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# Life cycle assessment of biosyngas from a multifunctional biomass gasification plant in Sweden

Master's thesis in Industrial Ecology

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Cover: The picture illustrates Meva Energy's gasification facility in Kisa. Picture provided by and printed with permission from Meva Energy

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## SUMMARY

The need to increase the use of renewable energy to meet the growing energy demand and minimize the reliance on fossil fuels is evident. One renewable technology option is bioenergy due to its availability and resemblance to fossil energy carriers. This study aimed to investigate the environmental impacts of a biomass gasification plant by conducting a life cycle assessment (LCA) from cradle to grave, including multiple impact categories and comparing the results to fossil alternatives.

An LCA of Meva Energy's gasification technology that produces biosyngas was conducted with three allocation scenarios. The scenarios consider mass allocation, energy allocation, as well as one scenario where all environmental impact was allocated to the biosyngas production and the carbon sequestration effect of the produced biochar was included.

The gasification system was divided into five sections: (i) the production of the plant components phase, (ii) the construction phase, (iii) the gasification phase, (iv) the use phase and (v) the end-of-life phase. The results showed that the gasification phase and use phase are the primary contributors to all impact categories, while the production of plant components phase, construction phase and end-of-life phase were shown to have negligible impacts. In terms of climate change, the biomass feedstock (wood pellets) in the gasification phase had the largest impact. The total results regarding climate change of the life cycle varied notably depending on the allocation approach applied, with a range from about 23 g CO<sub>2</sub>-eq/kWh for the mass allocation scenario to -6 g CO<sub>2</sub>-eq/kWh for the carbon sequestration scenario.

Furthermore, the results varied also based on secondary material allocation and the classification of products as either waste or by-products. For example, when the sawdust used to produce wood pellets was treated as a waste stream and the emissions started upon the collection of the sawdust, the environmental impact was reduced. Moreover, considering the produced tar as a by-product rather than a waste stream had a lower but notable influence on the results, especially in the energy allocation scenario.

The findings of this study highlight that energy produced by Meva Energy's gasification technology can contribute to a climate positive impact, assuming that the application of the biochar equates a negative emission. The study also shows that the thermal energy produced by this gasification of biomass has lower climate-change impacts than the fossil alternative (liquid petroleum gas).

Keywords: Biochar, Biosyngas, Gasification, Life cycle assessment (LCA), Climate change



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# Abbreviations

<b>Abbreviation</b>	<b>Definition</b>
ALCA	Attributional life cycle assessment
CFF	Circular Footprint Formula
CPH	Combined heat and power plant
EF	Environmental footprint
EFTA	European free trade association
EU	European Union
EPD	Environmental Product Declaration
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
HVO	Hydrotreated vegetable oil
IAI	International aluminium institute
iLUC	Indirect land use change
ISO	International organization for standardisation
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LHV	Lower heating value
LPG	Liquid petroleum gas
OEF	Organisational environmental footprint
PEF	Product environmental footprint
PEFCR	Product environmental footprint category rules
RED II	Renewable energy directive II
SOC	Soil organic carbon

# 1 Introduction

There is a strive towards an increased use of renewable energy to meet the growing energy demand and reduce the reliance on fossil fuels. The anticipated emissions from fossil energy production are projected to reach approximately 640 million metric tons of carbon by the year 2100 (AINouss, et al., 2020). The energy sector is responsible for over 75% of the European Unions (EU) greenhouse gas (GHG) emissions and is therefore a key sector to reach the Fit for 55 package, which is a set of adopted policies from the EU to reduce net GHG emissions by at least 55% by 2030 (Regeringskansliet, 2023; European Commission, n.d). Consequently, the EU has established binding targets, mandating a minimum of 42.5% renewable energy in their overall energy consumption by 2030 (European Commission, n.d.). To reach the set target and secure the energy supply, a priority is to develop and expand alternative solutions to conventional fossil-based energy generation (AINouss, et al., 2020).

There are several common renewable energy sources, including hydropower, solar energy, wind energy, geothermal energy, and bioenergy. The potential of bioenergy has been recognized due to its availability and its carbon-neutral potential in relation to global warming (Kirubakaran, et al., 2009). This is because the carbon emissions from bioenergy are biogenic, potentially making it part of the natural carbon cycle.

Bioenergy production is the process where energy from biomass is converted by either bio-chemical or thermo-chemical processes (Tezer, et al., 2022). The bio-chemical processes include bio-methanization while thermo-chemical processes include combustion, pyrolysis and gasification. Since a cleaner gas is obtained from gasification compared to the other thermo-chemical processes, gasification has an important role in future bioenergy provision (Tezer, et al., 2022).

The company Meva Energy has created a renewable energy gasification technology that is built on site next to customers (Meva Energy, n.d.). The company was founded in 2008 and has since then developed technology within thermo-chemical process engineering, gasification and biosyngas cleaning. Their vision is to make better use of local biomass waste from the manufacturing industry. This foremost includes low-quality second-generation biomass that is converted into high-quality biosyngas for heat and power generation or process heating in the manufacturing industry. Today, Meva Energy has one operational plant in Kisa, Sweden, that produces biosyngas to replace liquefied petroleum gas (LPG) in a paper industry. Additionally, there is one plant planned in Zbaszynek, Poland, for a furniture manufacturing company.

Meva Energy's gasification plant in Kisa contains a multifunctional process that produces mainly biosyngas used for process heating but also biochar as a by-product. Their concept involves taking care of a locally-generated waste stream to produce and sell biosyngas while also selling the biochar. Through the production and utilization of biochar, the company contributes with a potential carbon sink product, while simultaneously gaining an additional business (Meva Energy, n.d.).

Meva Energy wanted to gain a better understanding of the environmental impact of its biomass gasification technology. A recognized tool to quantify the environmental impact of a product is life cycle assessment (LCA). Therefore, an LCA from cradle-to-grave was carried out to evaluate Meva Energy's gasification process.

The aim of this study was to quantify the environmental performance of the gasification process constructed and operated by Meva Energy. This was done by developing an LCA model from cradle to grave. Different methodological choices in the LCA were investigated to determine their influence for the case of a multifunctional gasification process. This includes evaluating the influence of different by-product allocation approaches, such as mass and energy allocation. Additionally, one scenario was investigated where all environmental impact was allocated to the biosyngas production and the carbon sequestration effect of the produced biochar is included. The results from the LCA were used to identify hotspots within the system, which can help future efforts toward reducing environmental impacts. Furthermore, the results were compared to fossil alternatives. The research questions of the study were:

1. What is the environmental performance of Meva Energy's biomass gasification plant for biosyngas production used for process heating to replace fossil gas in Kisa?
2. In which stages of the life cycle does the most environmental impact occur?

## 2 Background

This section covers the background about the carbon cycle and biochar, challenges of biomass as an energy source, gasification of biomass and a literature review of previous LCA studies on the topic. Furthermore, the LCA framework, its key features and different LCA directives are described.

### 2.1 The carbon cycle and biochar

The carbon cycle starts with the removal of carbon from the atmosphere through photosynthesis, which is then released back upon biomass decay (Azzi, et al., 2023). When instead energy is derived from biomass feedstock through pyrolysis or gasification, a share of the feedstock is transformed into gases and liquids. Upon combustion, these products release biogenic carbon back into the atmosphere (Figure 1).

During this thermo-chemical transformation, a fraction of the remaining carbon in the biomass forms a highly stable organic material called biochar. Biochar mainly consists of aromatic structures holding extracted carbon from the atmosphere. The produced biochar can be placed in soil where it can help regulate disadvantageous soil acidity/alkalinity/salinity as well as remediate contaminated soil (Palansooriya, et al., 2019). It can also increase the preservation of soil organic carbon (SOC) and water content which can lead to higher crop yield. A study by Sanei (2024) reports that it takes thousands of years before the biochar releases half of its carbon content back to the atmosphere, making it function as a carbon sink. However, due to regulatory reasons in the EU concerning fertilising products, biochar may need to be used for other applications instead, for example to replace fossil carbon in iron and steel production (Maeng, et al., 2024; European Parliament, 2019).

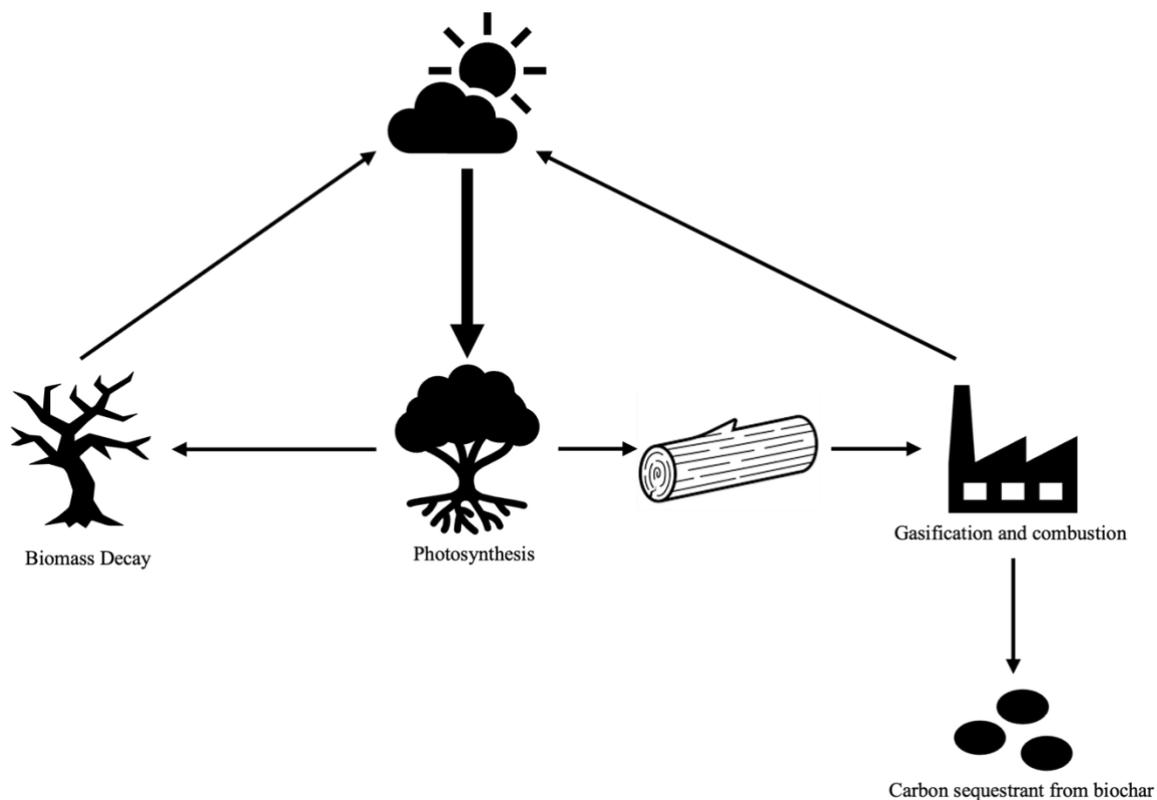


Figure 1: The alternative ways for the carbon cycle: biomass decay and thermo-chemical conversion through gasification. The arrows represent the carbon flows between the processes. Figure produced by the authors.

## 2.2 Challenges of biomass energy

Using biomass as an energy source aims to reduce GHG emissions. However, there are some environmental and social concerns relating to bioenergy. One example is the occupation of land, which can compete with other sustainable development goals (SDG), such as food security and biodiversity conservation (Vera, et al., 2022). It is therefore important to ensure sustainable management of biomass to not counteract the climate-advantageous factors associated with bioenergy (Ladanai & Vinterbäck, 2009). This includes developing and following criteria related to sustainable management of biomass feedstock to minimize the negative impact it might have on biodiversity and minimize land competition.

Further solutions include mapping and respecting biodiversity areas and cultivating bioenergy feedstock in low-risk areas (Usmani, et al., 2021). Another alternative involves utilizing waste streams from, for example, the food industry or manufacturing industry. However, for handling of food waste, it is important to ensure that no further use of the food waste is possible before it is utilized as a biomass waste stream (Energy Transitions Commission, 2021).

Another challenge for the biomass energy sector is to efficiently manage the supply chain and logistics of biomass (Nunes, et al., 2020). A large cost of biomass energy comes from logistic operations. Therefore, transporting high volumes of low-density biomass from production sites to facilities and finally to the customer requires a lean and efficient supply chain to lower the cost. An alternative is to reduce the transport distance from the supplier of biomass to its utilization by relying on more local biomass supply (Nunes, et al., 2020).

## 2.3 Gasification of biomass

Thermo-chemical conversion processes enable the use of chemically stored energy in biomass. The conversion processes can be either direct with combustion or indirect by pyrolysis or gasification (Sistek, 2021). When gasifying biomass, the organic feedstock is turned into biosyngas and the solid by-product biochar (Molino, et al., 2016). The energy carriers in biosyngas produced via biomass gasification are a mix of hydrogen ( $H_2$ ), carbon monoxide (CO), methane ( $CH_4$ ), but also contains biogenic carbon dioxide ( $CO_2$ ). Additionally, hydrocarbons such as tars, propane, and ethane are produced. The presence of unwanted gases in the biosyngas, such as nitrogen ( $N_2$ ), hydrochloric acid (HCl), ammonia ( $NH_3$ ) and hydrogen sulfide ( $H_2S$ ) are dependent on the gasification technology and type of biomass used. The gasification process demands a substantial energy input due to the endothermic nature of the reaction (Ahmad, et al, 2016). Given the considerable energy consumption involved, efforts to optimize and improve the process are important for ensuring the continuous development of gasification processes.

The produced biosyngas can further be used for oxidization by adding a sufficient supply of oxygen, thereby generating thermal energy (Sistek, 2021). The products of the oxidation reaction of biosyngas depend on the supply of oxidant. Given an insufficient supply of oxidants, CO alongside other non-oxidized, unoxidized or partially oxidized higher hydrocarbon compounds are generated. Contrary, if there is a sufficient supply of oxidants, full oxidation of biosyngas occurs, generating biogenic  $CO_2$  and water ( $H_2O$ ). The generated thermal energy in the biosyngas can, for example, be used to replace fossil LPG or oxidized to generate electricity in a generator.

The GHG emissions from LPG, which could be substituted by biosyngas, vary depending on the source. According to the Renewable Energy Directive II (RED II), the fossil equivalent to biofuels utilized for generating useful heat (including then LPG) have GHG emissions of 80 g  $CO_2$ -eq/MJ, equivalent to 288 g  $CO_2$ -eq/kWh (Energimyndigheten, 2021). The Swedish Environmental Protection Agency provides a guideline value of similar magnitude, about 234 g  $CO_2$ -eq/kWh, for the combustion of LPG (Naturvårdsverket, 2024).

## 2.4 Previous LCAs on gasification technologies

In 2017, K ppler did an LCA study on the gasification technology used by a company in Austria (K ppler, 2017). The LCA was performed with a cradle-to-grave perspective and investigated the environmental impact of producing thermal energy and electricity from a wood chip feedstock. The functional unit (FU) was set to 1 kWh of energy as heat and electricity. What differentiates K ppler's study from previous LCAs on heat and power gasification plants is that it includes the environmental impact from constructing and operating the local heating network, as well as the entire supply chain of wood chips. The investigated plant by K ppler is designed for 29% electricity production, 55% heat production, and 10% biochar production in relation to energy content from the feedstock input. (Due to energy losses, the electricity, heat and biochar production do not match the 100% of energy content from the feedstock input.)

K ppler (2017) did not investigate any by-product allocation approaches. Instead, all environmental impact was assigned to the production of heat and electrical energy. Two results were presented, one where biochar was considered a carbon sink and one where it was not. In the results presented, the production of energy from the gasification plant has an overall negative climate impact at about -37 g CO<sub>2</sub>-eq/kWh when the carbon sequestration effects of the produced biochar are included. When the carbon sequestration effects of biochar were not included, the investigated process caused 28 g CO<sub>2</sub>-eq/kWh.

The same year, Gu and Bergman (2017) performed an LCA of a renewable natural gas system producing electricity from syngas. Different from the study by K ppler, this study placed the manufacturing of needed construction facilities outside of the system boundaries. The FU was set to 1 kWh of electricity generated. Gu and Bergman allocated all environmental burden to the syngas and included the carbon sequestration effects of the produced biochar. The result was 330 g CO<sub>2</sub>-eq/kWh electricity. The reasons for this comparatively high value are that this gasification technology requires much energy to convert biomass to electricity and 61% of the 16.51 MJ needed to produce 1 kWh of electricity came from non-renewable resources.

Costas et.al (2022) performed a sustainability assessment of the whole biomass-to-energy chain of a combined heat and power plant (CHP) in Italy based on biomass gasification. The unit assessed was designed to produce 20 kW of electric power and 40 kW of thermal power in nominal conditions using a mixture of wood chips and olive branch waste as feedstock. The results are estimated at 8 g CO<sub>2</sub>-eq/MJ, which the author argues demonstrates the benefits related to a short-range supply chain of biomass considered in this study. 8 g CO<sub>2</sub>-eq/MJ equals 29 g CO<sub>2</sub>-eq/kWh, which is close to the results of K ppler without carbon sequestration.

In 2021, an LCA was conducted as an extension of K ppler's previous study. The FU was defined as 1 kg of wood chips utilized as fuel feedstock (Sistek, 2021). Economic allocation was applied to the two primary products, biochar and syngas, leading to an allocation of 64% of the impacts to syngas. The syngas was assessed to have a global warming impact of about 45 g CO<sub>2</sub>-eq/kg of wood chips, accounting for a 40% water content. Subsequently, the syngas was divided between heat production at high temperatures and electricity generation. The impact allocated to heat production at high temperatures was 3.6 g CO<sub>2</sub>-eq/MJ (or 12.96 g CO<sub>2</sub>-eq/kWh), whereas electricity production resulted in about 14 g CO<sub>2</sub>-eq/MJ (or 50.4 g CO<sub>2</sub>-eq/kWh) of electricity generated. A summary of the reviewed LCA studies is shown in Table 1.

Table 1: Comparison of LCA studies on biomass gasification.

	<b>Scope definition</b>	<b>Allocation</b>	<b>Impact assessment method</b>	<b>Climate impact per FU</b>
Käppler (2017)	FU: 1 kWh as heat and energy  Type of plant: Gasification plant  Geographical region: Austria	All environmental burden assigned to the syngas	ReCiPe 2016	-37 g CO <sub>2</sub> -eq/kWh with carbon sequestration of biochar  28 g CO <sub>2</sub> -eq/kWh without carbon sequestration of biochar
Gu and Bergman (2017)	FU: 1 kWh of generated electricity  Type of plant: Renewable natural gas unit with biomass pyrolysis  Geographical region: United States	All environmental burden assigned to the syngas	TRACI 2.1	330 g CO <sub>2</sub> -eq/kWh
Costas et.al (2022)	FU: 24 kg biomass fuel per hour  Type of plant: Heat and power plant  Geographical region: Italy	Not stated	EDIP	29 g CO <sub>2</sub> -eq/kWh
Sistek (2021)	FU: 4.47 MJ of heat  Type of plant: Gasification plant  Geographical region: Austria	Economic allocation:  64% to syngas  36% to biochar	ReCiPe 2016	12.96 g CO <sub>2</sub> -eq/kWh

## 2.5 Life cycle assessment methodology

The study broadly follows the LCA framework of the International Organization of Standardisation (ISO) (2006) standard to assess the environmental impacts. The LCA methodology according to the ISO14040 and ISO14044 standards involves four steps: (i) Goal and scope definition, (ii) inventory analysis, (iii) impact assessment and (iv) interpretation of results. In Figure 2, the four steps of an LCA and their interplay are illustrated.

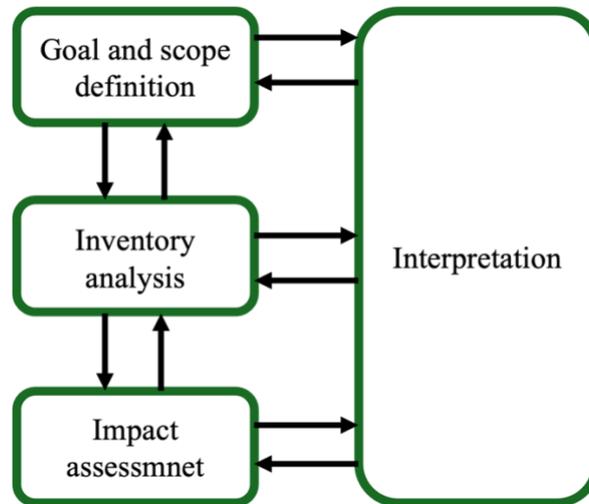


Figure 2: The four steps of LCA-framework according to the ISO standards. Figure produced by the authors based on Hauschild (2018).

The first step is the goal and scope definition. This step is performed to define the purpose of the study, which questions to answer and for whom it is performed (Hauschild, 2018). The scope involves defining a FU, choosing impact categories and impact indicators, deciding on the handling of multifunctional processes, choosing data quality requirements and setting up the system boundaries.

The second step is the inventory analysis, which involves collecting data on the inflows of resources as well as the outflows of waste and emissions from the system (Hauschild, 2018). All the identified processes belonging to the system are analysed and quantified with the help of a reference flow that is based on the selected FU. A flowchart is created to illustrate the product system investigated.

Impact assessment is the third step and translates the inventory flows of the product system into environmental impacts (Baumann & Tillman, 2004). The impact assessment involves impact category definition, classification, characterization, and sometimes normalization and weighting. Impact category definition is a selection of impact categories and models of cause-effect chains with associated endpoints. Classification is a process in which the elementary flows from the inventory are assigned to impact categories according to their environmental impact contribution. Moreover, characterization involves quantifying the contribution of the flows to relevant impact categories. The impact scores are expressed in units relevant to each impact category. The optional normalization step is performed to better understand the magnitude of each impact category by expressing them in relation to a reference point, such as the highest result obtained among a set of products studied. Lastly, weighting is the final optional step of the impact assessment, during which a comparison of the impact categories can be performed to identify the most important categories (Hauschild, 2018).

Interpretation is the final step in the LCA framework, where the results from the inventory analysis and impact assessment are analysed to answer the questions asked in the goal definition. Hotspots and other information to support decision-making are identified in this step (Hauschild, 2018). To test the robustness of the study, uncertainty analysis and sensitivity analysis are additionally performed during the interpretation step.

## 2.6 LCA directives

As stated in Section 2.5, this LCA broadly follows the ISO 14040 and 14044 methods. However, there exist several directives containing guidelines on how to perform an LCA. To investigate possible methodological choices for LCA of a multifunctional bioenergy system, two additional directives were investigated in addition to the ISO standard: The Renewable Energy directive II (RED II) and the Environmental footprint (EF) method. These directives have been chosen after dialogue with Meva Energy based on the directives' common use and relevance to gasification. This section summarizes their methodological guidelines, specifically focusing on the definition of FU, handling of multifunctionality and impact assessment methods.

### 2.6.1 ISO14040 and 14044

ISO 14040 and 14044 are standards developed by the International Organization of Standardization, describing principles, frameworks and guidelines for LCAs. The ISO standard recommends that the functional unit for an LCA study should be defined in line with the goal of the study (Ahlgren, et al., 2015).

Regarding allocation, the ISO standard recommends that allocation should preferably be avoided by increasing the level of detail in the system or, if this is unfeasible, by system expansion (Ahlgren, et al., 2015). In cases where allocation cannot be avoided, ISO states that allocation should preferably be based on physical relationships or, alternatively, on other relationships (e.g., economic).

The ISO standards does not prescribe a specific life cycle impact assessment method (LCIA) (Jannes, et al., 2023). Instead, different impact categories can be used depending on the goal of the study, for example climate change, acidification and eutrophication (Ahlgren, et al., 2015).

### 2.6.2 Renewable Energy Directive II

RED II is an initiative to implement more renewable energy in the EU (European Commission, n.d.). The goal of the directive is to have a renewable energy consumption of 32% by 2030. When investigating the environmental impact of an energy production system, RED II states that the FU should be set to 1 MJ of fuel (Ahlgren, et al., 2015).

According to RED II, allocation should be performed by partitioning based on the products lower heating value (LHV), whereas system expansion should only be used for excess electricity (Ahlgren, et al., 2015). Using LHV as the basis for allocation may encounter challenges, particularly since wet materials such as heat and steam may have a low LHV, sometimes even a negative value. The issue could be solved by using exergy as the basis for allocation. However, this would leave some products unrecognized, such as plastics and wood, since the exergy for carbon-containing molecules is based on oxidation (Meester, 2013).

For secondary material allocation, RED II recommends a cut-off approach where waste and agricultural residues do not contribute to any GHG emissions before the process of waste collection (European Union, 2018). The RED II directive does not recommend a special LCIA, since it only considers emissions of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O, which contribute to global warming (Ahlgren, et al., 2015). These emissions are aggregated according to a characterizing factor where fossil CO<sub>2</sub> has the value of 1, CH<sub>4</sub> 23 and N<sub>2</sub>O 296 for 100-year global warming potential (GWP100) (Erlandsson & Martin, 2018). In addition, land use change should be accounted for but only if the land use is not classified as farmland (Ahlgren, et al., 2015). Regarding indirect land use change (iLUC), it is categorized into high iLUC and low iLUC. High iLUC biomass fuels include fuels with a significant expansion in land with high carbon stocks and therefore cannot be accounted for towards member states' renewable energy targets. Low iLUC areas can be certified to ensure sustainable production of bioenergy (European Commission, n.d.).

### 2.6.3 Environmental Footprint methodology

The Environmental Footprint (EF) method consists of both the Product Environmental Footprint (PEF) and the Organizational Environmental Footprint (OEF) methods. It is a proposal from the European Commission to reach a common way of assessing environmental performance (European Commission, n.d.). No specific FU is proposed, but the EF gives guidance on how the functional unit should be formulated depending on the aspects "what", "how much", "how well" and "how long" (Ahlgren, et al., 2015).

By-product allocation in the EF methodology follows the same guidelines as in the ISO standards (Ahlgren, et al., 2015). However, it gives some specific examples that system expansion should only be applied if a direct substitution effect can be robustly modelled. To allocate the environmental burden of waste and recycled materials in a system, the Circular Footprint Formula (CFF) should be used, which is a particular equation developed within the EF method.

Moreover, the EF methodology has its own LCIA called EF3.1 LCIA (Andreasi Bassi, et al., 2023). In the EF3.1 LCIA, the inventory data is aggregated into 16 characterized midpoints categories, which can be normalized and weighted. The weighted impact categories can then be summed to obtain an EF single overall score.

The PEF provides Product Environmental Footprint Category Rules (PEFCRs) to be able to compare products (Jogner & Nojpanya, 2021). The PEFCRs provide methodological rules on how to assess products within the same category at a process and/or a product level. By using PEFCRs, the quality and consistency of the PEF assessment can be improved. Different product category rules have been developed during the PEF's transition phase. However, there are currently no specific PEFCRs available for bioenergy (European Commission, n.d.).

## 3 Technical system under study

This section describes Meva Energy's gasification technology for biosyngas and biochar production. Meva Energy has provided this study with information regarding their plant in Kisa. To gain further information, both academic and grey literature have been consulted. The system under study has been divided into five phases. These are (i) the production of plant components phase, (ii) the construction phase, (iii) the gasification phase, (iv) the use phase and (v) end-of-life phase.

### 3.1 Production of plant components phase

The production of plant components phase includes the production of materials and components used in the gasification plant building in Kisa. This covers the entire process from extracting raw materials to producing the materials and components necessary for constructing the plant and related transports.

The materials produced for the gasification plant in Kisa include:

- Concrete for the foundation
- Iron rebars for the foundation
- Carbon steel for structural steel and gasification equipment
- Stainless steel for underground pipes and gasification equipment
- Stone wool for insulation in façade and roofing
- Aluminium for façade and roofing
- Electrical cables

### 3.2 Construction phase

The construction phase involves the construction of the plant as well as the installation and assembly of all parts needed to run the gasification process. In this phase, the use of electricity and fuel are the main inputs.

### 3.3 Gasification phase

Wood pellets from a local supplier are used as feedstock to produce biosyngas. The supplier treats and compresses sawdust from nearby sawmills under high pressure to create wood pellets. Once the pellets are manufactured, they are transported to Meva Energy's gasification plant and stored in a silo. The pellets from the silo are transferred into the gasification plant and milled into biomass powder. In the plant, the bio-powder goes from atmospheric pressure to overpressure and is placed into two feeding tanks with a feeding screw. While one tank is being filled, the other is feeding the reactor, always keeping the system running and maintaining the needed pressure.

Inside the gasification reactor, there is about 1000°C and an oxygen-controlled environment that converts the biomass into biosyngas. An airblower blows a continuous air stream from two sides, which picks up the biomass powder and creates a cyclone inside the reactor. To initiate the gasification process, the reactor needs to be preheated with LPG. Approximately 3-5% of the biomass inputs are transformed into biochar. The biochar leaves the reactor at the bottom via a rotating screw and is then collected and stored in big bags.

The biosyngas exits the reactor to be cooled and cleaned. During the cleaning process, water is added to capture tar particles generated during the gasification. The mixed tar and water are collected at the bottom of the gas cleaner. To effectively separate the tar from the water, organic extraction solvents are added, specifically Alkaline N10-N13. The separated tar is dried in a decanter centrifuge and today sent off for waste management. However, the plant is designed to feed the tar back into the gasification reactor as it still is possible to extract energy from the tar, which would result in increased efficiency

and less waste management. Once the extraction solvent reaches full saturation, they are returned to the reactor to be gasified.

To avoid moisture in the downstream system after the cooling process, the cleaned biosyngas undergoes a superheating process. The final step before the biosyngas can be used as heat involves its passage through a polishing filter, removing the remaining particulate matter. Figure 3 graphically illustrates Meva Energy's gasification process in Kisa.

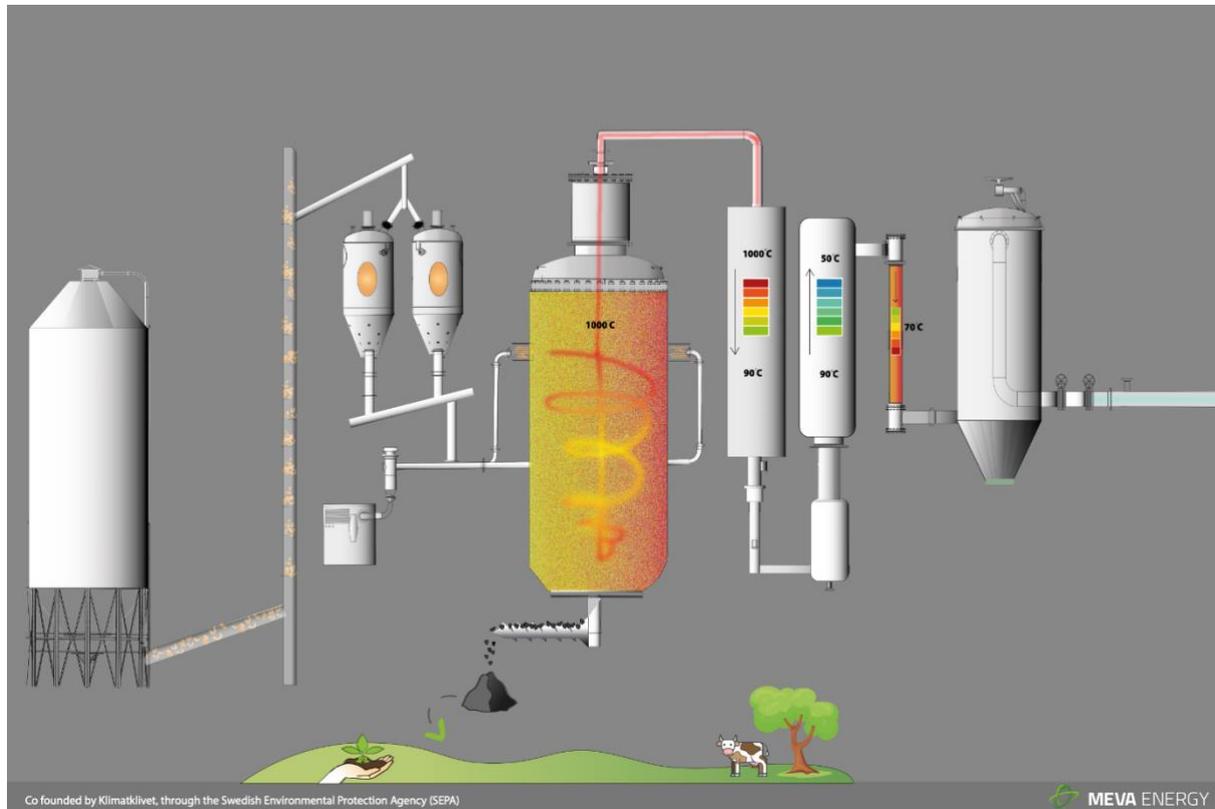


Figure 3: The system process of Meva Energy's gasification plant in Kisa. Reprinted with permission from Meva Energy.

### 3.4 Use phase

The biosyngas from Meva Energy's facility in Kisa is delivered as gaseous fuel and combusted at the consumer to generate heat. The produced and collected biochar is assumed to be used as soil amendment. Since, the biochar is assumed not to be combusted, its long-term bound carbon content can function as a carbon sink (Azzi, et al., 2023).

### 3.5 End-of-life phase

The life of biosyngas and biochar ends when they are consumed (or, for the biochar, applied) in the use phase, so it does not enter the end-of-life phase. However, the end-of-life phase involves the dismantling and waste management of the gasification plant.

## 4 Goal and scope definition

The goal of this LCA study is equivalent with the aim formulated in Section 1. The focus of this study was Meva Energy's gasification plant producing biosyngas for process heating based on data from the Kisa plant. An attributional LCA (ALCA) was conducted to analyse the environmental impacts associated with the plant from cradle to grave, including (i) the production of plant components phase, (ii) construction phase, (iii) gasification phase, (iv) use phase and (v) end-of-life phase. An ALCA is an LCA aiming to evaluate how much of the global environmental impact that belong the product under study (Ekvall, 2020).

The intended audience for this study was Meva Energy, as it offers insights into the environmental performance of their technology and suggests potential improvements to reduce their environmental impact. In addition, other producers and customers of biosyngas may find this study useful, as well as LCA practitioners working with multifunctional biomass energy systems.

### 4.1 Functional unit

The main function of the gasification plant is to produce biosyngas for energy purposes. The ISO standards and EF-methodology have no recommendations on which specific FU to apply. In this study, the FU was set to 1 kWh. This does not align with the recommendation of RED II to have the FU set to 1 MJ of fuel. However, several previous LCA studies on gasification process (Käppler, 2017; Gu and Bergman, 2017) had the FU set to 1 kWh. Additionally, 1 kWh can easily be converted to fit RED II's recommended FU of 1 MJ.

For the investigated scenario including the carbon sequestering effects of the produced biochar, an additional FU was defined. For this scenario, the FU was 1 kWh plus 9.3 g of produced biochar, because for every 1 kWh of produced biosyngas, 9.3 g of biochar is produced in Meva Energy's gasification system. In this scenario, the by-product is not 'removed' from the product system by allocation but instead included in the functional unit.

### 4.2 System boundaries

The system under study was divided into five main parts as mentioned in Section 3. An overview of the system under study can be found in Figure 4. The background system is the grey area and includes processes outside of Meva Energy's direct influence. In the background system, Meva Energy can decide on suppliers but not directly influence the environmental impact. The foreground system is the white area and includes the processes under direct control of Meva Energy.

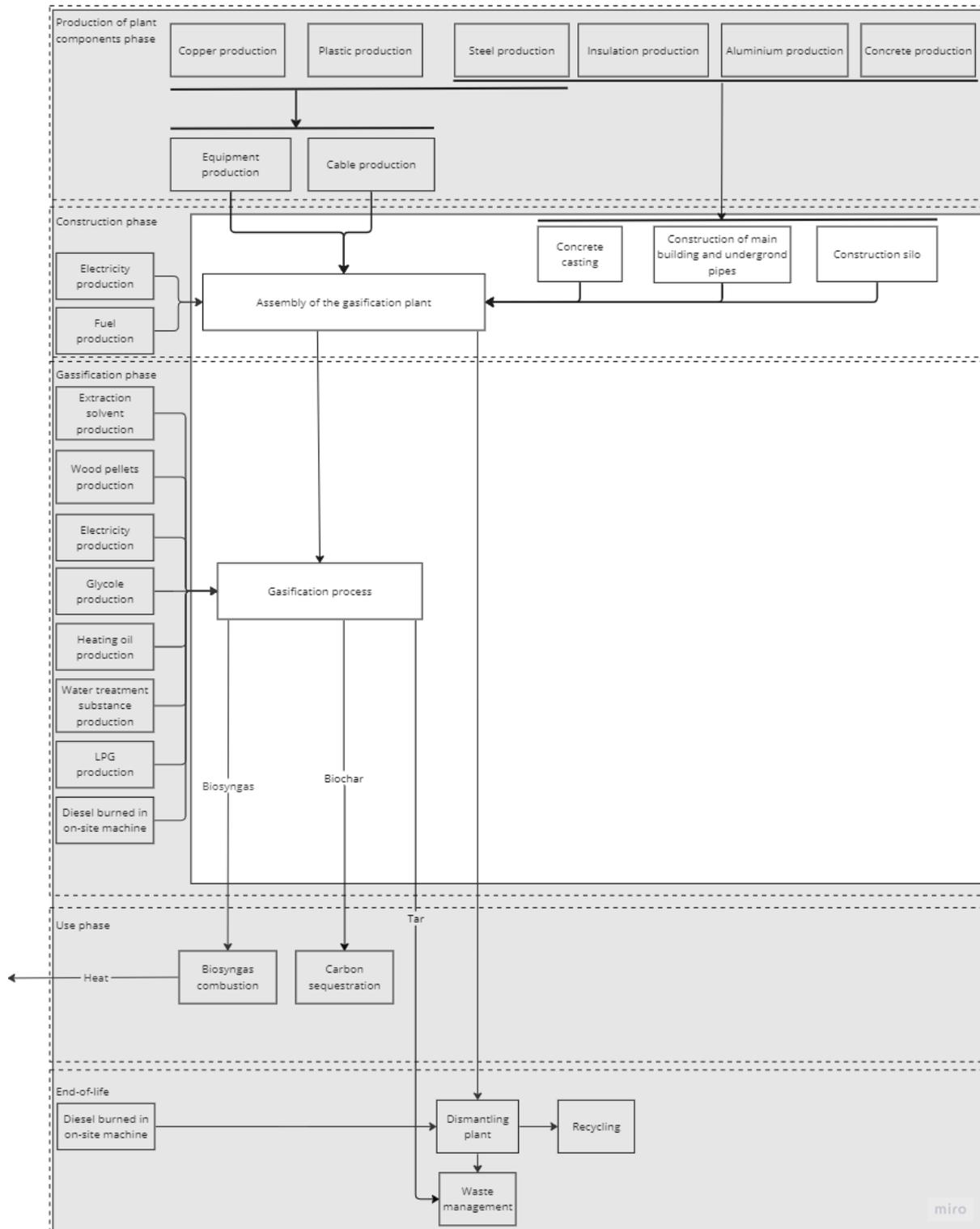


Figure 4: Flowchart of Meva Energy's system with background system in grey and foreground system in white. Figure produced by the authors.

The combustion of biosyngas is not necessary for the production of biochar itself. Therefore, all emissions in the use phase were allocated to biosyngas in the allocation scenarios. However, inputs to the gasification and waste treatment of the tar were allocated between the two products. The allocation boundary is illustrated in Figure 5.

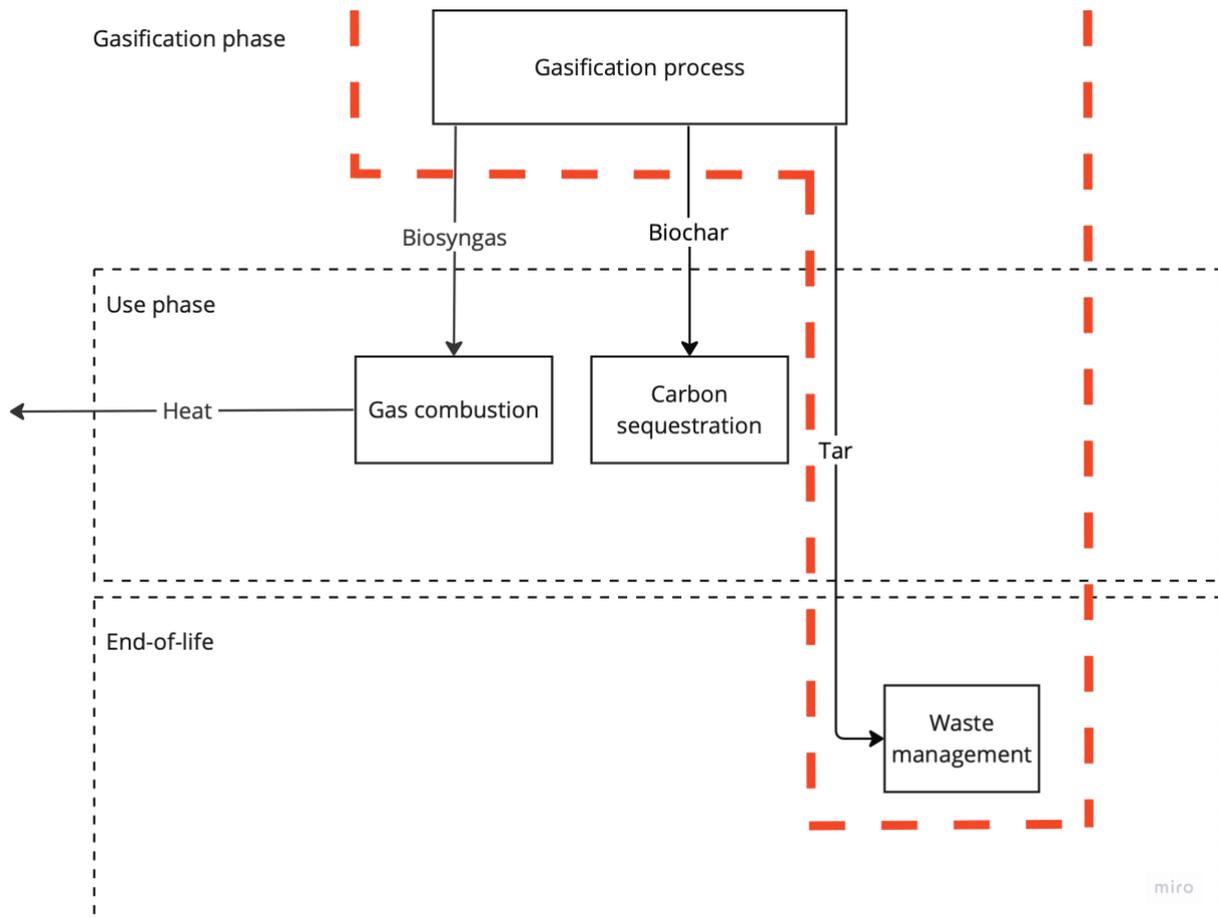


Figure 3: Allocation boundary. The red line illustrates where allocation position occurs. Figure produced by the authors.

#### 4.2.1 Geographical boundaries

The geographical focus was set to Sweden as this is where the gasification plant is located. Meva Energy's business plan revolves around having a local biomass feedstock. Therefore, the wood pellets supplier is located nearby and the forest is harvested in Sweden. However, many of the inputs like LPG and carbon steel are sourced and produced outside of Sweden.

#### 4.2.2 Temporal boundaries

The time horizon has focused on the present and near future, using as current data as possible. This LCA has not accounted for future changes regarding electricity mix, optimization of the plant and changes in emissions from transportation. However, data representing different future scenarios could easily be implemented in the developed LCA model in the future, if found relevant. There is no exact known lifespan of Meva Energy's gasification technology. An approximate lifespan of the gasification plant was estimated at 30 years based on discussions with Meva Energy.

#### 4.2.3 Technical boundaries

Meva Energy's technology is multifunctional and provides two different products: biosyngas and biochar. Arvidsson and Ciroth (2021) mention that there is no generally accepted solution for handling the multifunctionality problem. However, it is generally recognized that different allocation approaches can influence the results of an LCA depending on the exact position of the multifunctional process in the products flow chart. It is therefore important to select a relevant allocation method to allocate the environmental burden per product.

As mentioned in Section 2, the directives considered suggest different approaches on how to handle the multifunctionality of a system. Therefore, it was decided to investigate three different scenarios

regarding by-product allocation between biochar and biosyngas. These three scenarios are (i) mass allocation, (ii) energy allocation, where the allocation is based on the LHV and (iii) one scenario where the system was not seen as multifunctional. Instead, all emissions were allocated to the production of biosyngas and the carbon sequestration effect of biochar was included as a negative emission value in the inventory analysis.

### 4.3 Data acquisition

Data from the Ecoinvent v.3.10 database have been used for most processes in this LCA. The Ecoinvent database has been integrated into the OpenLCA software, where additional processes representing the foreground system have been created manually based on specific information from Meva Energy or its suppliers. The datasets from Ecoinvent have been used with the allocation procedures as pre-defined in each process.

Datasets from Ecoinvent was compared to Environmental Product declarations (EPD) for similar processes to verify the datasets. The environmental impacts of these processes have been exported to Excel, where an LCA model was developed. This way, Meva Energy can replace generic data with more specific data as it becomes available.

Inputs for the amount of materials, energy usage, and transport distances have been provided by Meva Energy. When information was unavailable, assumptions were made for the inputs.

### 4.4 Impact categories and indicators

There is a range of LCIA methods available and the suggested methods according to the considered directives are described in Section 2.6. Previous studies have shown that the choice of LCIA method can influence the results notably (Jannes, et al., 2023). These differences arise due to variations in the environmental pathways considered, the temporal and regional scales considered and the research focus of the institution developing the LCIA method.

A common LCIA method is the ReCiPe method, which includes environmental impact categories at both midpoint and endpoint levels, with 18 midpoint impact categories and 3 endpoint impact categories (Köppler, 2017). According to a study in 2020, where methodological choices in assessments of bio-energy systems were evaluated, ReCiPe was the most commonly used LCIA method (Martin-Gamboa, et al., 2020). For this reason, and since the ISO standards does not prescribe a specific LCIA method, ReCiPe 2016 with a hierarchist perspective has been chosen as the LCIA method for this study. The hierarchist perspective was chosen because it is based on the most common policy principles with regards to timeframe and is considered the default model (Huijbregts, et al., 2017).

The global warming category was in focus for this study. However, four additional midpoint impact categories were chosen because of their relevance to the system under study and frequent use in other published LCAs on gasification processes (Köppler, 2017; Sistik, 2021). The five selected midpoint categories were global warming, terrestrial acidification, freshwater eutrophication, land use and particulate matter, which are further described below.

#### 4.4.1 Climate change

GHG released into the atmosphere can trap incoming solar radiation, which otherwise would have radiated back into space, thereby contributing to anthropogenic global warming. This impact category was chosen since most processes within the system contribute to emitting GHG. The impact category climate change is also included in this study because the RED II includes global warming as the only impact category. Additionally, climate change is one of the impact categories included in the EF methodology.

#### 4.4.2 Terrestrial acidification

Terrestrial acidification is associated with SO<sub>2</sub> and NO<sub>x</sub> emissions, mainly from burning fossil fuels (European Environment Agency, 2020). NO<sub>x</sub> emissions often occur from vehicles such as trucks and cars (United States Environmental Protection Agency, n.d.). In the value chain of producing Meva Energy's biosyngas, several transports are included that cause NO<sub>x</sub> emissions. In addition, the combustion of the biosyngas causes NO<sub>x</sub> emissions. Acidification is an impact category included in the EF methodology and was therefore included in this study.

#### 4.4.3 Freshwater eutrophication

Eutrophication is often associated with a shift in species composition and increased biological productivity (e.g., algal blooms) caused by the release of nutrients, mainly nitrogen (N) and phosphorous (P). The impact category was examined due to the inclusion of eutrophication in similar LCA studies (Gu and Bergman, 2017; Sistek, 2021)

#### 4.4.4 Land use

Since Meva Energy uses wood pellets as feedstock, there is harvesting of forests included in the value chain, causing occupation and/or transformation of land for a specific use. This can have an indirect and direct impact on biodiversity, life support functions and potential future uses of the land (Ahlgren, et al., 2015).

#### 4.4.5 Particulate matter

Particulate matter covers fine particles emitted directly as well as NO<sub>x</sub> and SO<sub>2</sub> (IFEU, n.d.). Meva Energy's gasification plant causes emissions of particulate matter during the combustion of biosyngas. Additionally, emissions of particulate matter could occur further upstream in the supply chain of wood pellets.

### 4.5 Limitations and assumptions

Meva Energy's gasification plant in Kisa is not yet operating at full capacity, while this LCA was based on the expected full capacity of the plant. As the plant has not reached its full operational capacity, there are uncertainties in this LCA study. There is a reliance on tests and assumptions for parameters such as the amount produced biosyngas, the ratio between produced biosyngas and biochar, and energy use within the plant. These parameters might contribute to a different result than if an LCA was carried out once the plant is fully operational.

Another limitation is that for some datasets, generic data was used. If specific data for these datasets would have been used instead, the results might have been different.

The transport of personnel to the plant and offices have not been included. This was because the need for an office building varies depending on location, customer need, and business set up. Similarly, it was decided not to account for the resources and energy required for planning the plant, as the emissions related to this are assumed to be much lower than those from the construction of the plant. The environmental impact of producing the tools used in the construction phase have not been included in the study either.

## 5 Inventory analysis

This section describes the data acquisition and calculations involved in the inventory analysis phase and was divided into five subsections presented previously: the production of plant components phase, construction phase, gasification phase, use phase and end-of-life phase. The unit processes for the different phases are presented in Appendix A.

The input of materials and resources were provided by Meva Energy and their suppliers. When specific data were not available, assumptions have been made. The geographical regions of the data from the datasets were selected to be as precise as possible, but when this is not possible, or when no exact information is provided, European or global averages have been applied.

The total amount of materials and resources for the different phases are presented in Appendix B. See Table B1 for the production of plant components phase, Table B2 for the construction phase, Table B3 for the gasification process, Table B4 for the use phase, and Table B5 for the end-of-life phase. Transport distances and vehicle types for the different phases are also presented in Appendix B in Tables B1-B5. In cases where the transport distance information was unavailable, it was assumed to be transported from a supplier that provides similar materials.

In table 2 the allocation rates for the three investigated scenarios are presented. The used allocation rates differ from a previous study by Sistek (2021) where a higher rate was allocated to the produced biochar through economic allocation.

Table 2: Allocation rates for the three allocation scenarios.

Allocation method	Allocated biosyngas	Allocated biochar
Mass	0.9866	0.0134
Energy	0.924	0.076
Carbon sequestration	1	-

### 5.1 Production of plant components phase

The input materials in the production of plant components phase consists of concrete, metals, cables and stone wool. The bill of construction material for the gasification plant can be seen in Figure 6.

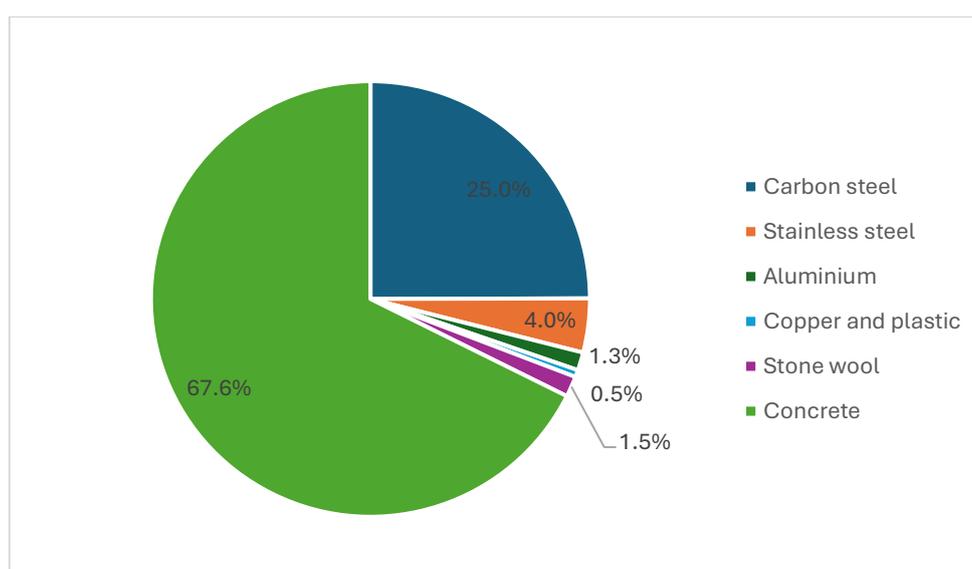


Figure 4: Bill of construction materials for Meva Energy's plant.

The concrete used for the foundation is produced in Sweden and are of the type C30/37. The dataset used in Ecoinvent have been changed to Swedish location regarding electricity mix used and waste management principles. The foundation also consists of reinforcement bars of carbon steel, which is the main metal used in the plant since all steel structures are made of carbon steel. The pipes, vessels and tanks and other equipment category is made of both carbon steel and stainless steel. The other equipment category in the production of plant components phase includes various smaller components such as the biochar screw, roof cooler, silo, and filters.

About 10% of the total weight of the metals used are stainless steel while the rest 90 % is carbon steel. The piping system in the plant is around 10% of the total metal weight. Therefore, a simplification has been made where the entire piping system is assumed to be made of stainless steel. All metal parts, including the walls and roofing elements, are manufactured and produced from a supplier in Europe.

The most common manufacturing process for producing the parts made up of carbon steel, stainless steel and aluminium is by rolling. According to the supplier, more than 90% of the material is produced by rolling, while forging and casting only occurs for smaller parts. Therefore, it is assumed that all metal components are processed by hot rolling.

Furthermore, the supplier has stated that the used carbon steel has an average content of recyclable material of 70-90%. Therefore, the ratio of steel scarp has been set to 80% for all carbon steel. The stainless steel has an average content of recycled material of 60% and a dataset was constructed in OpenLCA with 60% recycled material. Regarding the aluminium, which has an average content of 76% recycled material, the dataset was developed with this specific recycled content. Additionally, the input “aluminium ingot, primary” was changed to only represent the IAI (International aluminium institute) area, EU27 and EFTA (European free trade association) region and the other region values were changed to 0 in the Ecoinvent dataset.

During the 30 years lifespan of the plant, the moving parts of the machinery will be most affected by wear and must be replaced. To account for replacement of moving parts, the steel in the other equipment category has been increased with 2 % from original amount received by Meva Energy.

The electric cables in the plant vary in size depending on application. The reference cable from a dataset in Ecoinvent for a three-conductor cable is based on a cable with the density of 1.04 kg/m. The cables installed at Meva Energy’s plant measure to 18.4 km, where 10% are cables with a weight of about 1 kg/m, 40% of the cables weigh about 0.2 kg/m and 50% of the cables weigh about 0.1 kg/m. The weight all cable types have therefore been recalculated to one type of cable with a density of 1.04 kg/m and a total weight of 4232 kg, see Table 3.

Table 3: Recalculations of electric cables.

Type of cable	Share of total used cables	Calculation to recalculate the weight	Recalculated weight
1 kg/m	10%	$18400 \text{ m} * 1 \text{ kg/m} * 0.1$	1840 kg
0.2 kg/m	40%	$18400 \text{ m} * 0.2 \text{ kg/m} * 0.4$	1472 kg
0.1 kg/m	50%	$18400 \text{ m} * 0.1 \text{ kg/m} * 0.5$	920 kg
Total	100%	-	4232 kg

No adjustments in the Ecoinvent dataset for stone wool have been made, since it represents well the stone wool used in the plant.

### 5.1.1 Transport production of plant components phase

For the transport of structural steel, pipes, vessels, tanks, walls and other steel equipment, trucks with a gross vehicle weight exceeding 32 tonnes have been selected. All materials come from a single supplier,

which is assumed to employ trucks of this size for transport. The EURO6 standard is used, as the supplier exclusively uses trucks compliant with these regulations.

Concrete and electrical cables are assumed to be transported by slightly smaller vehicles with a gross vehicle weight ranging between 16-32 tonnes. It is assumed that all transports occur within Sweden and adhere to the EURO6 standard, as required for all newly produced vehicles in Sweden (Miljöfordon.se, 2024). The distances for transporting the materials are determined from the location of the supplier.

## 5.2 Construction phase

The construction phase has three inputs: electricity, diesel for the construction machines and fuel oil used for heating due to cold climate during the construction of the plant.

Meva Energy buys all their electricity from renewable sources, including hydro power, wind power and solar power. The percentage share has been recalculated, based on the Swedish electricity mix where non-renewable energy sources has been removed and based on data from 2022 (Statistikmyndigheten, 2023). For Meva Energy’s electricity mix, “the Meva mix” (Table 4), the data used for wind power represent onshore turbines since most wind power produced in Sweden comes from onshore wind turbines (Energimyndigheten, 2019).

*Table 4: Share of electricity produced in Sweden based on only renewable sources.*

Electricity source	Share of Swedish electricity mix (%)	The Meva mix (%)
Hydropower	41	67
Nuclear power	29	-
Wind power	19	31
Cogeneration	10	-
Solar power	1	2

The Ecoinvent datasets representing the diesel burned in building machine and heating oil used during the construction phases reflect European and global processes. The dataset regarding diesel burned in building machine was altered to include European values for diesel and construction of machine. Notably, the diesel dataset includes not only the combustion emissions associated with construction activities but also the manufacturing processes of constructing the machine and the combustion of diesel.

## 5.3 Gasification process

The inputs to the gasification phase include wood pellets, electricity, extraction solvent, LPG, glycol, heating oil and air. In addition, active carbon and ionic resin is used in the internal water treatment system. Furthermore, a construction machine is used on the site for daily tasks. The outputs are biosyngas, biochar and tar (Figure 7).

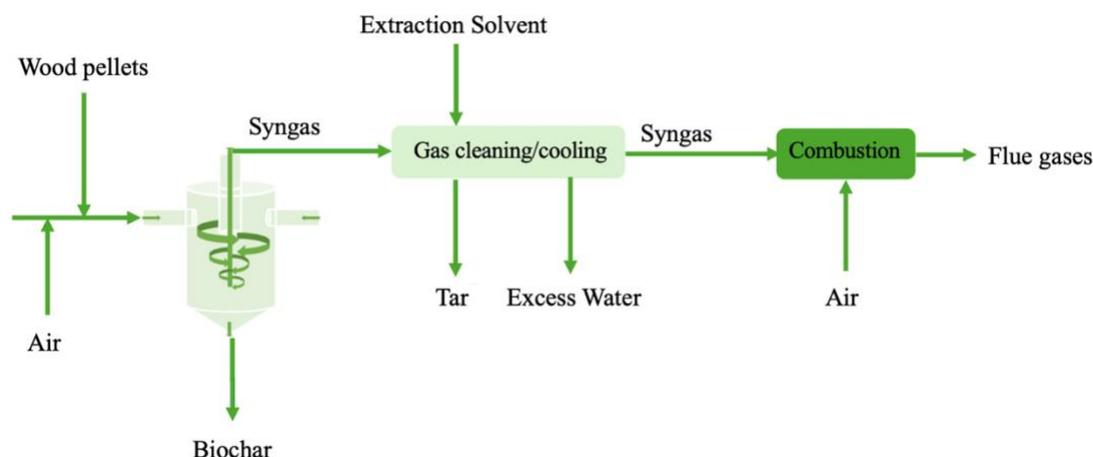


Figure 5: Flowchart of Meva Energy's gasification process.

Table 5 shows the flows of the resources in the gasification process, which provides the basis for the unit process and the allocation.

Inputs	Mass flow (kg/h)	LHV (kWh/kg)	Energy flow (kW)
Wood pellets	1300	5	6525
Extraction Solvent	5.5		
Electricity			200
<b>Outputs</b>			
Biosyngas	3107	1.45	4502
Moisture biosyngas	213		
Tar	37,5	9.7	365
Biochar	42	8.8	371
Water	150		
Heat losses			150
Gas cooling			1300

Table 5: Flows for Meva Energy's gasification process.

An own dataset for wood pellets production was modelled built on information from the supplier. The wood pellets producer provided information regarding mass flows of sawdust and usage of electricity, thermal energy and fuel. The dataset was constructed included also the upstream process of sawdust, electricity used, heat used to dry and compress the sawdust to wood pellets, hydrotreated vegetable oil (HVO) used in machines on site and a wood pellet factory. The supplier uses electricity from hydropower, and the heat used to produce the pellets are obtained from burning small residue wood parts. Regarding the HVO dataset used in the working machines, it was constructed using data from The Swedish Knowledge Centre for Renewable Transportation Fuels (Hallberg, et al., 2013). For the wood pellet factory input, the amount used per produced kg of wood pellets were assumed to be the same as in the Ecoinvent dataset for wood pellet production.

No exact data were found for the production of the extraction solvent, which are saturated hydrocarbons, specifically alkanes C10-13 (i.e., alkanes with 10-13 carbon atoms). Instead, the production of paraffin was used as a substitute, representing alkanes C20-40 (i.e., alkanes with 20-40 carbon atoms). This was considered reasonable since they are produced in a similar way from crude oil but at different temperatures (Kostecki, et al., 2005; García, 2001). In the gasification process, only the production of extraction solvents is included, since the combustion of the chemical is accounted for in the use phase.

In the gasification process, both the production and combustion of LPG ( $C_3H_8$ ) is included since the propane is used for preheating and is flared before the combustion of biosyngas. To produce propane, a global dataset has been used since no region-specific dataset was found. Complete combustion of the propane is assumed, see Reaction 1 (R1). Thus, for every kg of combusted propane, 2.99 kg of fossil  $CO_2$  is released as air emission, see Table 6.

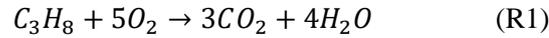


Table 6: Molar mass and calculations for  $C_3H_8$ .

Molar mass $C_3H_8$	44.09 g/mol
Molar mass $CO_2$	44.01 g/mol
Moles per kg $CO_2$	22.68 mol/kg
Moles $CO_2$ upon complete combustion of 1 kg $C_3H_8$	68.04 mol/kg
kg $CO_2$ per kg $C_3H_8$	2.99 kg/kg
kg $H_2O$ per kg $C_3H_8$	1.63 kg/kg

As in the construction phase, all electricity used in the gasification phase comes from renewable energy sources. Therefore, the Meva mix is used, see Section 5.2 and Table 4.

The heating oil and propane glycol used for heating and cooling stays within the system. They are filled once at start and are refilled during service due to small leakages. It is assumed that 5% of the original input to the system needs to be refilled every year. To produce heating oil, a dataset for paraffin production in Europe was used. This assumption was made because the heating oil consists of long hydrocarbons produced in a similar way as paraffins (García, 2001). Only the environmental impact of producing the heating oil is considered, as it is not combusted.

The activated carbon and anionic resin used in the internal water treatment system are not expected to be lost. Instead, when the filters are full, they are cleaned and recirculated, resulting in a negligible additional input needed for these materials.

The generated tar is classified as a hazardous waste and incinerated at a hazardous waste plant facility in a nearby county (Huang, et al., 2021). The generated tar is biogenic and therefore an Ecoinvent dataset representing waste management of biowaste has been chosen to represent this process.

The diesel fuel used in this phase is burned in a wheel loader. The Ecoinvent dataset employed is identical to the one used in the construction phase outlined in Section 5.2.

### 5.3.1 Transport gasification process

Trucks with a gross vehicle weight over 32 tonnes are assumed to be used for transport of wood pellets. For transport of tar waste, trucks with a gross vehicle weight of 16-32 tonnes have been assumed to be used. Trucks with a gross vehicle weight of 3.5-7.5 tonnes are assumed to transport propane and glycol. The size of the vehicles is based on the weight of the material that needs transport and the assumed frequency of deliveries. It is assumed that all transports occur within Sweden and adheres to the EURO6 standard.

To transport extraction solvent, heating oil, activated carbon, and anionic resin, it is assumed that light commercial vehicles are used due to the relatively small loads involved. A dataset representing a light commercial vehicle compliant with EURO2 standards, capable of carrying a maximum load of 1000 kg was used, since no dataset for a light commercial vehicle meeting EURO6 standards was available.

## 5.4 Use phase

The use phase is modelled to include the combustion of biosyngas, the extraction solvents and the utilization of biochar. The complete combustion of biosyngas results in fossil and biogenic CO<sub>2</sub>, O<sub>2</sub>, and H<sub>2</sub>. NO<sub>x</sub> emissions are obtained from measurements on the emitted flue gas.

The fossil emissions from combusting the biosyngas comes from the extraction solvent. Complete combustion is assumed to take place and an average of emissions from the three different hydrocarbons (C10-13, i.e., 10-13 carbon atoms) is calculated and multiplied with the amount of extraction solvent used per kWh (Table 7). Complete calculations can be found in Appendix C.

Table 7: Release of CO<sub>2</sub> upon complete combustion of the extraction solvent.

Decane, C <sub>10</sub> H <sub>22</sub>	kg CO <sub>2</sub> per kg C <sub>10</sub> H <sub>22</sub>	3.1 kg/kg
Undecane, C <sub>11</sub> H <sub>24</sub>	kg CO <sub>2</sub> per kg C <sub>11</sub> H <sub>24</sub>	3.1 kg/kg
Dodecane, C <sub>12</sub> H <sub>26</sub>	kg CO <sub>2</sub> per kg C <sub>12</sub> H <sub>26</sub>	3.1 kg/kg
Tridecane, C <sub>13</sub> H <sub>28</sub>	kg CO <sub>2</sub> per kg C <sub>13</sub> H <sub>28</sub>	3.4 kg/kg
<b>Average</b>	<b>kg CO<sub>2</sub> per kg extraction solvent</b>	<b>3.2 kg/kg</b>

As described in Section 2.1, biochar can have various applications. However, it is assumed that all produced biochar from the plant is bought and used as a carbon sink. The carbon sequestration effect of the biochar is -3.15 kg CO<sub>2</sub>/kg biochar, see Equation 1 (Eq1). This was based on the tested carbon content of Meva Energy's biochar, as well as the molar masses of carbon and CO<sub>2</sub> (Table 8).

Table 8: Biochar data for determining CO<sub>2</sub> binding.

Molar mass C	12.01 g/mol
Molar mass CO <sub>2</sub>	44.01 g/mol
Carbon content Meva Energy's biochar	86%

$$\text{Sequestered carbon} = \frac{44.01}{12.01} * 0.86 = 3.15 \frac{\text{kg CO}_2}{\text{kg biochar}} \quad (\text{Eq1})$$

### 5.4.1 Transport use phase

For the scenario when biochar is not seen as a by-product, the transportation of biochar to a customer is included. This transport is then performed by a truck with a gross vehicle weight ranging from 16-32 with an EURO6 standard.

## 5.5 End-of-life phase

After 30 years, it is assumed that the gasification plant has reached its end-of-life. The assumed disposal of material used for constructing the building are based on Swedish waste management principles and statistics. The steel, aluminium, copper, and plastics are assumed to be recycled. About 90% of the steel products in the building sector are recycled (MVR, 2023), about 95% of the aluminium from the building sector is recycled (SGU, 2013) and about 70% of electrical waste is recycled (Cirkulera Mera, 2021). For mineral wool, it is assumed that 100% ends up in landfills. The cut-off approach is applied for recycled material, meaning that environmental impact related to the recycled materials (e.g., recycling processes) are excluded since their impacts are allocated to the product using the recycled materials. Only the environmental burden for waste treatment of non-recycled material is accounted for (e.g., landfill and incineration).

The foundation and buried pipes are assumed to be left in the ground, potentially serving future purposes like storage areas or similar installations. They are thus effectively considered inert landfills or hibernating stocks. The glycol used for cooling in the gasification phase is assumed to be reused when the plant has reached its end-of-life (Recyctec, 2016).

Demolition of the plant is also included in the end-of-life phase. It is assumed that a diesel-powered machine is used for this purpose. The dataset employed are identical to the one used in the construction phase described in Section 5.2.

### 5.5.1 Transport end-of-life phase

Datasets containing various trucks meeting the EURO6 standard were used for transporting waste materials. Specifically, for steel scrap transportation, a vehicle with a gross weight of 16-32 tonnes was selected. For aluminum scrap and electrical waste, a vehicle weight of 3.5-7.5 tonnes was applied, due to the smaller quantity of materials transported.

## 6 Impact assessment

In the following section, the LCIA results from the study are presented for the five chosen impact categories and the three allocation scenarios. All results from the LCIA can be found in Appendix D. The total impact for the entire lifecycle for the three allocation scenarios is presented in Table 9. In Tables 10-14, the impact for the five different life-cycle phases is presented.

Figure 8 illustrates the percentage share the different phases contribute to each impact category for mass allocation and energy allocation scenario. Figure 9 illustrates the precentral share the different phases contribute to each impact category for carbon sequestration scenario.

Figure 10 illustrates the contribution of different components to each impact category during the production of plant components phase. Figure 11 shows the contributions of the different inputs to each impact category during the construction phase. Figure 12 illustrates the share of contribution for the different inputs to the gasification phase. For the use phase, Figure 13 represents the contribution of inputs to the mass and energy allocation scenario, while Figure 14 illustrates their contribution to the carbon sequestration scenario. Figure 15 shows the contributions of the inputs to each impact category in the end-of-life phase.

### 6.1 Total impact

Table 9: Impact assessment of the entire life cycle of biosyngas, absolute values per FU.

Impact category	Mass allocation	Energy allocation	Carbon sequestration	Unit
<b>Acidification, terrestrial</b>	0.159	0.152	0.161	g SO <sub>2</sub> -eq/kWh
<b>Climate Change</b>	22.8	21.6	-5.95	g CO <sub>2</sub> -eq/kWh
<b>Eutrophication, freshwater</b>	0.0068	0.0063	0.0069	g P-eq/kWh
<b>Particulate matter formation</b>	0.149	0.140	0.151	g PM 2,5-eq/kWh
<b>Land use</b>	0.126	0.118	0.127	m <sup>2</sup> * a crop-eq/kWh

The gasification phase stands out as the primary contributor to all impact categories (Figure 8 and 9). This is primarily caused by the large constant flow of wood pellets necessary to generate biosyngas. Acidification and particulate matter categories are predominantly influenced by the emission of NO<sub>x</sub> and PM < 2.5, respectively, during heat production in wood pellet manufacturing. Furthermore, land use is primarily caused by forest occupation required for pellet production, while CO<sub>2</sub> emissions and eutrophication are associated with harvesting and forest management activities.

For the scenario biosyngas including carbon sequestration, the climate change impact category has a negative impact of -5.95 g CO<sub>2</sub>-eq due to the use of biochar as a carbon sink. Without the utilization of biochar as a carbon sink, the biosyngas has an impact of 22.8 g CO<sub>2</sub>-eq for the mass allocation scenario and 21.6 g CO<sub>2</sub>-eq for the energy allocation scenario.

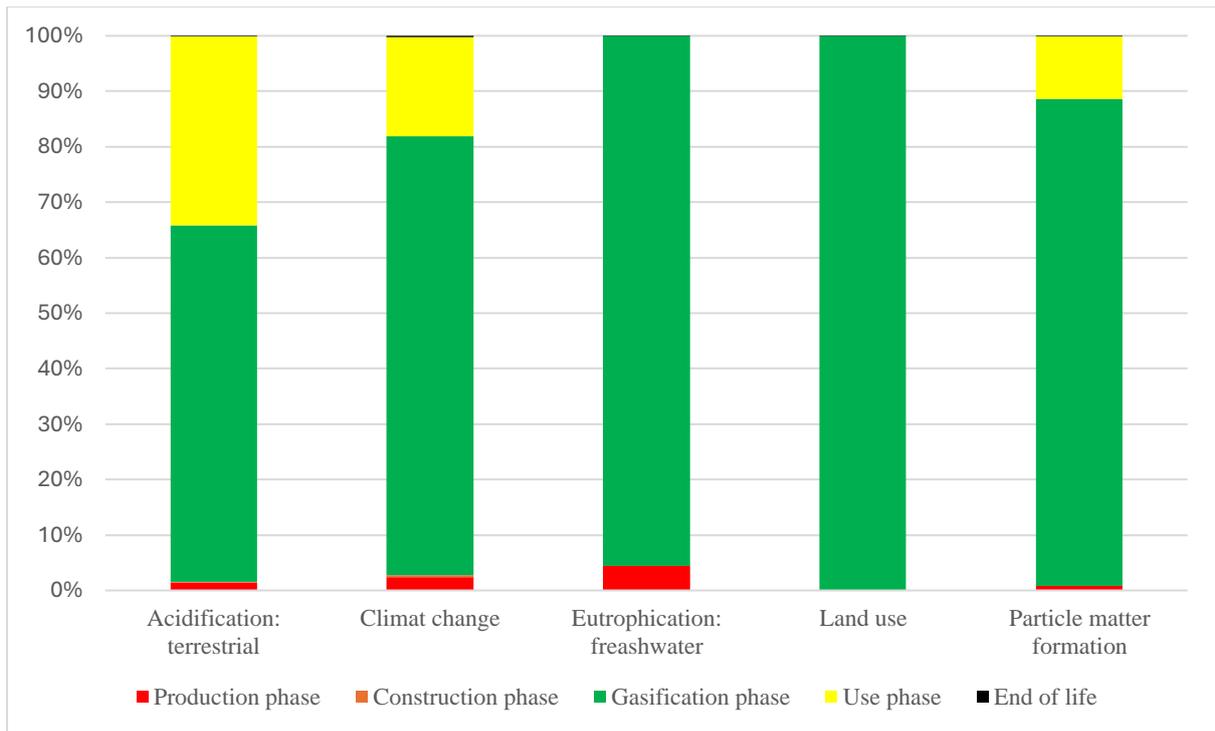


Figure 8: Impact assessment of the life cycle, percentage share from inputs per FU for the mass and energy allocation scenarios.

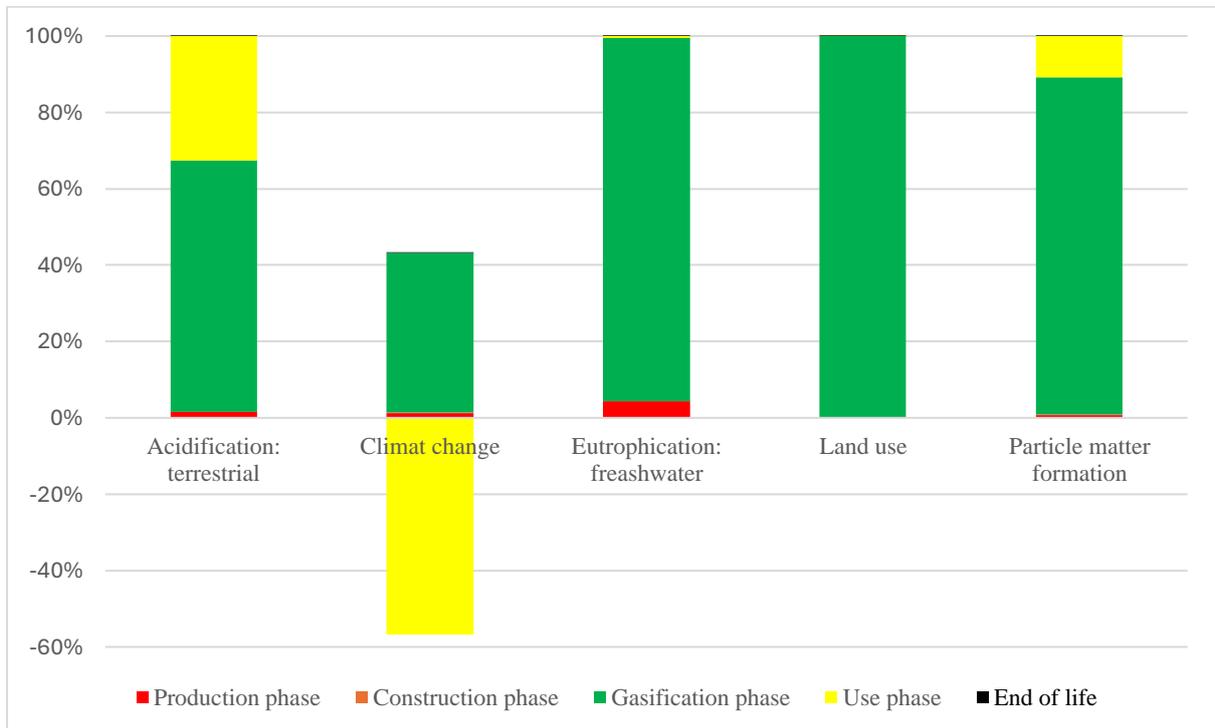


Figure 9: Impact assessment of the life cycle, percentage share from inputs per FU for the carbon sequestration scenario.

## 6.2 Production of plant components phase

Table 10: Impact assessment of production of plant components phase, values per FU.

Impact category	Mass allocation	Energy allocation	Carbon sequestration	Unit
<b>Acidification, terrestrial</b>	0.0024	0.0023	0.0024	g SO <sub>2</sub> -eq/kWh
<b>Climate change</b>	0.56	0.52	0.57	g CO <sub>2</sub> -eq/kWh
<b>Eutrophication, freshwater</b>	0.00029	0.00028	0.00031	g P-eq/kWh
<b>Particulate matter formation</b>	0.0012	0.0011	0.0012	g PM 2,5-eq/kWh
<b>Land use</b>	0.000014	0.000013	0.000014	m <sup>2</sup> * a crop-eq/kWh

The production of electrical cables is the largest contributor to terrestrial acidification. This is explained by the large direct emission of SO<sub>2</sub> occurring during the smelting of copper. The production of electrical cables contribute notably to freshwater eutrophication, land use and particulate matter formation too. However, carbon steel used to produce structure steel, vessels and tanks, as well as other equipment are the largest contributors for the other impact categories, because of the large mass of carbon steel used in all these components.

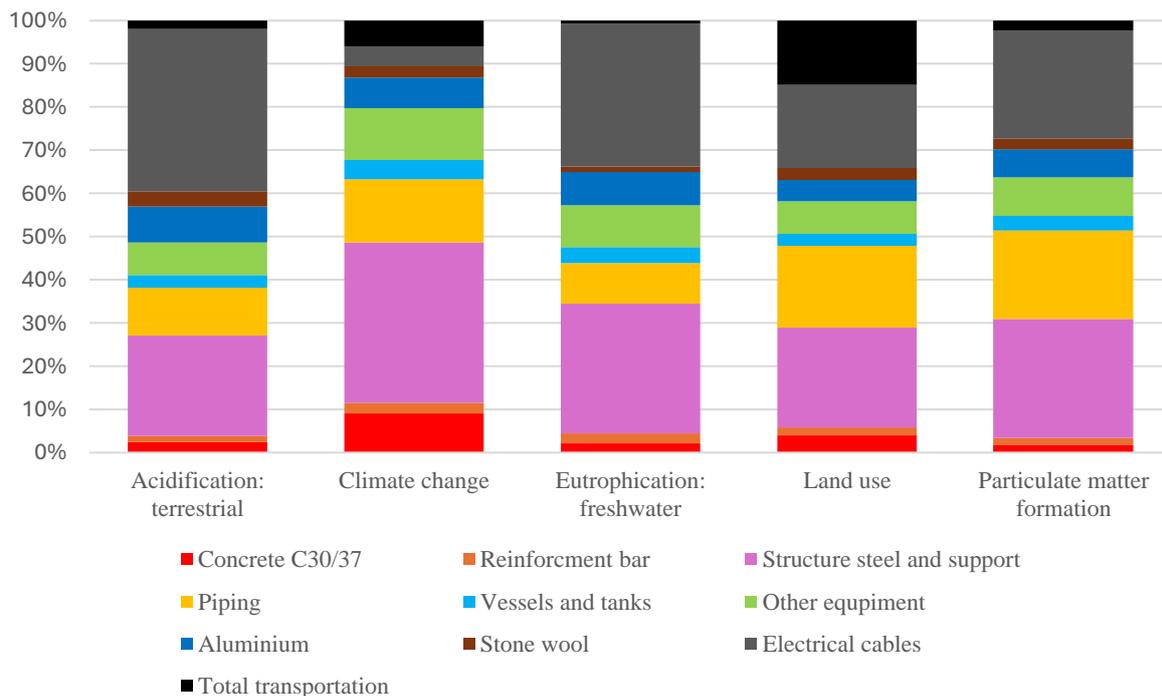


Figure 10: Impact assessment results for the production of plant components phase: percentage share from inputs per FU (representing all three allocation scenarios).

## 6.3 Construction phase

Table 11: Impact assessment of construction phase, values per FU.

Impact category	Mass allocation	Energy allocation	Carbon sequestration	Unit
Acidification, terrestrial	0.00022	0.00021	0.00023	g SO <sub>2</sub> -eq/kWh
Climate Change	0.070	0.066	0.0711	g CO <sub>2</sub> -eq/kWh
Eutrophication, freshwater	0.000003	0.000002	0.000003	g P-eq/kWh
Particulate matter formation	0.00011	0.00010	0.00011	g PM 2,5-eq/kWh
Land use	0.00024	0.00023	0.00025	m <sup>2</sup> * a crop-eq/kWh

The primary contributor to all impact categories is the diesel burned in the building machine during the construction phase. Both the fuel oil and diesel used in this phase are derived from fossil crude oil. The larger emissions from the diesel burned in the machines are due to the larger quantity of diesel used compared to fuel oil.

Both acidification, climate change and particulate matter is mostly affected by the combustion of diesel, which causes emissions such as NO<sub>x</sub> and CO<sub>2</sub>. The land occupation for diesel stems from the occupation of industrial areas during its production. The freshwater eutrophication mostly stems from the waste and waste management related to producing the building machine.

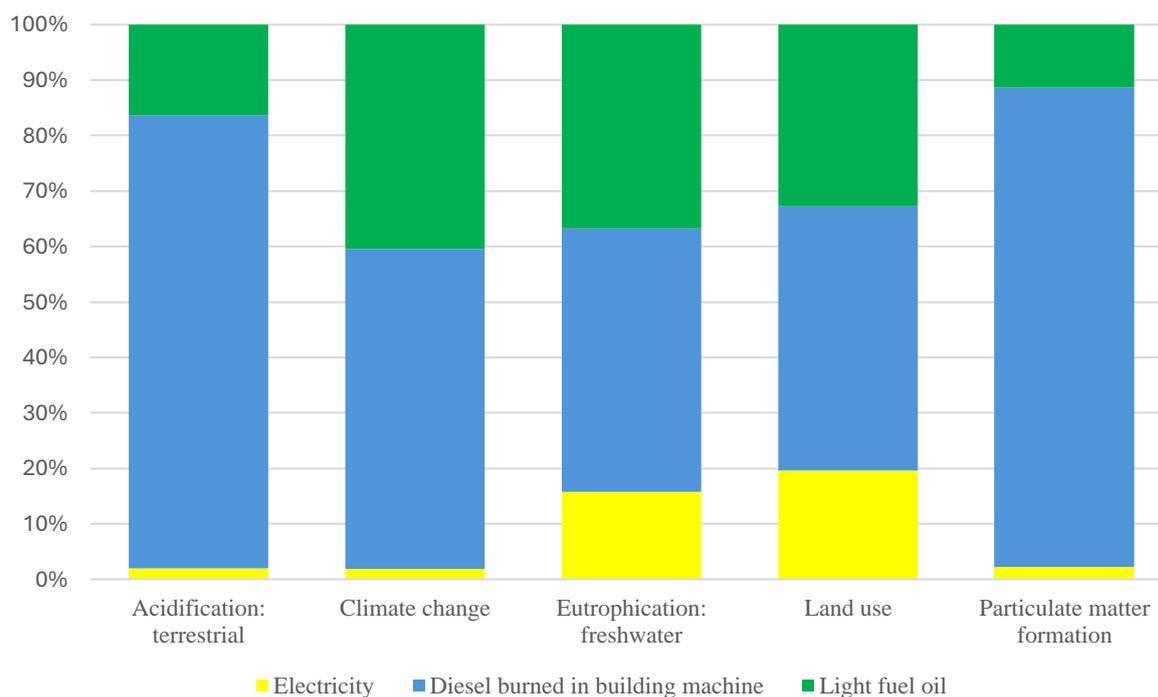


Figure 11: Impact assessment of construction phase: percentage share from inputs per FU (representing all three allocation scenarios).

## 6.4 Gasification phase

Table 12: Impact assessment of gasification phase, values per FU.

Impact category	Mass allocation	Energy allocation	Carbon sequestration	Unit
<b>Acidification, terrestrial</b>	0.104	0.098	0.106	g SO <sub>2</sub> -eq/kWh
<b>Climate Change</b>	18.3	17.1	18.5	g CO <sub>2</sub> -eq/kWh
<b>Eutrophication, freshwater</b>	0.0065	0.0060	0.0065	g P-eq/kWh
<b>Particulate matter formation</b>	0.131	0.123	0.133	g PM 2,5-eq/kWh
<b>Land use</b>	0.126	0.118	0.127	m <sup>2</sup> * a crop-eq/kWh

The largest contributor in the gasification phase for all impact categories is wood pellets. This is because of the large quantities of wood pellets used compared to the other inputs.

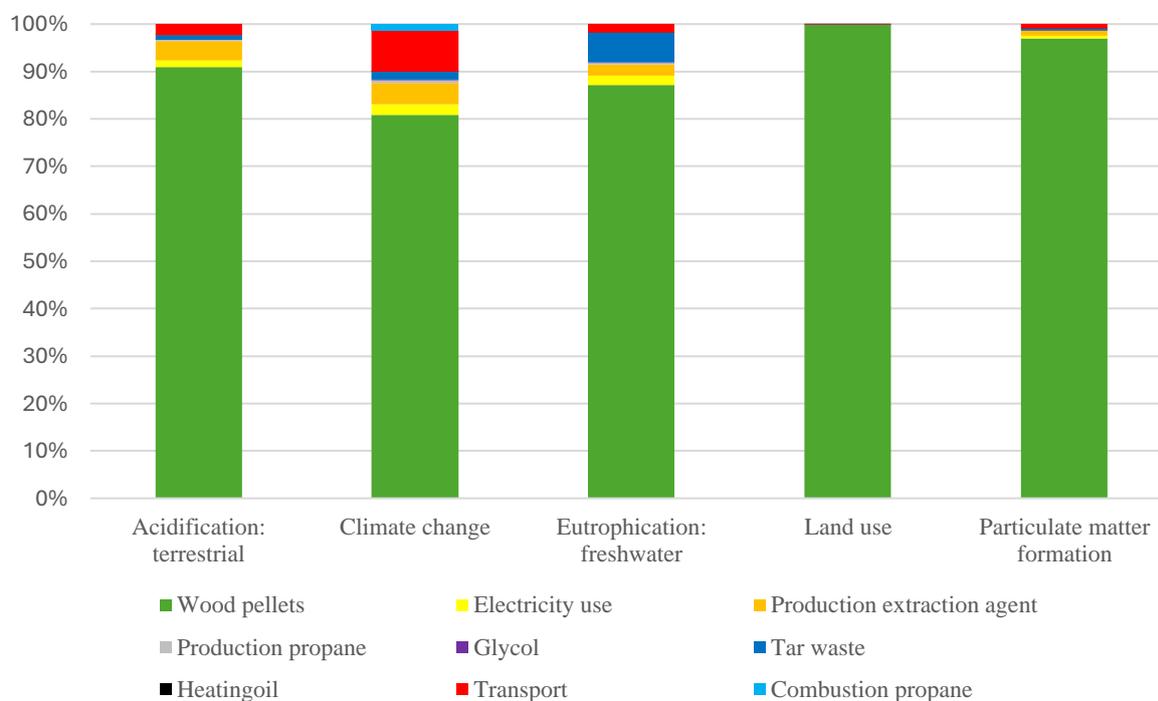


Figure 12: Impact assessment of gasification phase, percentage share from inputs per FU (representing all three allocation scenarios).

## 6.5 Use phase

The results in the use phase are presented in two different graphs. Figure 13 illustrates the mass and energy allocation scenarios while Figure 14 illustrates the scenario with biosyngas including carbon sequestration.

Table 13: Impact assessment of use phase, values per FU.

Impact category	Mass allocation	Energy allocation	Carbon sequestration	Unit
<b>Acidification, terrestrial</b>	0.052	0.052	0.052	g SO <sub>2</sub> -eq/kWh
<b>Climate Change</b>	3.87	3.87	-25.1	g CO <sub>2</sub> -eq/kWh
<b>Eutrophication, freshwater</b>	0	0	0.00003	g P-eq/kWh
<b>Particulate matter formation</b>	0.016	0.016	0.017	g PM 2,5-eq/kWh
<b>Land use</b>	0	0	0.000016	m <sup>2</sup> * a crop-eq/kWh

In the mass and energy allocation scenarios, the only contributing input is the combustion of biosyngas. Therefore, the only affected impact categories are acidification potential, climate change and particulate matter formation due to NO<sub>x</sub> and fossil CO<sub>2</sub> emissions related to the combustion.

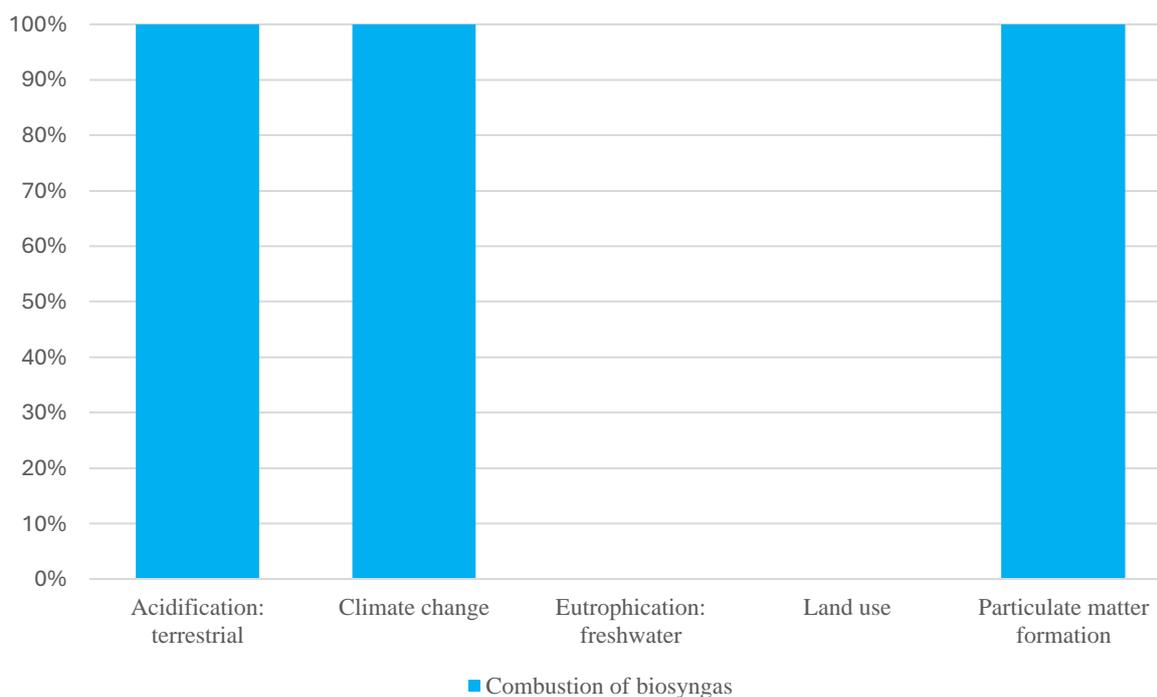


Figure 13: Impact assessment of gasification phase, percentage share from inputs per FU for the mass- and energy allocation scenarios.

For the allocation scenario with biosyngas plus carbon sequestration of biochar, the combustion of biosyngas is the main contributor to terrestrial acidification and particulate matter formation due to the release of NO<sub>x</sub> emissions. Transportation of biochar only accounts for a few percent and biochar itself does not influence these categories.

The carbon sequestering effect of biochar has a reducing impact on climate change, causing the impact category to be negative. For both freshwater eutrophication and land use, only the transportation of biochar contributes to these impact categories.

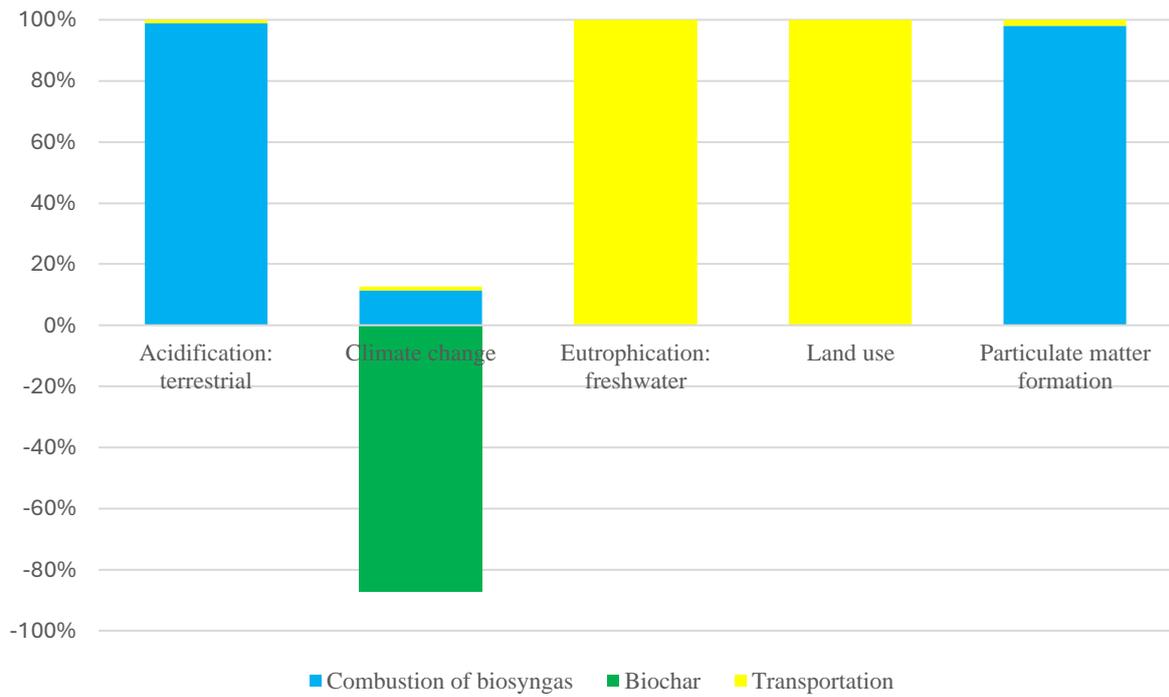


Figure 14: Impact assessment of use phase, percentage share from inputs per FU for the carbon sequestration scenario.

## 6.6 End-of-life phase

Table 14: Impact assessment of end-of-life phase, values per FU.

Impact category	Mass allocation	Energy allocation	Carbon sequestration	Unit
Acidification, terrestrial	0.00018	0.00017	0.00019	g SO <sub>2</sub> -eq/kWh
Climate Change	0.044	0.041	0.044	g CO <sub>2</sub> -eq/kWh
Eutrophication, freshwater	0.000002	0.000001	0.000002	g P-eq/kWh
Particulate matter formation	0.000009	0.000009	0.000010	g PM 2,5-eq/kWh
Land use	0.0000002	0.0000002	0.0000002	m <sup>2</sup> * a crop-eq/kWh

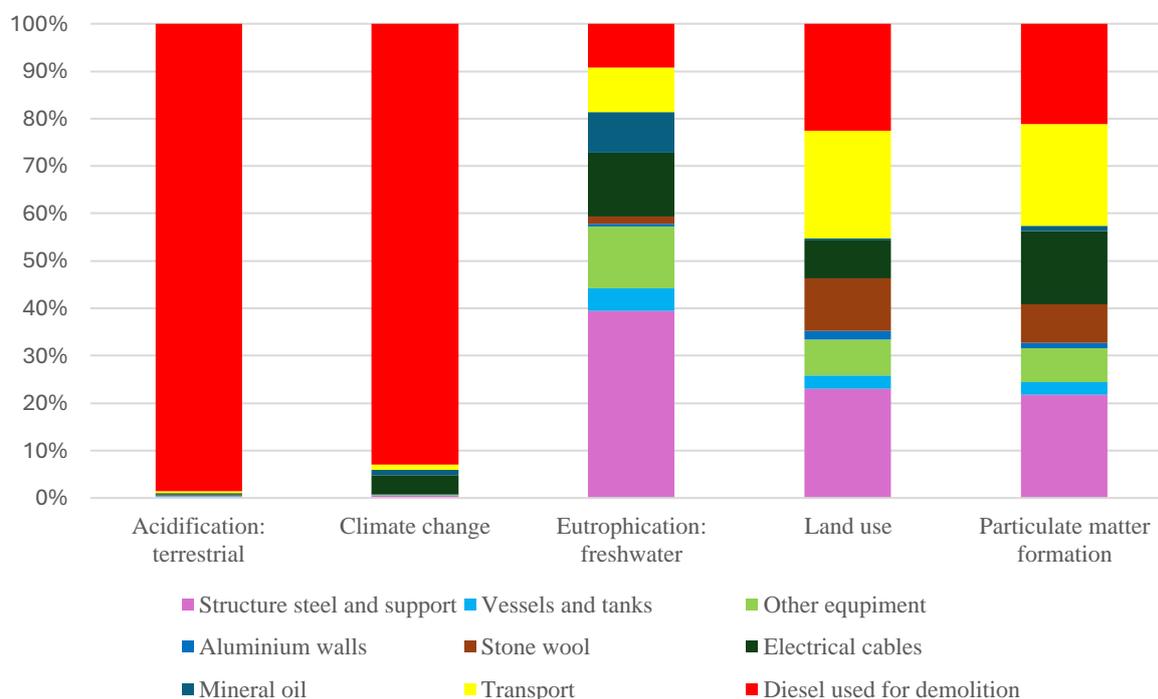


Figure 15: Impact assessment of end-of-life phase, percentage share from inputs per FU (representing all three allocation scenarios).

The predominant contributor to acidification and climate change within the end-of life phase is the use of diesel fuel, primarily due to the emitted SO<sub>2</sub> and fossil CO<sub>2</sub> during both the production and operational phases of a diesel-powered construction machine. Furthermore, the emission of particulate matter formation primarily comes from the waste management of carbon steel, including structure steel, other equipment and vessels and tanks, due to the construction of landfills.

The principal drivers of eutrophication and land use arise from the management process associated with non-recycled carbon steel. Eutrophication effects are primarily caused by the treatment of bottom ash at incineration facilities, resulting in the formation of slag products and phosphate emissions. Moreover, the occupation of infrastructural areas related to carbon steel waste management predominantly influences land use, particularly because of landfill sites.

# 7 Interpretation

This section covers the sensitivity analysis, a comparison with fossil LPG and a comparison with previous studies.

## 7.1 Sensitivity analysis

A sensitivity analysis covering three changes was performed. The first is about the wood pellets data and LCA methods. The second is about how the impact changes if tar is seen as a by-product instead of a waste stream. The third is about a change in transportation fuel for delivery of the wood pellets from diesel to HVO100.

### 7.1.1 Wood pellets feedstock

As observed in the result, the largest impact comes from the supply of wood pellets. Therefore, a generic dataset for wood pellets production in Europe from Ecoinvent (named Ecoinvent dataset in Figure 17) was tested instead of the supplier-specific wood pellets dataset, used in this study, to see how the impact changed. Additionally, it was investigated how the results were changed if the sawdust from the sawmill used to produce wood pellets was seen as a waste stream instead of a by-product, and cut-off was applied to all emissions before the collection of sawdust (named Sawdust-as-waste in Figure 17). The mass allocation scenario was used for comparison and the base scenario in Figure 17 represents the total impact for the mass allocation scenario from Section 6.1.

If the generic dataset in Ecoinvent for a wood pellets supplier in Europe was chosen, the results for the climate change impact category was notably higher than for the base scenario. The higher impact can partly be explained because the generic dataset uses wood pellets for heat production instead of forest residues and a different electricity mix. Additionally, it was seen that the sawdust-as-waste scenario gave a lower impact. The sawdust-as-waste scenario was based on a simplified LCA by Meva Energy's supplier where a cut-off approach had been applied where sawdust was viewed as a waste stream and only included CO<sub>2</sub> emissions. The sawdust-as-waste scenario method is the recommended approach on how to treat sawdust in the RED II.

By considering the sawdust used to produce wood pellets as a waste, the impact on climate change could be reduced by 12.5 g CO<sub>2</sub>-eq per produced kWh compared to the base scenario. The sawdust-as-waste scenario shows that to minimize the environmental impact, it would be beneficial to find a waste stream as a biomass feedstock instead of wood pellets.

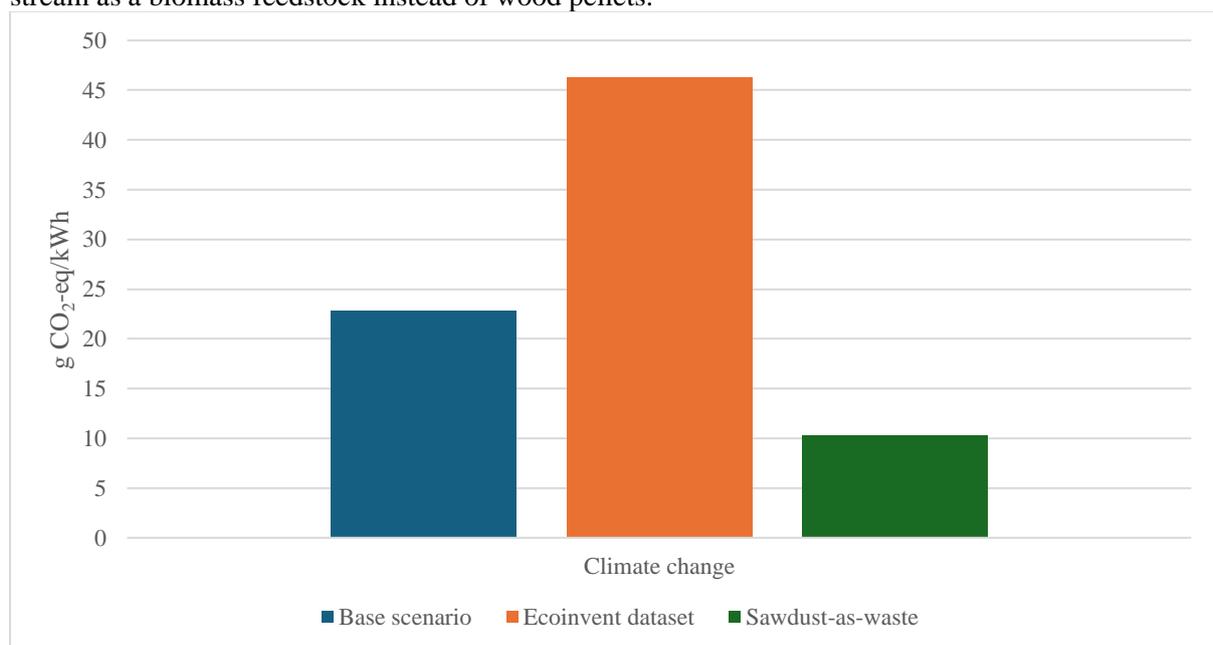


Figure 17: Sensitivity analysis, wood pellets feedstock, based on FU and mass allocation scenario.

### 7.1.2 Tar as a by-product instead of a waste

The generated tar is classified as hazardous waste and sent to an incineration plant for waste management. However, at the incineration plant, the tar is seen as a resource and combusted to generate energy. It was therefore decided to investigate how the results would change if tar was treated as a by-product instead of as a waste stream. The allocation share was therefore changed to include the generated tar as a by-product, resulting in a reduced allocation factor for biosyngas to 0.975 for mass allocation and 0.859 for energy allocation, based on the values in Table 5.

The change in results can be seen for the impact categories eutrophication, acidification, climate change and particulate matter in Figure 18. They are all reduced because the incineration process for tar does not burden the biosyngas if the generated tar is seen as a by-product since it is further utilized instead of being a waste stream.

The sensitivity analysis reveals that the largest change occurred for the energy allocation scenarios for all impact categories. This is due to high energy content of the tar and that less impact is then allocated to the biosyngas. The smaller change in the mass allocation scenario is explained by tars low weight compared to the biosyngas. The results from the sensitivity analysis shows that the waste handling of tar itself has negligible impact, but the type of allocation method has a larger influence on the results.

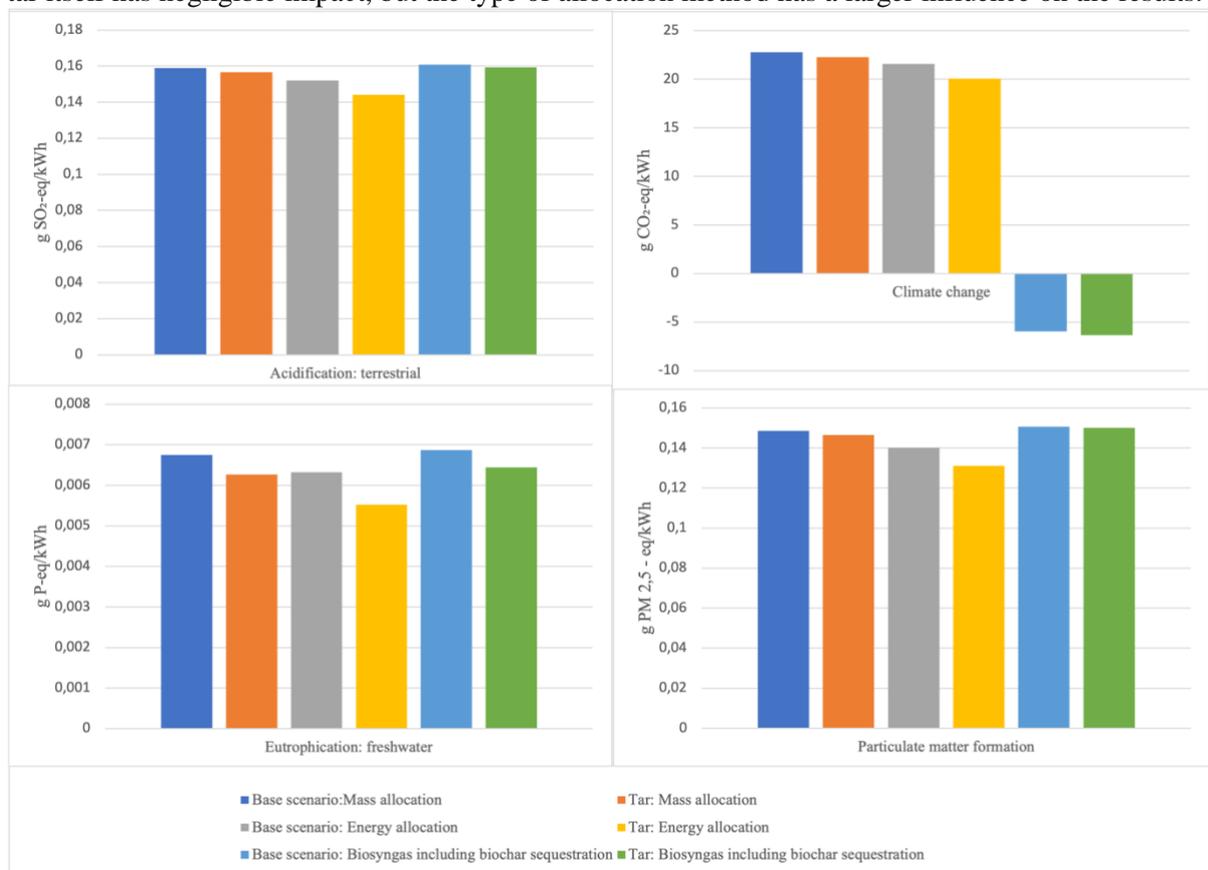


Figure 18: Sensitivity analysis of tar as a by-product per FU.

### 7.1.3 HVO100 transportation

Lastly, a sensitivity analysis has been carried out where all deliveries from the wood pellet supplier are by vehicles driven on HVO100 instead of diesel. The wood pellet supplier has already started incorporating vehicles powered by HVO100 to some extent. Additionally, the supplier has set a future goal where all their deliveries will be carried out using vehicles fueled by HVO100 and therefore this sensitivity analysis is performed. Data regarding emissions from HVO production and combustion was obtained from the Swedish Knowledge Centre for Renewable Transportation Fuels (Hallberg, et al., 2013). The results are presented in Figure 19, for all allocation scenarios.

If all transports from the wood pellet supplier to Meva Eneqys plant were driven on HVO100 from slaughterhouse waste residues instead of diesel, it would result in a reduction of 3.6-14% CO<sub>2</sub>-eq per kWh depending on allocation scenario. Switching to HVO100 as fuel for all transports in the value chain would result in an even bigger reduction of CO<sub>2</sub>-eq, something that Meva Energy could take into consideration when comparing different transportation options.

The sensitivity analysis indicates that switching to HVO100 as fuel for transportation of wood pellets would have a negligible impact on terrestrial acidification, freshwater eutrophication and particulate matter formation since both investigated trucks follow EURO6 standard. HVO100 also releases, for example, NO<sub>x</sub> emissions and particulate matter during combustion.

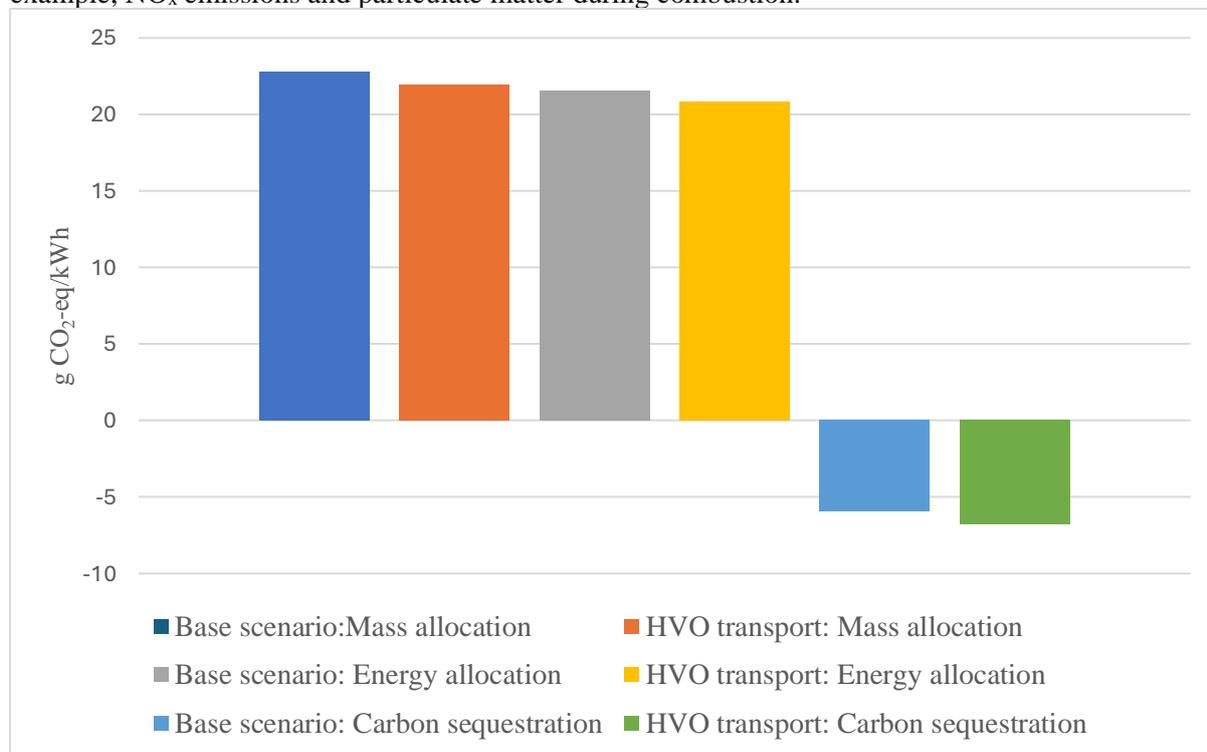


Figure 19: Sensitivity analysis of HVO100 used as fuel.

## 7.2 Comparison with LPG

Meva Energy's gasification technology was installed to replace fossil LPG at a paper industry. Various values have been investigated for the climate impact of LPG. The Swedish Environmental Protection Agency (2024) reports a value of 234 g CO<sub>2</sub>-eq/kWh, which includes the combustion of the LPG. The reference value used in RED II for fossil equivalents to biofuels utilized for generating useful heat is set at 288 g CO<sub>2</sub>-eq/kWh (Energimyndigheten, 2021). If data from Ecoinvent was used for the production of 1 kWh of propane results in a climate impact of 90 g of CO<sub>2</sub>-eq and the full combustion of around 233 g CO<sub>2</sub>-eq/kWh, based on the energy content of propane being 12.8 kWh/kg (Rydgård, et al., 2024). This results in a impact of 323 g CO<sub>2</sub>-eq/kWh.

As can be seen in Figure 20, replacing fossil LPG with biosyngas notably reduces the climate impact, regardless of allocation scenario and exact LPG reference values. The result that biosyngas is preferable to fossil LPG from a climate-change perspective is thus considered robust.

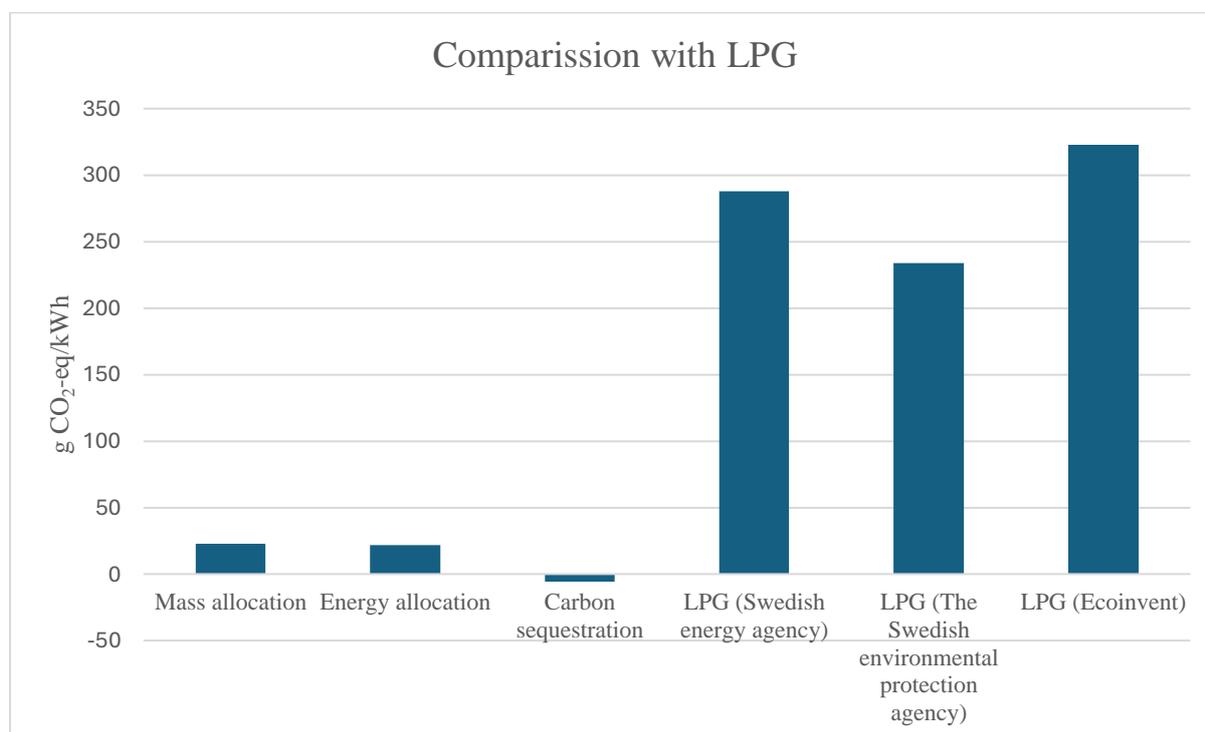


Figure 20: The three allocation scenarios of Meva Energy's biosyngas compared to fossil LPG.

## 7.3 Comparison to previous studies

In Section 2.4, previous LCA studies on biomass gasification technologies are summarized. The most similar study was the LCA performed by K  ppler (2017). K  ppler (2017) presented two sets of results in the study, one that included the carbon sequestration effects of the produced biochar and one that did not. When carbon sequestration effects were included, the energy production from the gasification plant had a climate-change impact of -37 g CO<sub>2</sub>-eq/kWh. Without the carbon sequestration effects, the climate-change impact was 28 g CO<sub>2</sub>-eq/kWh. The lower impact in the carbon sequestration case from K  ppler's study, compared to this study, could be explained by the larger amount of biochar produced and the slightly higher carbon content of the produced biochar in her study, resulting in a larger carbon sink. In the result without the inclusion of the carbon sink, the impact of 28 g CO<sub>2</sub>-eq/kWh in K  ppler's study constitutes a slightly higher impact compared to this study. This could be explained by differences in electricity mixes and biomass feedstocks.

## 8 Discussion

In this section, the results of this study and methodological choices relating to a multifunctional biomass gasification process are discussed.

### 8.1 Discussion of results

As observed in Section 6, the gasification phase is the primary contributor to all the investigated impact categories. The production of plant components phase, construction phase and end-of-life phase have negligible effects on the results, as shown in Section 6. This is due to the large quantities of wood pellets used for biosyngas production. Although materials such as carbon steel and concrete, used when building the plant, have a higher impact per kilogram produced compared to wood pellets, their overall contribution per produced kWh is lower. During the use phase, the combustion of biosyngas has a notable effect on the environmental impact. Discussions with Meva Energy have revealed challenges in replacing the fossil-based extraction solvent used, which through combustion contributes to fossil CO<sub>2</sub> emissions during the use phase.

Given that the wood pellets contribute considerably to the environmental impact of biosyngas, it could be argued that a gasification process using wood pellets as feedstock should consider their choice of supplier if they aim to reduce their environmental footprint. The wood pellets feedstock sensitivity analysis demonstrated that the use of the predetermined dataset for wood pellet production in Europe from Ecoinvent resulted in a larger contribution to climate change compared to the base scenario, in which a dataset in Ecoinvent had been modified based on information from Meva Energy's wood pellets supplier. Additionally, methodological choices regarding allocation of secondary material have a notable impact on the climate change results. For the sawdust-as-waste scenario in Section 7.1.1 the climate impact is lower as it excludes some upstream emissions in the production chain of wood pellets.

The different allocation scenarios provide varying results for the environmental impact of biosyngas. The energy allocation scenario gives the lowest environmental impact for biosyngas across all impact categories, except for climate change. The lower impact depends on the lower share of allocated emissions to the biosyngas in this scenario compared to the other two scenarios. The allocation scenario when the carbon sequestration effects of biochar are included has the highest environmental impact across all considered categories, except for climate change. In this scenario, climate change shows a notably lower impact compared to the energy-based and mass-based scenarios, this is due to the inclusion of the carbon sequestration effects of biochar.

Furthermore, when tar is considered a by-product rather than a waste, the choice of allocation method, particularly when employing energy allocation, has a greater influence on the result due to tar's high energy content. Even if tar is classified as a hazardous waste, it is a biogenic resource that could be used for energy production. Therefore, when evaluating the environmental impact of a process generating tar, it is important to evaluate the benefits and drawbacks when applying methodological choices. Tar could be a biogenic input for energy production that could decrease the use of fossil energy sources even further. However, it could also have a negative effect on humans and the environment due to hazardous substances in the tar unless handled correctly. The methodological approaches must be carefully considered to strike a balance between environmental impact and direct human health hazard.

Lastly, lack of specific data, approximations and assumptions within this study may influence the result. Gathering more specific data on materials, resources and process, especially for those with large influence on the environmental impact, is recommended to gain a more precise representation of Meva Energy's process.

## 8.2 Methodological choices

When determining what methodological approaches from different frameworks that are suitable to adopt for conducting an LCA on a multifunctional biomass gasification plant, there are different directives which offer guidance of varying relevance for informative assessments.

This study broadly follows the ISO standards. However, it does not follow the other two directives investigated in this study. For example, the FU was set to 1 kWh instead of the predetermined FU from RED II. However, the results can be converted from kWh to MJ. It was decided to use 1 kWh for easy comparison with similar LCAs and thereby be able to validate the results without first converting them to a different unit.

One difference that separates RED and PEF is the inclusion of multiple impact categories and the allocation of secondary material. PEF considers more impact categories than the RED II and includes the CFF for secondary materials. The broader inclusion could provide a more comprehensive description of a product's environmental impact. The inclusion of more impact categories could thus minimize the risk of overlooking environmental concerns other than climate change.

Due to the methodological differences between the RED and the PEF for the allocation of by-products and allocation of secondary materials, the environmental performance of a product will differ depending on what methodology that is used.

The interpretation of the results in Section 7 showed that methodological choices regarding by-product allocation, allocation of secondary material and how to account for the carbon sequestration effects of produced biochar have impact on the results. Therefore, these methodological choices should be taken into consideration when comparing the environmental performance of different gasification technologies.

## 9 Conclusion

This study has improved the understanding of the environmental impacts of Meva Energy's gasification technology. It was found that the gasification phase is the life cycle phase where the highest impacts occur for all impact categories due to the large constant flow of wood pellets used as fuel. The production of plant components phase, construction phase and end-of-life phase proved to have a negligible impact.

The results regarding climate change of the life cycle varied depending on the allocation approach applied, with a range from about 23 g CO<sub>2</sub>-eq/kWh for the mass allocation scenario to -6 g CO<sub>2</sub>-eq/kWh for the carbon sequestration scenario.

The interpretation of the results further revealed that methodological choices affect the accounted environmental impact. These include decisions on by-product allocation, secondary material allocation and accounting for the carbon sequestration effects of produced biochar. Therefore, these methodological choices must be considered when comparing the environmental impact of different gasification technologies.

The findings of this study highlight that biosyngas produced by Meva Energy has a considerably lower climate change impacts than the compared fossil LPG. Furthermore, the produced biosyngas can contribute to a climate positive impact, assuming that the carbon sink effects of the biochar are considered as negative emission values.

## 10 References

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## Appendix A

### Production of plant components phase

Table A1: Unit process for hot rolling steel production

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
hot rolling, steel	1	kg	hot rolling, steel   hot rolling, steel   Cutoff, U	Global
steel, low-alloyed	1	kg	steel production, electric, low-alloyed   steel, low-alloyed   Cutoff, U	Global
<i>Output</i>				
steel, low-alloyed, hot rolled	1	kg	-	Global

Table A2: Unit process for steel chromium steel pipe production

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
drawing of pipe, steel	1	kg	market for drawing of pipe, steel   drawing of pipe, steel   Cutoff, U	Global
iron scrap, sorted, pressed	0.6	kg	iron scrap, sorted, pressed, Recycled Content cut-off   iron scrap, sorted, pressed   Cutoff, U	Global
steel, chromium steel 18/8	0.4	kg	market for steel, chromium steel 18/8   steel, chromium steel 18/8   Cutoff, U	Global
<i>Output</i>				
chromium steel pipe	1	kg		Global

Table A3: Unit process for sheet rolled aluminum production

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Aluminium, wrought alloy	0.24	kg	Aluminium ingot, primary, to aluminium, wrought alloy market   aluminium, wrought alloy   Cutoff, U	Global
Aluminium, wrought alloy	0.76	kg	Treatment of aluminium scrap, prepared for recycling, at remelter   aluminium, wrought alloy   Cutoff, U	RER
Sheet rolling, aluminium	0.4	kg	Sheet rolling, aluminium   sheet rolling, aluminium   Cutoff, U	RER
<i>Output</i>				
Sheet rolled, aluminium	1	kg		

Table A4 – Unit process for the production of construction materials for 1 gasification plant

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Concrete	230	m <sup>3</sup>	Concrete production, 37MPa, for civil engineering, with cement, CEM II/A   concrete, 37 MPa  Cutoff, U	SE
Reinforcement steel	20 000	kg	Reinforcing steel production   reinforcing steel	Europe - without Austria
steel, low-alloyed, hot rolled	179 982	kg	A.1	
Chromium steel pipe	32 000	kg	A.2	
Sheet rolled, aluminum	10 680	kg	A.3	
Electrical cable	4 232	kg	Cable Production, three-conductor cable  , three-conductor cable   Cutoff, U	GLO
Stone wool	12 250	kg	Stone wool, production   stone wool   Cutoff, U	CH
<i>Output</i>				
Gasification plant	1	item	-	

## Construction phase

Table A5: Unit process for the Meva mix

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
electricity, high voltage	0.311	kWh	Electricity production, wind, 1-3MW turbine, offshore   electricity, high voltage   Cutoff, U	SE
electricity, high voltage	0.672	kWh	Electricity production, hydro, run-of-river   electricity, high voltage   Cutoff, U	SE
electricity, high voltage	0.016	kWh	Electricity production, solar thermal parabolic trough, 50MW   electricity, high voltage   Cutoff, U	Rest of World
<i>Output</i>				
Custom, electricity	1	kWh		SE

Table A6: Unit process for the construction of 1 gasification plant

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Custom, electricity	151 215	kWh	A.5	SE
Diesel burned in building machine	426 651,6	MJ	diesel, burned in building machine   diesel, burned in building machine   Cutoff, U	GLO
heat, central or small-scale, other than natural gas	291 927		Heat production. Light fuel oil, at boiler 10kW, non-modulating   heat, central or small scale, other than natural gas   Cutoff, U	Europe without Switzerland
<i>Output</i>				
Construction of one gasification phase	1	item		

## Gasification phase

Table A7: Unit process for HVO from animal residues. Data from: Hallberg, et al (2013). Energy content from MJ to kg from: World nuclear association (2020).

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Coal, brown	0.00058	kg		
Coal, hard	0.00069	kg		
Gas, natural	0.123	m <sup>3</sup>		
Oil, Crude	0.000457	kg		
Uranium	5.435E-9	kg		
<i>Output</i>				
HVO100 from animal residues	1	MJ		
Ammonium	2.08E-8	kg		
Carbon dioxide, fossil	0.029	kg		
Carbon monoxide from soil or biomass feedstock	0.0000179	kg		
Dinitrogen monoxide	0.000000514	kg		
Methane fossil	0.0000882	kg		
Nitrate	0.000000522	kg		
Nitrogen Oxides	0.0000323	kg		
NM VOC, non methane volatile organic compounds	0.0000112	kg		
Particulate matter <2,5 um	0.00000257	kg		
Particulate matter >10 um	0.00000264	kg		
Particulate matter >2,5 and < 10um	0.000000668	kg		
Phosphate	0.000000804	kg		
Sulfur dioxide	0.0000261	kg		

Table A8: Unit process for HVO100 burned in working machine. Data regarding output emissions from Hallberg, et al (2013).

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Building machine	0.000000134	Item(s)	Market for building machine, building machine Cutoff, U	Global
HVO from animal residues	1	MJ	A7	Sweden
<i>Output</i>				
HVO burned in working machine	1	MJ		
Carbon monoxide, fossil	0.000489	kg		
Dinitrogen monoxide	0.00000611	kg		
Methane, fossil	0.00000196	kg		
Nitrogen oxides	0.0000562	kg		
NM VOC, non methane volatile organic compounds	0.0000176	kg		
Particulate matter >2,5 and < 10um	0.00000122	kg		
Sulfur dioxide	0.000000136	kg		

Table A9: Unit process for custom wood pellet production

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Electricity, medium voltage	0.107	kWh	Electricity production, hydro, run-of-river   electricity, high voltage   Cutoff, U	SE
Heat, central or small scale, other than natural gas	0.95	kWh	Heat production, softwood chips from forest, at furnace 50kW, state-of-the art 2014 heat, central or small scale, other than natural gas	CH
HVO burned in working machine			A.8	
Sawdust measured as dry mass	1	kg	Market for sawdust, wet, measured as dry mass  sawdust, wet, measured as dry mass   Cutoff, U	Europe without Switzerland
Wood pellet factory	4*10 <sup>-10</sup>	items	Wood pellet factory production   wood pellet factory  Cutoff, U	RER
<i>Output</i>				
Custom Wood pellets	1	kg		

Table A10 – Unit process for the gasification process

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Custom, electricity	0.044	kWh	A5	SE
Custom wood pellets	0.288	kg	A9	SE
Diesel burned in building machine	0.00036	MJ	diesel, burned in building machine   diesel, burned in building machine   Cutoff, U	GLO
Glycol production	0.000003	litre	market for propylene oxide, liquid   propylene oxide, liquid   Cutoff, U	Europe
Propane production	0.000084	kg	natural gas liquids fractionation   propane   Cutoff, U	GLO
Combustion of propane	0.000084	kg	See Appendix C	
Activated coal	5.83 E-06	kg	market for hard coal   hard coal   Cutoff, U	Europe, without Russia and Türkiye
Anionic resin	0.000024	kg	market for chloroform   chloroform   Cutoff, U	RoW
Heating oil	5.43 E-07	kg	Paraffin production   paraffin   Cutoff, U	Rest of Europe
Extraction solvent production	0.0012	kg	Paraffin production   paraffin   Cutoff, U	Rest of Europe
<i>Output</i>				
Biosyngas	1	kWh		
Tar waste	0.00833	kg	treatment of biowaste, municipal incineration   biowaste   Cutoff, U	GLO
Biochar	0.0093	kg		

## Use Phase

Table A11 – Unit process for the use phase

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Biosyngas	1	kWh	Table 24	
<i>Output</i>				
Thermal energy	1	kWh		
Emissions from combustion of extraction solvent	0.00122	kg	See Appendix C	SE
NO <sub>x</sub> emissions	0.000144	kg	Data from tests.	SE
Carbon sequestration effects of Biochar	-0.02943	kg CO <sub>2</sub>	Eq 1, Section 5.4.	SE

## End-of-life phase

Table A12 – Unit process for end-of-life phase, treatment of waste

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Diesel burned in building machine	426 651.6	MJ	diesel, burned in building machine   diesel, burned in building machine   Cutoff, U	GLO
Gasification plant	1	item	Gasification plant	SE
Gasification process	1	item	Table 24	SE
<i>Output</i>				
Waste mineral wool	12.3	tonnes	Treatment of waste mineral wool, inert material landfill   waste mineral wool, for final disposal   Cutoff, U	Europe without Switzerland
Scrap steel	179*0,1	tonnes	Treatment of scrap steel, municipal incineration   scrap steel   Cutoff, U	Europe without Switzerland
Waste aluminium	10.7* 0,05	tonnes	Treatment of waste aluminium, sanitary landfill   waste aluminium   Cutoff, U	Rest-of-World
waste electric wiring	4.3 *0,3	tonnes	treatment of waste electric wiring, collection for final disposal   waste electric wiring   Cutoff, U	Rest-of-World
Waste mineral oil	235	kg	Market for mineral oil   waste mineral oil   Cutoff, U	Europe without Switzerland

## Transport

Table A13 – Unit process for transportation of wood pellet

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of wood pellets	10400*40	ton*km	transport, freight, lorry >32 metric ton, EURO6	Europe
<i>Output</i>				
Yearly transport of wood pellets	1	transport		

Table A14 - Unit process for transportation of carbon steel, aluminum and mineral wool

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of carbon steel, aluminium and mineral wool	232*1161	ton*km	transport, freight, lorry >32 metric ton, EURO6	Europe
<i>Output</i>				
Transport of carbon steel aluminium and mineral wool	1	transport		

Table A15 - Unit process for transportation of concrete

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of concrete	551*36	ton*km	transport, freight, lorry 16-32 metric ton, EURO6	Europe
<i>Output</i>				
Transportation of concrete	1	transport		

Table A16 - Unit process for transportation of extraction solvent

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of extraction solvent	44*173	ton*km	transport, freight, light commercial vehicle, EURO2	ZA
<i>Output</i>				
Yearly transportation extraction solvent	1	transport		

Table A17 - Unit process for transportation of electric cables

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of electric cables	4,9*190	ton*km	transport, freight, lorry 16-32 metric ton, EURO6	Europe
<i>Output</i>				
Transport electric cables	1	transport		

Table A18 - Unit process for transportation of propane

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of propane	3*42	ton*km	transport, freight, lorry 3,5-7,5 metric ton, EURO6	Europe
<i>Output</i>				
Yearly transport of propane	1	transport		

Table A19 - Unit process for transportation of glycol

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of glycol	3.38*105	ton*km	transport, freight, lorry 3,5-7,5 metric ton, EURO6	Europe
<i>Output</i>				
Transport of glycol	1	transport		

Table A20 - Unit process for transportation of heating oil

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of heating oil	0.587*250	ton*km	transport, freight, light commercial vehicle, EURO2	ZA
<i>Output</i>				
Transport of heating oil	1	transport		

Table A21 - Unit process for transportation of activated carbons and anionic resin

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of activated carbons and anionic resin	1.1*122	ton*km	transport, freight, light commercial vehicle, EURO2	ZA
<i>Output</i>				
Transporta of activated carbons and anionic resin	1	transport		

Table A22 - Unit process for transportation of tar waste

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of tar waste	300*157	ton*km	transport, freight, lorry 16-32 metric ton, EURO6	Europe
<i>Output</i>				
Yearly transportation of tar waste	1	transport		

Table A23 - Unit process for transportation of biochar

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of biochar	336*243	ton*km	transport, freight, lorry 16-32 metric ton, EURO6	Europe
<i>Output</i>				
Yearly transport of biochar	1	transport		

Table A24 - Unit process for transportation of steel waste

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of steel waste	18*161	ton*km	transport, freight, lorry 16-32 metric ton, EURO6	Europe
<i>Output</i>				
Transport of steel waste	1	transport		

Table A25 - Unit process for transportation of aluminum waste

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of aluminium waste	0.5*5	ton*km	transport, freight, lorry 3,5-7,5 metric ton, EURO6	Europe
<i>Output</i>				
Transport of aluminium waste	1	transport		

Table A26 - Unit process for transportation of electric waste

<i>Input</i>	<i>Amount</i>	<i>Unit</i>	<i>Provider</i>	<i>Location</i>
Transport of electric waste	1.3*0,5	ton*km	transport, freight, lorry 3,5-7,5 metric ton, EURO6	Europe
<i>Output</i>				
Transport of electric waste	1	transport		

## Appendix B

Table B1- Amount of material and resources in the production of plant components phase

Material (Description)	Amount	Per functional unit
Concrete	230 m <sup>3</sup>	2.13E-07 m <sup>3</sup>
Carbon Steel	179 982 kg	0.00499 kg
Reinforcing steel	20 000 kg	1.85E-05 kg
Stainless steel	32 000 kg	2.96E-05 kg
Aluminium	10 680 kg	9.98E-06 kg
Stone wool	12 250 kg	1.13E-05 kg
Electric cables	4232 kg	3.92E-06 kg
Transport of steel, aluminium, and mineral wool with HDV>32 tonnes, EURO 6	232*1161 ton*km	2.39E-04 ton*km
Transport of concrete with HDV 16-32 tonnes, EURO 6	551*36 ton*km	1.84E-05 ton*km
Transport of electric cables with HDV 16-32 tonnes, EURO 6	4.2*190 ton*km	7.45E-07 ton*km

Table B2 - Amount of material and resources in the construction phase

Material (Description)	Amount	Per functional unit
Hydroelectricity	101 616 kWh	9.41E-05 kWh
Wind power	47 028 kWh	4.35E-05 kWh
Solar power	2419 kWh	2.24E-06 kWh
Diesel used in building machine	13.159 m <sup>3</sup>	3.95E-04 MJ
Oil used for heating	8.191 m <sup>3</sup>	2.70E-04 MJ

Table 3 - Amount of material and resources in the gasification phase

Material (Description)	Amount	Per functional unit
Wood pellets	10400000 kg/year	0.29 kg
Extraction Solvents	44 000 kg/year	0.0012 kg
Propane	3024 kg/year	0.000084 kg
Glycol	3250 litres	3.13E-06 kg
Activated coal	210 kg/year	5.83E-06 kg
Anionic resin	864 kg/year	0.000024 kg
Hydroelectricity	1075 MWh/year	2.99E-05 kWh
Wind power	497.6 MWh/year	1.38E-05 kWh
Solar power	25.6 MWh/year	7.11E-07 kWh
Tar waste	300 000 kg/year	0.0083 kg
Mineral oil	587.25 kg	5.43E-07 kg
Diesel used in building machine	0.40 m <sup>3</sup> /year	0.00036 MJ
Transport of wood pellets with HDV 16-32 tonnes, EURO6	10400*40 (ton*km)/year	0.289 ton*km
Transport of Tar with HDV 16-32 tonnes, EURO6	300*157 (ton*km)/year	0.00131 ton*km
Transport of propane with truck 3,5-7,5 tonnes, EURO6	3*42 (ton*km)/year	0.000003514 ton*km

Transport of glycol with truck 3,5-7,5 tonnes, EURO6	3,38*105 (ton*km)/year	9.86E-06 ton*km
Transport of extraction solvent with light commercial vehicle, EURO2	44*173 (ton*km)/year	0.00021 ton*km
Transport of heat oil with light commercial vehicle, EURO2	0.587*250 (ton*km)	4.08E-06 ton*km
Transport of activated carbons and anionic resin with light commercial vehicle, EURO2	1.1*122 (ton*km)/year	0.0013 ton*km

Table 4 - Amount of material and resources in the use phase

Material (Description)	Amount	Per functional unit
Combustion of extraction solvents	44 000 kg/year	0.00122 kg
NOx emissions	399 888 kg/MJ	0.000144 kg
Biochar	336 000 kg/year	0.0093 kg
Transport of biochar with HDV 16-32 tonnes, EURO6	336*243 (ton*km)/year	0.0027 ton*km

Table 5 - Amount of materials and resources in the end-of-life

Material (Description)	Amount	Per functional unit
Waste treatment of aluminium, sent to landfill.	10.7* 0.05 tonnes	4.94E-07 kg
Waste treatment of scrap steel, sent to incineration.	179*0,1 tonnes	0.0000167 kg
Waste treatment of electric cables	4,3 *0,3 tonnes	1.2E-06 kg
Waste treatment of mineral wool	12,3 tonnes	1.13E-05 kg
Diesel used for demolition	13,2 m <sup>3</sup>	3.94E-04 MJ
Transport of scrap steel with HDV 16-32 tonnes, EURO6	18*161 ton*km	2.68E-06 ton*km
Transport of aluminium scrap with truck 3,5-7,5 tonnes, EURO6	0.5*5 ton*km	2.47E-09 ton*km
Transport of electric waste with truck 3,5-7,5 tonnes, EURO6	1.3*0.5 ton*km	6.0E-09 ton*km

## Appendix C

Decane  $C_{10}H_{22}$ :

Balanced reaction:  $2 C_{10}H_{22} + 31 O_2 \rightarrow 20 CO_2 + 22 H_2O$

Undecane  $C_{11}H_{24}$ :

Balanced Reaction:  $C_{11}H_{24} + 17 O_2 \rightarrow 11 CO_2 + 12 H_2O$

Dodecane  $C_{12}H_{26}$ :

Balanced reaction:  $2 C_{12}H_{26} + 37 O_2 \rightarrow 24 CO_2 + 26 H_2O$

Tridecane  $C_{13}H_{28}$ :

Balanced reaction:  $C_{13}H_{28} + 20 O_2 \rightarrow 13 CO_2 + 14 H_2O$

Molar mass  $CO_2$ : 0.04401 kg/mole

<b>Decane:</b>		
Weight per mole $C_{10}H_{22}$	142.276	g/mole
Moles $C_{10}H_{22}$ per kg decane	7.02859231	$C_{10}H_{22}$ mole/kg
At full combustion it is formed 10 mole $CO_2$ per mole $C_{10}H_{22}$	70.2859231	$CO_2$ mole/kg
kg $CO_2$ per kg of $C_{10}H_{22}$	3.1	kg $CO_2$ /kg $C_{10}H_{22}$
<b>Undecane:</b>		
Weight per mole $C_{11}H_{24}$	156.302	g/mole
Moles $C_{11}H_{24}$ per kg undecane	6.39787079	$C_{11}H_{24}$ mole/kg
At full combustion it is formed 11 mole $CO_2$ per mole $C_{11}H_{24}$	70.3765787	$CO_2$ mole/kg
kg $CO_2$ per kg of $C_{11}H_{24}$	3.1	kg $CO_2$ /kg $C_{11}H_{24}$
<b>Dodecane:</b>		
Weight per mole $C_{12}H_{26}$	170.328	g/mole
Moles $C_{12}H_{26}$ per kg dodecane	5.87102532	$C_{12}H_{26}$ mole/kg
At full combustion it is formed 12 mole $CO_2$ per mole $C_{12}H_{26}$	70.4523038	$CO_2$ mole/kg
kg $CO_2$ per kg of $C_{12}H_{26}$	3.1	kg $CO_2$ /kg $C_{12}H_{26}$
<b>Tridecane:</b>		
Weight per mole $C_{13}H_{28}$	170.328	g/mole
Moles $C_{13}H_{28}$ per kg Tridecane	5.87102532	$C_{13}H_{28}$ mole/kg
At full combustion it is formed 13 mole $CO_2$ per mole $C_{13}H_{28}$	76.3233291	$CO_2$ mole/kg
kg $CO_2$ per kg of $C_{13}H_{28}$	3.4	kg $CO_2$ /kg $C_{13}H_{28}$
<b>Propane</b>		
Weight per mole $C_3H_8$	44.094	g/mole
Moles $C_3H_8$ per kg Propane	22.6788225	$C_3H_8$ mole/kg
At full combustion it is formed 3 mole $CO_2$ per mole $C_3H_8$	68.0364675	$CO_2$ mole/kg
kg $CO_2$ per kg of $C_3H_8$	2.99	kg $CO_2$ /kg $C_3H_8$

	Production of plant components phase + transport	Construction phase	Gasification phase + transport	Use phase	End of life + transport	Total impact
Mass allocation scenario (98.7%)						
Acidification: terrestrial   kg SO2-eq	2,38462E-06	2,21696E-07	0,000104289	0,000005184	1,83632E-07	0,000158919
Climate change Kg CO2-eq	0,000559065	7,01752E-05	0,018255554	0,003865324	4,3588E-05	0,022793707
Ecotoxicity: freshwater Kg 1,4 -DCB-eq	0,000251111	7,69801E-07	0,001477993	0	9,1845E-05	0,001821719
Ecotoxicity: marine Kg 1,4 -DCB-eq	0,000362008	1,60164E-06	0,002337434	0	0,000110141	0,002811185
Ecotoxicity: terrestrial Kg 1,4 -DCB-eq	0,035891387	0,000547879	0,484275022	0	0,0003899	0,521104188
Energy resources: non-renewable, fossil   kg oil-eq	0,000127425	2,01862E-05	0,005915931	0	1,20981E-05	0,00607564
Eutrophication: freshwater kg P-eq	2,96536E-07	2,49775E-09	6,44966E-06	0	1,52124E-09	6,75021E-06
Eutrophication: marine Kg N-eq	7,72456E-08	7,47126E-10	7,53282E-07	0,00001296	4,3383E-10	1,37917E-05
Human toxicity: carcinogenic Kg 1,4 -DCB-eq	0,005191919	1,00886E-05	0,007523	0	7,35433E-06	0,012732361
Human toxicity: non-carcinogenic Kg 1,4 -DCB-eq	0,001839814	1,0422E-05	0,044788573	0	3,73535E-05	0,046676163
Ionising radiation kBq CO-60-eq	3,10092E-05	7,3138E-07	0,002767924	0	3,55891E-07	0,00280002
Land use m2*a crop-eq	1,35298E-05	2,4349E-07	0,125550955	0	1,82111E-07	0,12556491
Material resources: metals/minerals kg Cu-eq	5,57101E-05	8,30682E-07	0,000502936	0	5,57879E-07	0,000560034
Ozone depletion kg CFC-11-Eq	1,26742E-10	1,88469E-11	5,92939E-08	0	1,50463E-11	5,94545E-08
Particulate matter formation kg PM2,5 - Eq	1,16947E-06	1,09142E-07	0,000131301	0,00001584	9,56653E-08	0,000148515
Photochemical oxidant formation: human health kg Nox-Eq	1,28307E-06	4,68856E-07	0,000193801	0,000144	4,42161E-07	0,000339995
Photochemical oxidant formation: terrestrial ecosystems kg Nox-eq	1,34276E-06	4,86517E-07	0,000200241	0,000144	4,55011E-07	0,000346526
Water use m3	6,03978E-06	6,11436E-08	0,000250811	0	6,2941E-08	0,000256975

## Appendix D

Energy allocation scenario (92,4%)	Production of plant components phase + transport	Construction phase	Gasification phase + transport	Use phase	End of life+ transport	Total impact
Acidification: terrestrial kg SO2-eq	2,23287E-06	2,07588E-07	9,76525E-05	0,00005184	1,71946E-07	0,000152105
Climate change kg Co2-eq	0,000523487	6,57094E-05	0,017093804	0,003865324	4,08141E-05	0,021589139
Ecotoxicity: freshwater kg 1,4-DCB-eq	0,000235131	7,20812E-07	0,001383936	0	8,60002E-05	0,001705788
Ecotoxicity: marine kg 1,4-DCB-eq	0,000338971	1,49972E-06	0,002188684	0	0,000103132	0,002632286
Ecotoxicity: terrestrial kg 1,4-DCB-eq	0,033607324	0,000513013	0,453456645	0	0,000365088	0,48794207
Energy resources: non-renewable, fossil kg oil-eq	0,000119316	1,89016E-05	0,005539452	0	1,13282E-05	0,005688997
Eutrophication: freshwater kg P-eq	2,77665E-07	2,3388E-09	6,03921E-06	0	1,42444E-09	6,32064E-06
Eutrophication: marine kg N-eq	7,23298E-08	6,9958E-10	7,05344E-07	0,00001296	4,06222E-10	1,37388E-05
Human toxicity: carcinogenic kg 1,4-DCB-eq	0,004861515	9,44658E-06	0,00704425	0	6,88632E-06	0,011922097
Human toxicity: non-carcinogenic kg 1,4-DCB-eq	0,001722732	9,75881E-06	0,04193831	0	3,49764E-05	0,043705777
Ionising radiation kBq CO-60-eq	2,90358E-05	6,84836E-07	0,002591778	0	3,33243E-07	0,002621832
Land use m2*a crop-eq	1,26688E-05	2,27995E-07	0,117561122	0	1,70522E-07	0,117574189
Material resources: metals/minerals kg Cu-eq	5,21648E-05	7,77819E-07	0,00047093	0	5,22376E-07	0,000524395
Ozone depletion kg CFC-11-Eq	1,18676E-10	1,76475E-11	5,55205E-08	0	1,40888E-11	5,56709E-08
Particulate matter formation kg PM2.5- Eq	1,09504E-06	1,02196E-07	0,000122945	0,00001584	8,95774E-08	0,000140072
Photochemical oxidant formation: human health kg Nox-Eq	1,20142E-06	4,39019E-07	0,000181468	0,000144	4,14023E-07	0,000327522
Photochemical oxidant formation: terrestrial ecosystems kg Nox-eq	1,25731E-06	4,55556E-07	0,000187498	0,000144	4,26055E-07	0,000333637
Water use m3	5,65542E-06	5,72525E-08	0,00023485	0	5,89355E-08	0,000240622

Carbon sequestration scenario	Production of plant components phase + transport	Construction phase	Gasification phase + transport	Use phase	Use phase transport	End of life + transport	Total impact
Acidification: terrestrial kg SO2-eq	2,41685E-06	2,24693E-07	0,000105699	0,00005184	5,74562E-07	1,86114E-07	0,000161
Climate change Kg Co2-eq	0,000566622	7,11238E-05	0,01850233	-0,02557201	0,000441507	4,41772E-05	-0,00595
Ecotoxicity: freshwater kg 1,4 -DCB-eq	0,000254505	7,80207E-07	0,001497972	0	1,19222E-05	9,30866E-05	0,001858
Ecotoxicity: marine Kg 1,4 -DCB-eq	0,000366902	1,62329E-06	0,002369031	0	2,68803E-05	0,00011163	0,002876
Ecotoxicity: terrestrial kg 1,4 -DCB-eq	0,036376561	0,000555285	0,490821386	0	0,013025936	0,000395171	0,541174
Energy resources: non-renewable, fossil kg oil-eq	0,000129148	2,04591E-05	0,005995901	0	0,00013693	1,22616E-05	0,006295
Eutrophication: freshwater kg P-eq	3,00545E-07	2,53152E-09	6,53684E-06	0	2,92197E-08	1,54181E-09	6,87E-06
Eutrophication: marine Kg N-eq	7,82898E-08	7,57226E-10	7,63464E-07	0,00001296	6,00792E-09	4,39695E-10	1,38E-05
Human toxicity: carcinogenic kg 1,4 -DCB-eq	0,005262102	1,0225E-05	0,007624694	0	8,04501E-05	7,45375E-06	0,012985
Human toxicity: non-carcinogenic Kg 1,4 -DCB-eq	0,001864685	1,05629E-05	0,045394019	0	0,000345071	3,78585E-05	0,047652
Ionising radiation kBq CO-60-eq	3,14284E-05	7,41267E-07	0,00280534	0	7,01117E-06	3,60702E-07	0,002845
Land use m2*a crop-eq	1,37127E-05	2,46782E-07	0,127248135	0	1,65623E-05	1,84573E-07	0,127279
Material resources: metals/minerals kg Cu-eq	5,64632E-05	8,41911E-07	0,000509734	0	8,60961E-06	5,6542E-07	0,000576
Ozone depletion kg CFC-11-Eq	1,28455E-10	1,91016E-11	6,00954E-08	0	1,96406E-10	1,52497E-11	6,05E-08
Particulate matter formation kg PM2,5 - Eq	1,18528E-06	1,10617E-07	0,000133076	0,00001584	3,00309E-07	9,69585E-08	0,000151
Photochemical oxidant formation: human health kg Nox-Eq	1,30042E-06	4,75194E-07	0,000196421	0,000144	6,86658E-07	4,48138E-07	0,000343
Photochemical oxidant formation: terrestrial ecosystems kg Nox-eq	1,36091E-06	4,93094E-07	0,000202948	0,000144	7,83882E-07	4,61162E-07	0,00035
Water use m3	6,12142E-06	6,19701E-08	0,000254202	0	6,90735E-07	6,37918E-08	0,000261





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