability of 1 mg of a substance to release H^+ ions compared to that of 1 mg of SO_2.

The substances that contribute most to acidification are SO_2, NO_X, NH_3, HCl and other acids. As stated above, the release of H^+ will depend on the conditions at the terrestrial or water system where the acid or acid-producing substance is deposited. Most sulphur is emitted as SO_2. It is either deposited as it is or transformed in the air into sulphuric acid, which subsequently will be deposited and will generate two protons, or will react in the air. If SO_2 is deposited, it will be transformed into sulphuric acid in the ecosystem and release two protons per atom of sulphur. In the air, sulphuric acid may react with ammonia to form ammonium sulphates. However, the deposition of ammonium sulphates will generate the same amount of H^+ as sulphuric acid and ammonia would if they were separately deposited.

The total contribution to the acidification potential from the life cycle is calculated as:

$$\mathrm{AP} = \sum \mathrm{AP}_j \cdot \mathrm{E}_j$$

where E_j is the amount of the output j and AP_j the characterisation factor for this output. The characterisation factors are measured in *mg* SO_2*-equivalents per g of the emitted substance*, and thus, the category indicator is measured in *mg* SO_2*-equivalents*.

Eutrophication (nutrient enrichment)

When the nutritional balance in the soil and waters is disturbed, it is called eutrophication (when the amount of nutrition is increased). In aquatic systems, this leads to increased production of biomass, which may lead to oxygen deficiency when it is subsequently decomposed. The oxygen deficiency, in turn, kills organisms that live in or near the bottom of the lakes or coastal waters. It also makes the reproduction of fish more difficult.

In terrestrial systems, deposition of nitrogen compounds leads to increased concentrations of nitrogen, which in turn leads to a change in the growing conditions. The nitrogen may leak into water systems, and cause increased levels of nitrogen in the aquatic systems. The effects in aquatic systems depend on the recipient. Different terrestrial and aquatic systems have different sensitivity to eutrophying and oxygen depleting substances. Phosphorous-containing substances increase biomass production where the availability of phosphorous limits the growth. In other case, biomass production is increased through emissions of N-containing substances. These local variations are not taken into account in this impact assessment.

The category indicator is the potential of the emissions from the system investigated to deplete oxygen in aquatic systems, e.g. through increased biomass production. The potential contribution to eutrophication is in this study expressed as phosphate-equivalents, i.e., the capacity of 1 mg of a substance to favour biomass formation compared to that of 1 mg of phosphate (PO_4^{3-}). Another unit that is used to measure eutrophication NO_x-equivalents. One unit of NO_x-equivalents corresponds to 0.13 g PO_4^{3-}-equivalents.

Oxygen depletion in aquatic systems is caused not only by emissions of nutrients that stimulate the biomass production, but also by direct emissions of organic material that is decomposed in the water. These emissions can be measured in terms of BOD (biological oxygen demand), COD (chemical oxygen demand) or TOC (total organic carbon). They are taken into account in the characterisation of this environmental impact.

The total contribution to the Eutrophication potential from the life cycle is calculated as:

$$\mathrm{EP} = \sum \mathrm{EP}_j \cdot \mathrm{E}_j$$

where E_j is the amount of the output j and EP_j the characterisation factor for this output. The characterisation factors used for eutrophication are measured in *mg* PO_4^{3-}*-equivalents per mg of the emitted substance*. Thus, the unit of the category indicator is *mg* PO_4^{3-}*-equivalents*.

Appendix B. Goal and scope details

B.1 System boundaries

The LCA includes all processes contributing to the environmental impacts of the system investigated.

B.1.1 Boundaries towards nature

For inputs of fuels, electricity and raw materials the cradle of their life cycle is nature. The boundary between nature and the product life cycle is crossed when the natural resource (e.g. crude oil or uranium) is extracted from nature. The “grave” of the life cycle is the air (e.g. emissions from combustion of fuels) or water (e.g. water emissions from wastewater treatment).

B.1.2 Boundaries within the life cycle

Electricity production and the conversion of energy resources into fuels are included in the life cycle system. This means that emissions and natural resource demand from electricity and fuel production are included.

Electricity demand is thus defined as an internal parameter of the system. It is the same for fuels; the fuel used by a process is accounted for as an internal parameter. Thus, the internal parameters are all energy carriers, while the inflows to the system are natural resources such as grot, wood etc.

B.2 Allocation approaches

The following stepwise allocation procedure is required by ISO 14044: 2006:

The first step of the procedure is: "wherever possible, allocation should be avoided by dividing the unit process to be allocated into two or more sub-processes and collecting the environmental data related to these sub-processes, or by expanding the product system to include the additional functions related to the co-products."

The second step of the procedure recommended by ISO 14044: 2006 is: "where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical causal relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products and functions delivered by the system”.

The third and final step of the ISO procedure is: "where physical causal relationships alone cannot be established or used as the basis for the allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.”

Note that ISO 14044 does not require that “other relationships” should be causal relationships. This means that virtually any allocation method is allowed as a final option.

In this study, we have chosen to allocate the environmental impact by expanding the system boundaries.

Appendix C. GaBi data and data creation

All processes are modelled with standard data, except for grot in the biomass, which is modelled with data from Lindholm, Berg, & Hansson (2010). The chosen datasets are described in Table 6.

Table 6. The datasets used in the model.

Resource - Processes raw materials	Dataset in GaBi	Nation	Type	Source	Parent Folder
Generic biomass (energy for the sensitivity analysis)	Thermal energy from biomass (solid)	SE	Agg	Thinkstep	Thermal energy from biomass
Biomass (15% fire wood)	Softwood forestry, spruce, sustainable forest management	SE	Agg	Ecoinvent 3.5	Logging
Biomass (14% bark)	Pine log with bark (70% moisture; 44% H2O content)	DE	Agg	Thinkstep	Products
Feed Water	Process water	EU-28	agg	Thinkstep	Water
Process Water	Waste water treatment (metal processing)	GLO	u-so	Thinkstep	Wastewater treatment
Sand	Sand	DE	LC	Thinkstep	Minerals
Ash	Market for wood ash mixture, pure	Europe without Switzerland	Agg	Ecoinvent	Treatment and disposal of non-hazardous waste
Nitrogen	Nitrogen (gaseous)	EU-28	LC	Thinkstep	Inorganic intermediate products
Propane	Propane at refinery	EU-28	Agg	Thinkstep	Refinery products
Methyldiethanolamine (MDEA)	Methylamine production	RER	Agg	Ecoinvent	Manufacture of basic chemicals

ZNO	Zinc oxide production	RER	Agg	Ecoinvent	Manufacture of basic chemicals
Al_2O_3	Alumina production 2015	EU-28	u-so	IAI	IAI unit processes 2015
Electricity	Electricity grid mix	SE	Agg	Thinkstep	Electricity mixer
Rapeseed Methyl Ester (RME, Scrubber oil)	Rapeseed methyl ester (RME)	DE	Agg	Thinkstep	Products
Flue Gas	Desulfurisation of lignite flue gas	GLO	Agg	Ecoinvent	Electric power generation, transmission and distribution

Appendix D. Load scenarios

In this chapter, the low and high case load are presented in Table 7 and Table 8.

Table 7. Low case per 1 MJ FT-crude produced.

	Mass flow kg	LHV wet MJ
Biomass	0.3	2.663
FT-crude	0.023	1
Flue gas	0.831	
Electricity produced		0.239
Electricity consumed		0.426
Scrubber oil		0.092
District heating produced		1.394
Feed water	0.091	
Process water	0.188	
Sand	0	
Ash	0.00013	
N2	0.000017	
Propane	0.00001	
Adsorbers		
Amine	0.00001	
Guard bed for S	0.000007	
Guard bed for Cl	0.000001	

Table 8. High case per 1 MJ FT-crude produced.

	Mass flow kg	LHV wet MJ
Biomass	0.432	3.93
FT-crude	0.023	1
Flue gas	1.44	
Electricity produced		0.536
Electricity consumed		0.426
Scrubber oil		0.092
District heating produced		2.485
Feed water	0.091	
Process water	0.263	
Sand	0	
Ash	0.00013	
N2	0.000017	
Propane	0.00001	
Adsorbers		
Amine	0.00001	
Guard bed for S	0.000007	
Guard bed for Cl	0.00000067	

Appendix E. Sensitivity Analysis Biomass

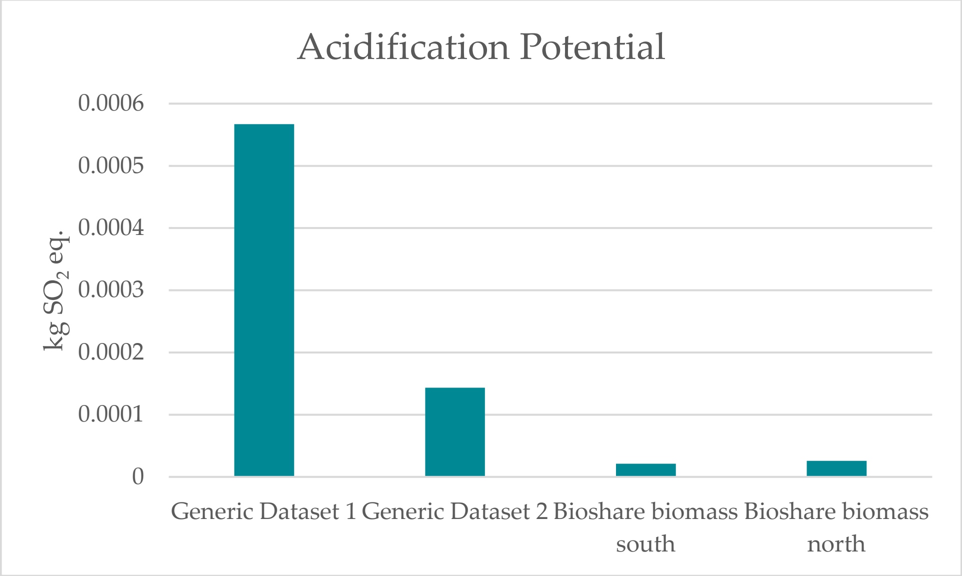

Figure 15. The result from a comparison between the different biomasses contribution on AP. The result shows the impact from each biomass evaluated.

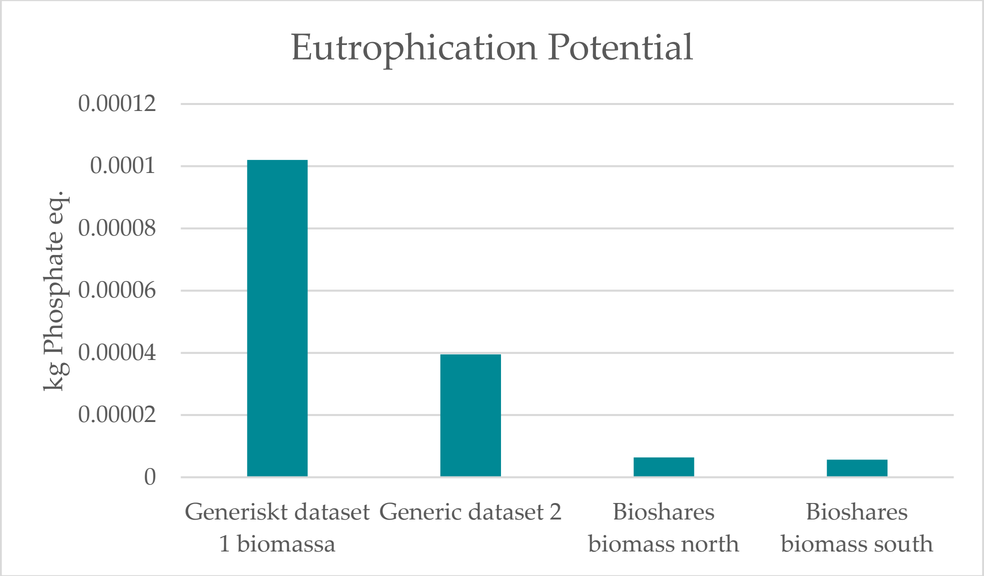

Figure 16. The result from a comparison between the different biomasses contribution on AP. The result shows the impact from each biomass evaluated.

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