Methanol produced from biomass gasification

Life cycle-assessment of the environmental impacts in the Netherlands for Torrgas

MSc thesis

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Abstract

This study investigates the environmental impacts of producing bio-methanol from various biomass feedstocks, including forest residues, demolition wood, barley straw, and wood chips scenario. Using a consequential Life Cycle Assessment (cLCA), the research compares the impacts of these feedstocks, evaluates the effect of incorporating an electrolyser, and contrasts bio-methanol production with conventional natural gas-based methanol. Biochar produced as a byproduct is assessed for its potential as a replacement for pulverized coal in steel manufacturing. Additionally, the study explores hydrogen production as an alternative to methanol.

Data were obtained from Torrgas, and the analysis was conducted using the SimaPro software, focusing on eight impact categories: Global Warming Potential (GWP), Terrestrial Acidification Potential (TAP), Freshwater Eutrophication Potential (FEP), Marine Eutrophication Potential (MEP), Land Use Potential (LOP), Mineral Resource Scarcity (MRS), Fossil Resource Scarcity (FRS), and Water Consumption Potential (WCP).

The results indicate that the forest residues scenario exhibits the highest environmental impacts, while the demolition wood scenario shows the lowest. The barley straw scenario demonstrates intermediate impacts across the assessed categories. Biochar, produced as a byproduct, presents a substantial opportunity for carbon sequestration and could replace pulverized coal in steel manufacturing at varying replacement ratios. The addition of an electrolyser increases methanol yield by 57% but also raises environmental impacts. Hydrogen production as an alternative product was found to have a better environmental profile compared to bio-methanol from a cradle-to-gate perspective, and it also outperforms hydrogen produced by steam methane reforming.

In conclusion, this LCA confirms that bio-methanol, particularly from demolition wood, offers a more sustainable alternative to fossil fuel-derived methanol, with significantly lower GWP. The use of biochar as a byproduct adds further environmental benefits by potentially replacing pulverized coal in industrial applications. However, the addition of an electrolyser, while enhancing methanol yield, also increases environmental impacts, highlighting the trade-offs between production efficiency and sustainability. Comparatively, hydrogen production demonstrates superior environmental performance from a cradle-to-gate perspective, and it also has a lower environmental impact compared to hydrogen produced via steam methane reforming. Nonetheless, bio-methanol remains more advantageous from a cradle-to-grave perspective due to savings in combustion emissions. Further research with more precise data and the exploration of additional feedstocks is recommended to optimize sustainable bio-methanol production technologies.

Executive summary

This thesis examines the environmental impacts of producing methanol through biomass gasification, utilizing the gasification technology developed by Torrgas. The primary goal of the research is to evaluate the sustainability and environmental feasibility of biomass gasification for methanol production in comparison to conventional fossil fuel-based methods. The study employs a Life Cycle Assessment (LCA) methodology with a focus on cradle-to-gate boundaries, analyzing various environmental impact categories such as Global Warming Potential (GWP), acidification, eutrophication, and fossil fuel depletion. By using 1 GJ of methanol as the functional unit, the analysis enables a consistent comparison across different energy production pathways.

The research addresses the scalability of biomass gasification in the Netherlands, highlighting its significant potential for reducing greenhouse gas (GHG) emissions while acknowledging challenges related to feedstock availability and technological development. The findings underline the importance of selecting the appropriate biomass feedstock to maximize environmental benefits while minimizing trade-offs. Although biomass gasification can substantially reduce GWP, careful consideration of other environmental impacts is crucial to ensure the overall sustainability of methanol production.

The study also underscores the critical role of sustainable biomass sourcing. The environmental benefits of biomass-derived methanol are heavily dependent on sustainable supply chains. Unsustainable practices in biomass harvesting could undermine the GWP advantages by leading to deforestation, biodiversity loss, and other ecological damages.

Additionally, the research explores the potential for further environmental benefits through the utilization of biochar, a byproduct of the gasification process. Biochar presents a valuable opportunity, particularly as a replacement for pulverized coal in steel manufacturing, offering a sustainable alternative to fossil fuels while enhancing the overall resource efficiency of the biomass gasification process.

Figure 1 illustrates the LCA results, revealing that all three biomass feedstocks have a substantially lower GWP compared to natural gas-based methanol production. Specifically, forest residues and demolition wood exhibit GWPs of 15 and 12 kg CO2-eq respectively, which are considerably lower than the 40 kg CO2-eq associated with natural gas methanol production (cradle-to-gate). The combustion of methanol (cradle-to-grave) would almost triple the GWP impact compared to just the production phase

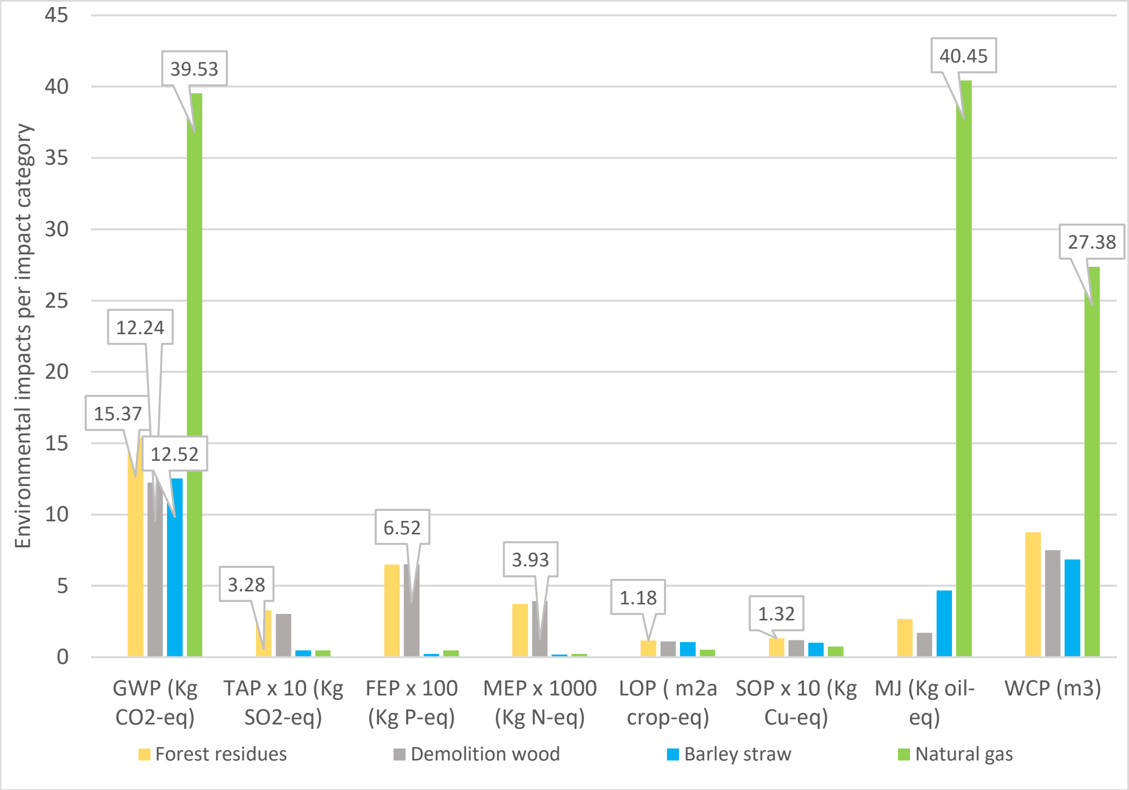

Figure 1: Comparative Environmental Impacts of Methanol Production from Different biomass feedstocks and natural gas.

In terms of other environmental impacts, the biomass feedstocks show varying levels of performance. For instance, in the categories of Terrestrial Acidification Potential (TAP) and Freshwater Eutrophication Potential (FEP), barley straw performs the best with the lowest impact values. However, all biomass options present higher impacts in Land Occupation Potential (LOP) and Water Consumption Potential (WCP) compared to natural gas, reflecting the trade-offs inherent in bio-based methanol production.

The results of this study reveal significant differences among the biomass scenarios analyzed. The forest residues scenario exhibits the highest environmental impacts, mainly due to transport-related emissions, while the demolition wood scenario shows the lowest impacts but requires significant infrastructure investment, such as the construction of a torrefaction unit in Amsterdam. Barley straw, while promising, requires technological advancements in the Torrgreen mobile torrefaction technology for its full potential to be realized. The study also highlights the substantial role of biochar, which, across all scenarios, offers considerable benefits in reducing overall GWP when used as a replacement for pulverized coal in industrial applications. This byproduct's potential for carbon sequestration adds a valuable dimension to the sustainability of biomass gasification.

Finally, the study's findings indicate that the forest residues scenario has the highest environmental impacts, largely due to significant transport-related emissions, whereas the demolition wood scenario demonstrates the lowest impacts. However, this scenario would require the construction of a torrefaction unit in Amsterdam, and further development and detailed analysis are necessary to evaluate its feasibility accurately. Similarly, the barley straw scenario shows promise, but its viability hinges on advancements in the Torrgreen mobile torrefaction technology. The integration of an electrolyser increases environmental impacts across most categories while boosting methanol yield by 57%, presenting a clear trade-off between production efficiency and environmental sustainability. Bio-methanol consistently exhibits a lower GWP compared to natural gas-based methanol, underscoring its potential as a more sustainable alternative. Nevertheless, while hydrogen production outperforms in environmental terms from a cradle-to-gate perspective, bio-methanol proves more beneficial from a cradle-to-grave perspective due to the savings in combustion emissions.

Further research is recommended to improve the sustainability of bio-methanol production. This includes gathering more precise data, especially for feedstock transportation and torrefaction processes, and exploring additional biomass feedstocks. Future studies should also investigate the long-term impacts of biochar use and consider integrating renewable energy sources to further reduce environmental impacts. These efforts will help optimize bio-methanol production and enhance its environmental benefits

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List of abbreviations

aLCA	Attributional Life cycle assessment
BECCS	Bioenergy with carbon capture and storage
BS	Barley straw
CH_4	Methane
cLCA	Consequential Life cycle assessment
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	carbon dioxide
CP	Current policy
DW	Demolition wood
FEP	Freshwater Eutrophication Potential
FR	Forest residues
FU	Functional unit
GHG	Greenhouse gas
GJ	Gigajoule
H_2	Hydrogen
H_2O	Water
HTG	High temperature gasifier
ISO	International Organization for Standardization
Km	Kilometre
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle Impact assessment
LOP	Land Occupation Potential
LPG	Liquefied petroleum gas
LTG	Low temperature gasifier
MEP	Marine Eutrophication Potential
MJ	Fossil Resource Depletion Potential

N_2	Nitrogen
NZ	Net-zero
SOP	Soil Organic Depletion Potential
SW	Wood chips scenario
TAP	Terrestrial acidification potential
VRES	variable renewable energy sources
WCP	Water Consumption Potential

1 Introduction

Achieving the reduction and eradication of GHG (greenhouse gas) emissions demands significant technical and societal changes. Energy production and transportation are of paramount importance regarding CO_2 emission in Europe. Biomass offers a potential solution for both activities, aiding in meeting electricity demands and generating high-density fuels. Nevertheless, the low-densitiy of biomass as a renewable resource means it can only serve as a supplement to variable renewable energy sources (VRES) for power generation and transport electrification (Korberg *et al.*, 2021).

Biomass undergoes processing into gaseous and liquid forms to convert it into usable fuels. Thermochemical processing in gasifiers transforms solid biomass like woodchips, forestry products, or straw into syngas. This syngas can be directly utilized in cogeneration units or converted into simpler liquids or gases, such as methanol or methane (Korberg et al., 2021). Methanol is highly sought after worldwide due to its liquid state at ambient temperature and pressure, facilitating easy transportation and storage. Furthermore, methanol serves as a versatile precursor for olefins, formaldehyde, and dimethyl ether, providing a valuable alternative to liquefied petroleum gas (LPG) and compressed natural gas (CNG) (Zhang et al., 2023).

One of the most demanded purposes for using biofuels is as fuel for maritime transport. Maritime transport plays a vital role in global trade, with over 80% of world merchandise trade volumes carried out via sea routes. This transportation is largely facilitated by ships fuelled by combustion of fossil fuels. The maritime sector consumes over 200 million tons of fuel annually. An effective strategy to mitigate emissions from shipping involves transitioning from fossil fuels to renewable alternatives like biofuels. Biofuels are often regarded as CO_2 neutral since the carbon emitted during combustion is absorbed by the growing plants, offering a promising solution to reduce carbon emissions in the shipping industry (Svanberg et al., 2018).

Torrgas Technology BV is a Dutch technology company whose main activity consist of producing sustainable syngas which can be applied existing conversion technologies to produce biofuels and green chemicals products through a (two-step) gasification process using torrefied feedstock from biomass residues. In this study, the woody biomass residues are pelletized and torrefied using Torrcoal[1] technology while the agricultural residues are pelletized and torrefied using Torrgreen[2] mobile technology. Once the green syngas is produced, the last step before developing the final biofuel includes a gas cleaning process and the final synthesis of the biofuel. In this study, methanol is the final product obtained, therefore the technological processes that includes gasification, syngas cleaning and methanol synthesis is referred to as Torranol.

This study will perform a Life-Cycle Assessment (LCA) of bio-methanol production, analysing four different scenarios, each utilizing raw biomass from distinct feedstock sources. Initially, two possible applications for the biochar produced as a byproduct were considered, but due to time constraints,

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[1] Torrcoal is a torrefaction technological supplier company with the aim of producing torrefied biomass from woody biomass residues.('PPT-4-Torr-Coal-Jan-Brouwers', no date).

[2] Torrgreen is a mobile torrefaction unit that can be placed next to the crop, use the crop byproducts that are originated after the harvest and convert it into torrefied pellets.

only one application will be developed. While marine biofuels are a possible alternative, the final product of this study is the bio-methanol itself. In addition to the three primary feedstock sources developed by Torrgas, this study includes an additional scenario using wood chips originated in Sweden as a feedstock source. This scenario is included as it represents a common biomass feedstock scenario for the entire IEA bioenergy intertask project. The wood chips are derived from forest residues in Sweden, with torrefaction and gasification processes occurring within Sweden. To facilitate clear comparisons, the torrefaction and gasification impacts for the Swedish wood chips scenario are assumed to be the same as those for the forest residues scenario studied in this project. This scenario will be referred as “wood chips scenario”.

1.1 Research question: Environmental impacts assessment

What are the environmental impacts caused from cradle-to-methanol production using torrefied pellets from four different sources?

The main focus of this thesis will be to determine and compare the following environmental impact categories: global warming potential, land use, water use, metal use, eutrophication and acidification. The LCA’s of the three sources will allow and simplify the process of comparing the different environmental impact categories. The two different strategies for the use of the resulting biochar entails another route where the final impact categories encountered can be compared.

The environmental impacts will involve the pre-treatment processes (such as the wood chipping process, the torrefaction and the pelletization), the gasification process (low temperature gasifier, high temperature gasifier, final conversion of the syngas to methanol and methane that includes a water gas shift process), and final exothermic routes that yield in the final methanol product.

1.1.1 Sub question 1

What are the impacts of the biochar produced as a by-product?

The two different strategies for the use of the resulting biochar consist in the use of biochar as a replacement of pulverized coal in the steel industry and a replacement of fertilizers for agriculture. These two routes will be modelled for the biochar produced from forest residues and barley straw. The biochar produced from construction and demolition waste wood[3], instead of final route as a fertilizer, will be considered as a soil improver in urban green spaces.

1.1.2 Sub question 2

What are the impacts caused by adding an electrolyser after the syngas is produced?

An alternative route to boost the methanol yield after the syngas is produced in the gasification process is by using an electrolyser. An electrolyser boosts methanol yield by adding hydrogen, thereby optimizing the H_2/CO ratio in syngas from biomass gasification. This enhances CO conversion efficiency and utilizes CO_2. When powered by renewable energy, it produces green hydrogen, reducing the carbon footprint and storing renewable energy in methanol. This study will compare

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[3] Construction and demolition waste (CDW) comprises solid wastes like building debris, rubble, concrete, steel, bricks, and timber from construction, demolition, or renovation activities. Demolition wood constitutes the second-largest portion of CDW, contributing 20–30% of the total waste stream (Jahan et al., 2022).

the positive and negative effects of using an electrolyser, including the benefits of the increased yield and sustainability and the drawback of higher electricity consumption.

1.1.3 Sub question 3

What are the environmental impacts if hydrogen is the end product of the entire project instead of methanol

The final environmental impacts calculated in this master thesis will be calculated per Gigajoule (GJ) of methanol produced. Torrgas provided the student with an estimation of the hydrogen that can be produced following the same steps to produce the syngas. A comparison of the final impacts allocated to a GJ of hydrogen produced is performed.

1.2 Case study

The case study included in this master thesis will determine and assess environmental impacts of the production of methanol through a gasification process and using torrefied pellets as feedstock source. The technology developed by Torrgas includes all the gasification processes that are explained in the methodology section. The torrefied pellets are the form of fuel used by the gasification process. The three different types of feedstocks selected are; forest residues, demolition waste wood and barley straw. For forest residues and demolition waste wood, the torrefaction and palletisation processes are developed in the local plant of the countries where the feedstock is gathered. The barley straw is pelletized and torrefied using the Torgreen mobile torrefaction technology. Additionally, an extra scenario using Swedish wood chips as a feedstock source is included. This scenario represents a common biomass feedstock scenario for the entire "IEA bioenergy Intertask 5" project. The wood chips are derived from forest residues in Sweden, with torrefaction and gasification processes occurring within Sweden. To facilitate clear comparisons, the torrefaction and gasification impacts for the Swedish wood chips scenario are assumed to be the same as those for the forest residues scenario studied in this project.

Biochar as a by-product of the low temperature gasifier can be either used for the steel manufacturing or reintroduced to the soil as an agricultural fertilizer for the forest residues and barley straw scenario. Biochar as a by-product of demolition waste wood feedstock is considered optimal to be used in the steel manufacturing industry and can be re-introduced into the soil of urban green spaces.

1.3 Relevance

The findings from this study will hold significance for Torrgas. It is crucial to define and compare the environmental impacts of Torranol to assess and quantify the advantages of producing methanol from biomass gasification compared to conventional (natural gas) methanol production methods.

1.4 Geographical scope

Torrgas pilot plant will be located in Westpoort, Amsterdam, The Netherlands. The feedstock coming from forest residues is produced, torrefied and pelletized in Estonia. In this country, forests cover a half (51,0%) of the total land territory (4,5 million ha)Haga clic o pulse aquí para escribir texto.. The torrefied pellets will be transported by truck from the torrefaction plant to the port of Tallin, shipped to the port of Rotterdam by maritime shipment, and finally the torrefied pellets are transported to the Torranol plant by barge.

Demolition wood is obtained, torrefied and pelletized in the Netherlands. The final torrefied pellets are obtained from Pre-Zero, located also in Westpoort, Amsterdam. The final transport process of the torrefied biomass between Pre-zero and Torranol can be easily arranged since both companies are located in Westpoort, Amsterdam.

Barley straw is produced as an agricultural residue of barley crops form the north of France, the straw is pelletized and torrefied at the crop using the Torgreen mobile technology. The final torrefied pellets are shipped from the port of Le Havre to the port of Rotterdam and finally transported by barge to the Torranol factory.

1.5 Identification of literature gap and literature review

Due to the specificity of the case study, finding articles with information about the transport of biomass and materials for the torrefaction and gasification units to compare with data provided by Torrgas was not possible. The two-step gasification process used to produce syngas and obtain biochar as a product is also a very uncommon topic. Therefore, instead of comparing the company's information with other articles, extended and detailed explanations provided during meetings with the company were essential to support the theoretical background of the project.

Previous LCA analyses in which the final product is methanol and the feedstock is biomass have been conducted. For instance, one study examined methanol production through the BTL (Biomass to Liquid) route, revealing significant differences in environmental performance among existing biofuel production systems, even when using the same feedstock. These differences are influenced by various factors such as farming practices and biomass conversion technology. For example, the production of methanol from sugarcane bagasse demonstrated to be a feasible alternative for replacing fossil methanol derived from natural gas (Renó et al., 2011).

Another study focused on bio-methanol production through a new process configuration designed to improve environmental performance compared to state-of-the-art technologies. This environmental evaluation, conducted according to the LCA methodology and using the ReCiPe impact assessment method, highlighted better environmental performance in eight of the nine impact categories studied for wooden biomass scenarios. This study evaluated wooden biomass as a feedstock source and performed a scenario analysis targeting different energy sources, demonstrating the significance of geographical location and energy source on environmental impacts (Galusnyak et al., 2023).

2 Technological background

2.1 Wood chipping

The wood chipping process is a crucial preparatory step in biomass conversion, involving the mechanical reduction of large woody materials into smaller, uniform chips. This process begins with the harvesting and collection of forestry residues, which are then directly processed on-site, eliminating the need for transportation. The biomass is fed into a woodchipper, where sharp blades cut it into chips of adjustable size. These chips are screened for uniformity and temporarily stored before further processing. Chipping increases surface area, ensures uniform processing, enhances efficiency, and prepares the biomass for subsequent stages like drying, torrefaction, and gasification. Processing at the same location as harvesting reduces logistics costs and streamlines the workflow (Johansson et al., 2006).

2.2 Biomass Torrefaction: Definition, Process, and Categorization

Biomass torrefaction is a mild pyrolysis process designed to enhance the fuel properties of wood. This thermal treatment typically occurs within a temperature range of 225 to 300°C in an inert atmosphere, preventing combustion. During torrefaction, the hemicellulose fraction of the wood undergoes decomposition, resulting in the formation of torrefied wood and volatile compounds. This process is also known as roasting or high temperature drying and occurs at atmospheric pressure (Prins, Ptasinski and Janssen, 2006);(Kota et al., 2022).

The volatiles released during torrefaction can be categorized into two types: condensable volatiles, which primarily include water and acetic acid, and permanent gases, which mainly consist of carbon dioxide (CO_2) and carbon monoxide (CO). This categorization is crucial for understanding the chemical changes occurring during torrefaction and for optimizing the process for various biomass types (Tumuluru *et al.*, 2021).

2.2.1 Improvements Using Torrefaction

Torrefaction significantly enhances various properties of biomass, making it more suitable for energy production and other applications. One of the most notable improvements is the increase in energy density; torrefied biomass exhibits approximately 30% higher energy density compared to its original form (Niu *et al.*, 2019). Additionally, torrefied biomass becomes more hydrophobic, improving its storage and handling characteristics by making it more resistant to moisture. The process also enhances the ignitability and combustion reactivity of biomass, making it easier to ignite and burn more efficiently. Furthermore, torrefied biomass shows improved gasification reactivity, which is beneficial for its use in gasification processes. The grindability of biomass is also improved, facilitating its use in various applications that require finely ground material (Tumuluru *et al.*, 2021).

2.2.2 Technological Advancements and Applications

Recent advancements in torrefaction emphasize low-temperature pyrolysis to convert biomass into energy-dense solid fuel with improved properties. This method is increasingly recognized as a promising pretreatment technique for producing solid biofuels with higher heating values and better mechanical properties. Such improvements make torrefied biomass a viable option for large-scale biomass utilization, contributing to more sustainable and effective bioenergy solutions (Kota *et al.*, 2022).

By utilizing torrefaction, significant improvements in the efficiency and utility of biomass as a renewable energy source can be achieved. This process not only enhances the fuel properties of biomass but also provides a sustainable method for converting various types of biomasses into valuable energy resources, supporting the transition to cleaner energy systems. Biomass torrefaction is a mild pyrolysis process that aims for improving the fuel properties of wood. This process typically occurs within a temperature range of 225 to 300°C, during which the hemicellulose fraction of the wood undergoes decomposition, resulting in the formation of torrefied wood and volatile compounds. In recent years, there has been a growing emphasis on low-temperature pyrolysis, known as torrefaction, which occurs in an inert atmosphere within the temperature range of 200 to 300°C (Prins, Ptasinski and Janssen, 2006).

Following torrefaction, significant improvements are observed in various biomass properties, including mass and energy density, hydrophobicity, ignitability, combustion and gasification reactivity, and grindability. Torrefaction, also referred to as roasting or high temperature drying, involves subjecting biomass to thermal treatment in an inert environment at atmospheric pressure and temperatures ranging from 200 to 300°C. This method is promising as a pretreatment technique for converting biomass into energy-dense solid fuel with improved grindability and increased heating value (Kota *et al.*, 2022).

During the torrefaction process, biomass, particularly the hemicellulose component, undergoes partial decomposition, releasing various types of volatiles. These volatiles can be categorized into condensable volatiles, primarily containing water and acetic acid, and permanent gases, primarily containing carbon dioxide and carbon monoxide. The resulting torrefied biomass in solid form exhibits approximately 30% higher energy density compared to the original biomass (Niu et al., 2019).

2.3 Pelletization of torrefied biomass

Pelletization is a critical step following the torrefaction of biomass to enhance its utility. The process addresses the naturally low bulk density of torrefied biomass by compacting it under specific conditions. This is typically achieved through pelletizing or briquetting methods, selected based on the equipment and desired product size. Temperature plays a significant role in this process by affecting the lignin softening point, aiding pellet formation. Additionally, compression pressure is crucial, as higher pressures generally increase pellet density, although the effect on hardness can vary(Chen, Peng and Bi, 2015).

In essence, pelletization not only improves the handling and transport of torrefied biomass but also optimizes its combustion characteristics. This densification process ensures that the biomass is more energy-dense and easier to manage, making it a more viable fuel source for various applications. Understanding the interplay between temperature, pressure, and the inherent property of biomass is essential for producing high-quality pellets (Niu *et al.*, 2019)

2.4 Gasification

Gasification is a thermochemical process that converts carbon-based fuels into synthesis gas (syngas) at high temperatures. This process involves partial oxidation of the fuel, resulting in a mixture primarily composed of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), water vapor

(H_2O), methane (CH_4), and nitrogen (N_2), along with trace amounts of hydrocarbons and contaminants like carbon particles, tar, and ash (Prabir Basu, 2013);(Couto et al., 2013).

In the gasification process developed by Torrgas technology, torrefied pellets are first fed into a low temperature gasifier (LTG). In the LTG, partial oxidation occurs at 700ºC, producing biochar and low temperature gas. The biochar is cooled and discharged, while the low temperature gas is fed into a high temperature gasifier (HTG). In the HTG, nitrogen-free gas is formed at 1200ºC. This high-temperature process ensures that no tar is produced, improving the purity and quality of the syngas. In this process, a Vacuum Pressure Swing Adsorption (VPSA) system is crucial for gas separation and purification (Zhang et al., 2022). The VPSA system efficiently separates the desired gases from the mixture, removing impurities and ensuring that the syngas meets the required specifications for subsequent processes. This system enhances the overall efficiency and output quality of the gasification plant (Xiao et al., 2021).

2.5 Biochar

Biochar is a type of char derived from biomass that is applied to soil as a soil amendment or a carbon sequestration agent. The practice of using biochar dates back millennia in certain agricultural traditions, but contemporary interest has surged due to the study of terra preta soils in the central Amazon. These exceptionally fertile soils contain man-made charcoal, which serves as a crucial component of soil organic matter, contributing to their remarkable fertility and productivity (Brewer et al., 2009).

Char is produced during both pyrolysis and gasification processes, constituting approximately 15–20% and 5–10% of the original feedstock mass, respectively. The optimal utilization of this byproduct depends on local economic conditions and the specific properties of the char (Brewer et al., 2009). A promising application of char produced as a byproduct of gasification is its use as biochar.

In addition to agricultural uses, the iron and steel industry has identified biochar as a potential replacement for fossil fuels such as coal and coke, which are extensively used for heat generation and as reducing agents in steel production. This sector is one of the largest globally, accounting for around 20% of industrial energy consumption and significant CO_2 emissions. The search for sustainable alternatives has led to considerable interest in biochar due to its acceptable adaptation and comparable metallurgical properties (Safarian, 2023).

2.6 Electrolyser

Electrolysis has been scaled to augment the hydrogen content of syngas, achieving a stoichiometric balance of hydrogen, carbon monoxide, and carbon dioxide for the subsequent catalytic methanol synthesis (De Padova, Giglio, and Santarelli, 2024). When an electrolyser is added to the production of methanol via biomass gasification, it can potentially eliminate the need for a VPSA system (Porter, Cobden and Mahgerefteh, 2022).

An electrolyser uses electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O_2), producing high-purity hydrogen. The syngas from biomass gasification typically consists of a mixture of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and other impurities. For methanol synthesis, an optimal ratio of H_2 to CO (typically around 2:1) is required. The hydrogen produced by the electrolyser can be directly added to the syngas, ensuring the desired H_2/CO ratio for efficient methanol production (Air Liquide, 2024). Since electrolyser-produced hydrogen is already pure, the main requirement for gas purification shifts towards adjusting the CO_2 levels. Electrolysers do not produce CO_2, so the need to remove CO_2 from the hydrogen stream using VPSA is eliminated. Consequently, with an electrolyser supplying high-purity hydrogen, there is no need to separate hydrogen from the syngas using VPSA.

2.7 Methanol from syngas

Methanol (MeOH) is produced from syngas by the hydrogenation of carbon oxides in the presence of a catalyst. Chromium oxide copper oxide or zinc oxide-based can both be used as catalyst (Rauch, Hrbek and Hofbauer, 2014). The equation for this reaction reads as follows:

$$CO + 2H_2 \leftrightarrow CH_3OH$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$$

The reactions release heat and result in a net decrease in molar volume. As a result, equilibrium is favoured by high pressure and low temperature. Traditionally, methanol is produced in two-phase systems, where the reactants and products constitute the gas phase, while the catalyst is in the solid phase(Rauch, Hrbek and Hofbauer, 2014).

Methanol is in high demand globally due to its numerous advantages, including its liquid state at ambient temperature and pressure, which facilitates transportation and storage. Additionally, methanol can be used to produce olefins, formaldehyde, and dimethyl ether, making it a valuable alternative to liquefied petroleum gas (LPG) and compressed natural gas (CNG) (Tammy Klein, 2020).

3 Theoretical background

The theoretical background of this thesis involves conducting a Life Cycle Assessment (LCA). Established by the International Standardization Organisation (ISO) in 1997 and updated in 2006 (ISO 14040:2006; ISO 14044:2006). The LCA method evaluates the entire life cycle of a product or system. It quantitatively assesses a wide range of environmental impacts, providing a comprehensive analysis of environmental performance (Hauschild, Rosenbaum and Olsen, 2017).

3.1 Concepts of Life Cycle Assessment

3.1.1 Goal and Scope

A fundamental aspect of defining the goal and scope of a Life Cycle Assessment (LCA) is the Functional Unit (FU), a quantifiable measure of the performance or functionality of the product or system under evaluation. In this study, the FU is one GJ of methanol produced from the biomass gasification process. This selected quantity serves as the reference point for all subsequent environmental impact assessments. Establishing a clear and precise FU is crucial for ensuring meaningful and fair comparisons between different systems and processes. All impacts in this study are represented per GJ of methanol produced. (ISO 14044, 2006).

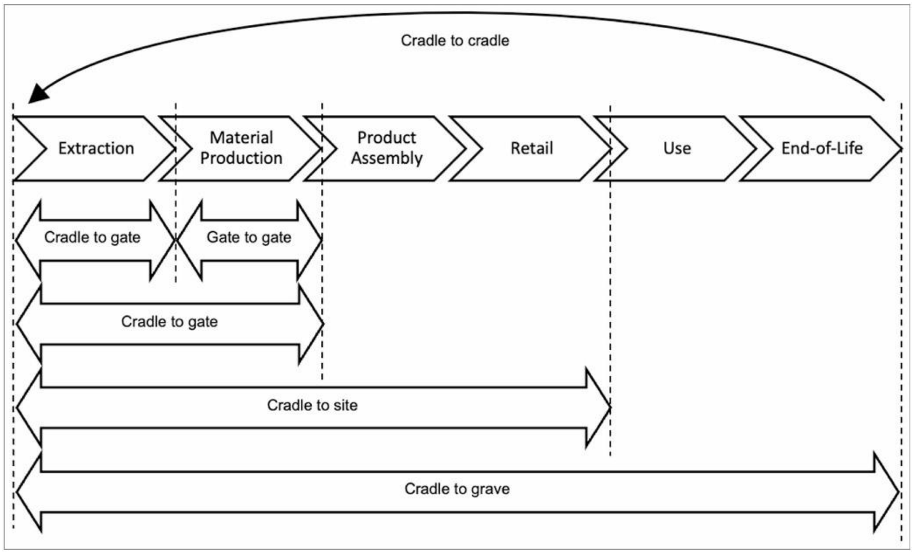

Figure 2: Lifecycle stages (Çimen, 2023).

Equally crucial in the goal and scope definition is the determination of system boundaries, which specifies the extent of the impacts considered across different stages of the product (ISO 14044, 2006). This can encompass all stages from raw material extraction, production, and transportation to the use phase and end-of-life scenarios, commonly known as cradle-to-grave. The cradle-to-gate system boundary evaluates only the environmental impacts from raw material extraction, transport to producer, and production phase. It does not include transportation to consumer, use phase, and end-of-life scenarios, Figure 2 represents the lifecycle stages previously described. For circular product design, the cradle-to-cradle approach is often chosen, replacing waste stages in the end-of-life scenarios with reuse/recycling steps. The selected system boundaries will depend on the research objectives and the availability of data or the feasibility of data collection in experiments (Çimen, 2023).

3.1.2 Inventory Analysis

An essential part of LCA is data collection and inventory analysis, in which data on inputs and outputs of each life cycle stage are gathered (ISO 14044, 2006). A distinction can be made between primary and secondary data. Primary data, in LCA terms called 'foreground' system, are measured or collected directly from a manufacturer and represent a specific facility or manufacturer. They are very specific and precise. Secondary data, in LCA terms called 'background' system, are sourced from third-party life cycle inventory databases. These data are usually less accurate, with a more general geographical and temporal scope(Muhammad and Kabir, 2016). Primary data is preferred because of its accuracy and completeness. However, it significantly increases time investments and makes the inventory phase of the research more complex. Secondary data are usually readily available in life cycle inventory databases, such as EcoInvent[4]. The accuracy and comprehensiveness of data collection are critical as they ensure the reliability and validity of the LCA results. Inventory analyses usually also include a flowchart or table of all modelled flows and processes within the system boundaries (ISO 14044, 2006).

3.1.3 Allocation Procedures

Allocation methods are essential for distributing environmental burdens over co-products when multifunctional processes are involved. Multifunctional processes are defined as processes with multiple outputs that cannot be related to separate parts of the production process. For example, in a natural gas processing plant, the environmental impact should be allocated between the production of natural gas and the associated co-products such as propane, butane, and ethane. Another example is in biofuel production, where the environmental burdens should be distributed between bioethanol and distiller grains (the co-product) (Pennington et al., 2010).

Allocation methods distribute environmental burdens to specific products or production processes and assess how changes in conventional systems impact the overall system (Azapagic and Clift, 1999). A distinction can be made between two types of LCAs: attributional (aLCA) and consequential (cLCA) (Ekvall, 2019). cLCA considers both direct and indirect outcomes, offering a more thorough understanding of the environmental, economic, and social effects linked to a specific product or process. Attributional Life Cycle Assessment (aLCA) uses fixed allocation methods to assess the environmental impacts of specific products by examining their life cycle from production to disposal. In contrast, Consequential Life Cycle Assessment (cLCA) employs dynamic modelling and scenario analysis to evaluate the real-world impacts of decisions and policies. A common approach in cLCA is allocation at the point of substitution, distributing environmental burdens and benefits among co-products or processes based on their ability to replace each other (Brander and Wylie, 2011). This method aims to allocate impacts according to the functional equivalency of the co-products, typically by comparing their performance or functionality this study, a cLCA will be performed, focusing on understanding the broader systemic consequences of changes in product demand, supply chains, and market dynamics. This approach goes beyond isolated product impacts to consider the effects of production or consumption changes on the entire system, providing a

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[4] EcoInvent is a comprehensive Life Cycle Inventory (LCI) database that provides detailed data on industrial and agricultural processes, covering global regions with specific data regionalized by country or continent (Wernet et al., 2016).

comprehensive understanding of the environmental impacts associated with the final product (Ekvall, 2019).

3.1.4 Impact Assessment

Impact assessment involves the quantification and evaluation of environmental impacts in various (ISO 14044, 2006). To quantify impacts, specific characterization factors and models tailored to each environmental category are used. These factors convert raw data into standardized impact scores, enabling comparisons between different products. In the biofuel sector, standardized methodological choices for the Life Cycle Impact Assessment (LCIA) have been agreed upon and defined by the participants of the IEA Intertask. This standardization facilitates the comparison of different LCAs within the sector, ensuring consistency and reliability in the evaluation of environmental impacts.

3.1.5 Interpretation

Following the impact assessment, the results are subject to interpretation, the final step in the LCA. In this part of the LCA, a sensitivity analysis may be performed, depending on the accuracy and completeness of the data gathered. The interpretation phase also includes the identification of the materials or process steps that are the key contributors to the results, known as ‘hotspot identification’.

4 Methodology

The methodology proposed for the research question selected, will utilize the Life Cycle Assessment (LCA) method. LCA is a systematic approach to evaluate the environmental impact associated with a product or system throughout its entire life cycle, from raw material extraction to disposal or recycling (Hauschild, Rosenbaum and Olsen, 2017). This method quantitatively assesses a wide range of environmental impacts, including resource depletion, emissions to air, water, and soil, energy consumption, and waste generation(Hauschild, Rosenbaum and Olsen, 2017). The comprehensive nature of LCA is crucial for conducting a thorough comparison between existing practices and new technologies, enabling researchers to identify which option has the lowest environmental impact. This makes LCA an ideal choice for this study.

As is depicted in Figure 3, the LCA method consists of four distinct steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. Due to the iterative nature of the LCA process, there are feedback loops between all four phases. It is common for additional information to become available during later stages of the LCA, prompting the need to refine or revise the initial scope. Therefore, an iterative approach is fundamental to ensuring the accuracy and reliability of the LCA results (Hauschild, Rosenbaum and Olsen, 2017).

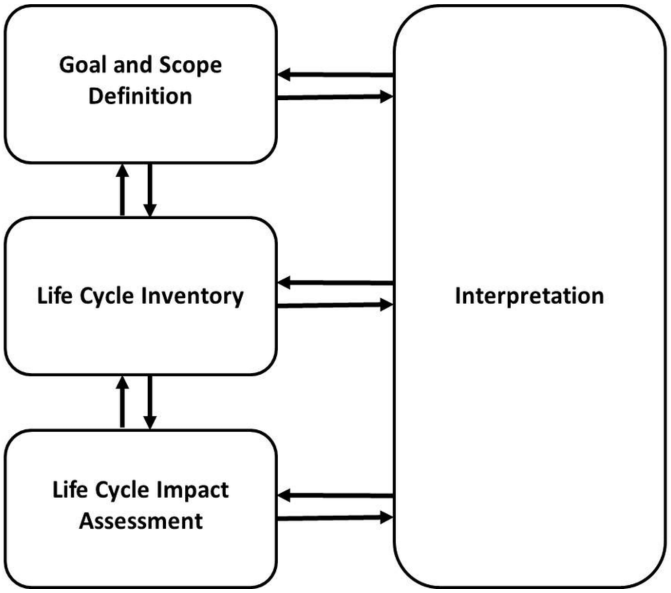

Figure 3: Phases of an LCA

4.1 Goal definition

The aim of this LCA is to analyse the environmental impacts associated with the gasification process of torrefied biomass, focusing on the production of methanol. Utilizing a cradle-to-grave approach, this study will encompass all stages and processes involved in the conversion of raw biomass into torrefied pellets, culminating in the production of methanol.

This study considers three distinct feedstock sources, initiating the assessment from the availability of raw biomass for conversion into torrefied pellets and concluding upon the production of methanol. Possible limitations due to methodological choices could take place, for instance, every different feedstock source is located in different regions of the world, for that reason, many soil properties are different from each other so the environmental impacts affecting the soil might be more sensitive in one or other region. Building upon a previous LCA conducted using similar data and scenarios, which primarily focused on quantifying the carbon footprint in grams of CO2 equivalent per MJ delivered, this study aims to broaden the scope by identifying and evaluating additional environmental impact categories. By doing so, Torrgas, the gasification company providing the data and information for this assessment, can gain insights into the overall environmental performance of different feedstock sources and make informed decisions regarding their suitability for use.

The intended audience for this assessment includes Torrgas, as the primary stakeholder in the gasification process, as well as the “IEA Bioenergy Task WP 5” which commissioned this project. This task involves collaboration among PhD and master's students from various European universities, who will collectively assess and synthesize information on technologies for hydrogen and biofuel production from biomass. Through this collaborative effort, the study aims to provide a comprehensive understanding of the environmental implications of different feedstock sources and production pathways, thereby facilitating informed decision-making and fostering sustainable energy practices within the industry.

4.2 Scope definition

To ensure a fair and relevant quantitative comparison of different methods of providing a function, understanding the functions provided by alternative product systems is essential in defining a functional unit. This unit determines both the qualitative and quantitative aspects of the function (Hauschild, Rosenbaum and Olsen, 2017).The functional unit used in this research is 1GJ of bio-methanol produced. This LCA will follow a consequential modelling framework, consequential LCA addresses the question of "what environmental impact can be attributed to product X?" or "what environmental impact is product X responsible for?" These questions hint at the subjective nature of attributing impacts to a product system or determining its impact responsibility (Hauschild, Rosenbaum and Olsen, 2017). As an additional functional unit, 1 GJ of hydrogen produced is utilized. Using two functional units allows for the comparison of the environmental impacts between these two potential final products of biomass gasification.

4.3 Inventory Analysis

During the life cycle inventory (LCI) analysis phase of an LCA, the collection of data and the modelling of the flows to, from and within the product system is done. This analysis phase is divided in five steps:

1. Identifying processes for the LCI model
2. Planning and collecting data
3. Constructing and quality checking unit processes
4. Constructing LCI model and calculating LCI results
5. Sensitivity analysis
6. Reporting

To continue with the inventory analysis exposition, the previously mentioned steps will be explained in the following paragraphs.

4.3.1 Identifying processes for the LCI model

The identification of the processes involved in the life cycle of the methanol production are visualized in Figure 4 and Figure 5. The wood chips scenario follows the same background processes than the demolition wood.

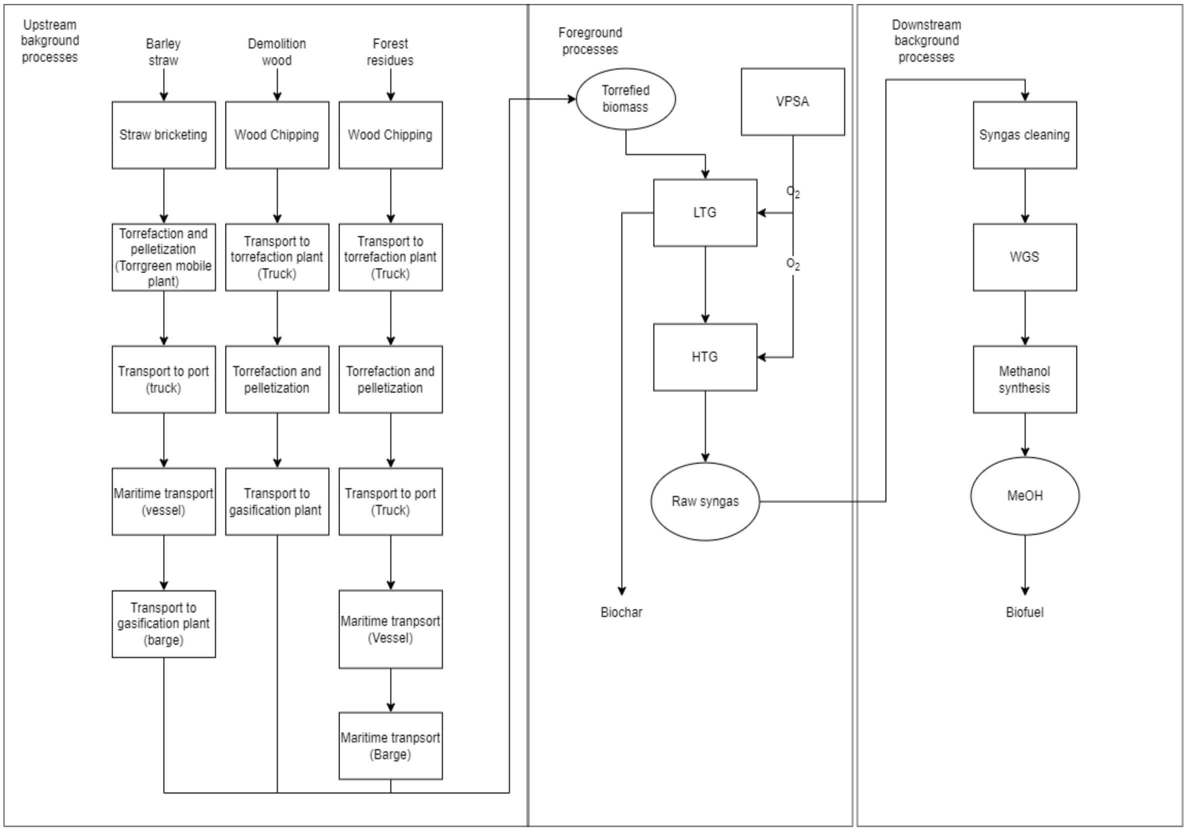

Figure 4: Flowchart of the methanol production processes.

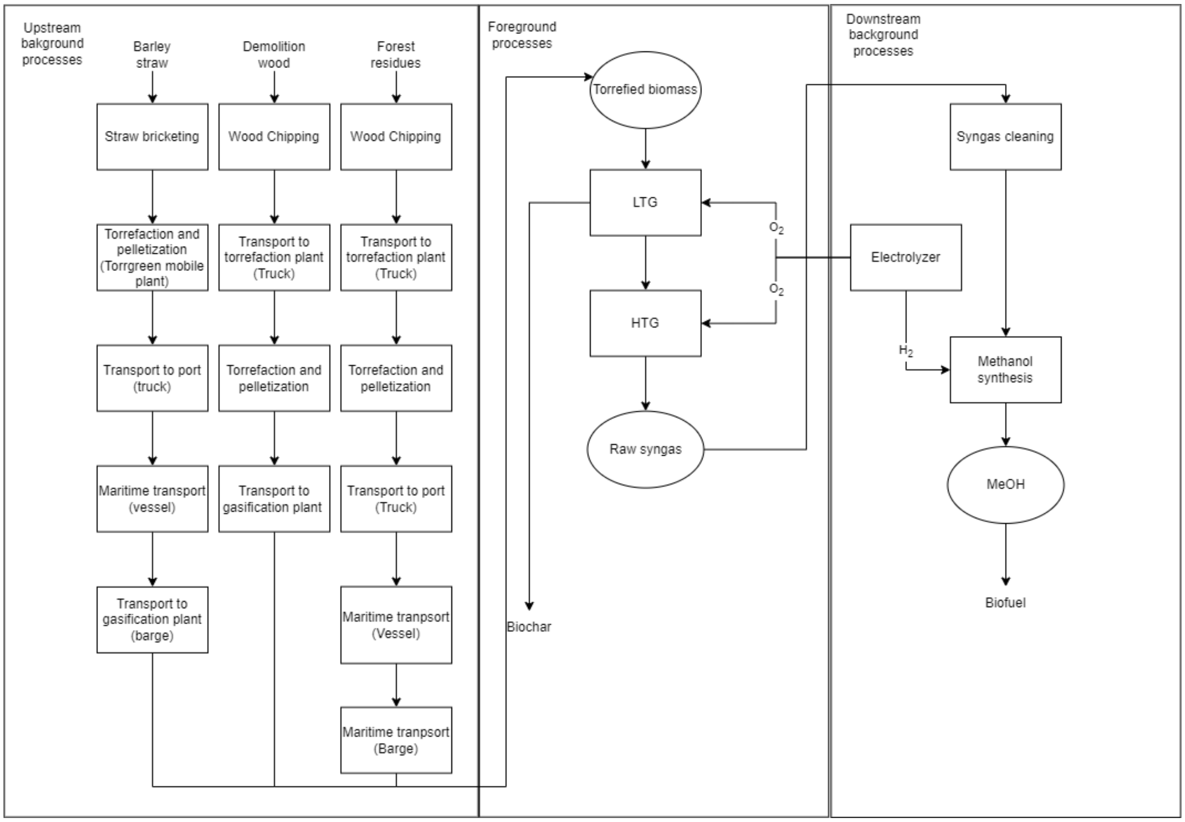

Figure 5: Flowchart of the methanol production using an electrolyser.

Multifunctionality is referred as the processes in the product system that deliver several outputs including the ones that are not being used by the reference flow of the study (Hauschild, Rosenbaum and Olsen, 2017). To handle multifunctionality, the ISO hierarchy is followed. Allocation will be avoided where subdivision is possible, if subdivision is not possible, then allocation will be avoided by system expansion or substitution approaches. Finally, allocation by physical relationship or nonphysical relationship could be performed as part of a sensitivity analysis.

4.3.2 Data collection

The part of an LCA study focused on the product system being modelled is commonly referred to as the foreground, while the sections reflecting the broader industrial economy and sourced from reference databases are termed the background (Pennington et al., 2010). Foreground data related with Torranol mass balances, utilities inputs and outputs, waste/by products and emissions were provided by the company to the student. Constructing LCI model and calculating LCI results

The Life-Cycle Inventory (LCI) model for this study follows the methodology agreed upon by the IEA Bioenergy strategic Intertask project. The primary LCI method is bottom-up, process-based, focusing on the biomass gasification technology developed by Torrgas. It includes energy and mass balances, inputs of utilities, and outputs of byproducts and emissions. For background data will use a common EcoInvent dataset using a common characterisation method ReCiPe 2016 Midpoint (H). The electricity mix will be the marginal mix for North-Western Europe in 2030. Finally, the impact categories include global warming potential, land use, water use, and metal use, with characterization methods discussed and included in SimaPro.

4.3.3 Sensitivity analysis

The sensitivity analysis conducted in this study involved two key parameters, selected by the student after analysing the results. The first analysis standardized all transport processes by using the transport data from the demolition wood scenario, which had the lowest impacts. The second analysis involved changing the marginal electricity mix to a combination of onshore and offshore wind energy, using a pre-modelled dataset that includes the environmental impacts of wind energy production in Europe

4.4 Impact assessment

Life cycle impact assessment (LCIA) aids in the interpretation of LCA studies by converting emissions and resource extractions into a concise set of environmental impact. This process utilizes characterization factors, which quantify the environmental impact per unit of stressor, such as per kilogram of resource extracted or emission released (Huijbregts, 2016).

4.5 Interpretation

The final phase of LCA involves analysing the results from the LCIA to draw conclusions and make recommendations. In this step the methods and the robustness of the results are evaluated. Furthermore, significant environmental impacts are identified and ways to reduce the environmental footprint of the product or process under study are suggested. As the LCA process is iterative in nature, there are feedback loops between all four phases. It is common in LCA for more information to become available during later stages, necessitating the refinement of the initial scope, which underscores the importance of an iterative approach (European Commission. Joint Research Centre. Institute for Environment and Sustainability., 2010).

4.6 Impact categories

The chosen impact categories for assessment are derived from commonly established methodological frameworks for LCAs, aligning with those planned to be conducted in 2024 as part of the IEA Bioenergy strategic intertask project on synergies of green hydrogen and bio-based value chains deployment. The selected categories are described in Table 1:

- Global warming potential (GWP)
- Land use
- Water consumption
- Mineral resource scarcity
- Fossil resource scarcity
- Terrestrial acidification
- Freshwater eutrophication
- Marine eutrophication

Table 1: ReCiPe 2016 impact categories (Huijbregts, 2016).

Impact category	Indicator	Abbr.	Unit
Global warming potential	Infra-red radiative forcing increase	GWP	kg CO2 to air
Land use	Occupation and time integrated transformation	LOP	m2 × yr annual crop land
Water consumption	Increase of water consumed	WCP	m3 water consumed
Mineral resource scarcity	Ore grade decrease	SOP	Kg Cu
Terrestrial acidification	Proton increases in natural soils	TAP	kg SO2 to air
Freshwater eutrophication	Phosphorus increases in fresh water	FEP	kg P to fresh water
Marine eutrophication	Nitrogen increases in marine water	MEP	Kg N to fresh water
Fossil resource scarcity	Upper heating value	MJ	kg oil

The selected impact categories for the LCIA are global warming potential (GWP), land use, water, consumption, mineral resource scarcity, fossil resource scarcity, terrestrial acidification, freshwater eutrophication, and marine eutrophication. GWP measures the potential impact of greenhouse gases on climate change. Land use evaluates effects on biodiversity and ecosystems. Water consumption highlights stress on water resources. Mineral resource scarcity considers depletion of minerals. Fossil resource scarcity reflects concerns about energy security. Terrestrial acidification assesses pollutants affecting ecosystems. Fresh water eutrophication evaluates nutrient runoff impacting water quality. Lastly, marine eutrophication assesses nutrient runoff effects on marine ecosystems. These categories provide a comprehensive assessment of environmental impacts, addressing sustainability, resource use, and ecosystem health. By using this method, all significant impacts are considered for a detailed understanding of the bio-methanol production process.

4.7 Marginal electricity mixes in Western Europe in 2030

The marginal electricity mix was determined using the methodology outlined by (Corona et al., 2020) which considers the annual growth and capital replacement ratio under both current policies and a net zero emission scenario by 2030. The calculation involved several steps. Initially, the difference between the current (2020) and projected (2030) installed capacity in Western Europe was assessed at a regional level using data from the Integrated Model to Assess the Global Environment (PBL, 2024).

Subsequently, annual growth rates were calculated considering the change in installed capacity and taking the time lapse into consideration. Then capital replacement rates were calculated based on expected plant lifetimes for each technology and subtracted from the annual growth rates, thus providing a net-growth rate. The net-growth rate defines whether a technology will be old (phased-out) or modern. Finally, a net growth is calculated for modern technologies to determine its contribution to the marginal mix. The result of marginal mix under current policy and net-zero scenarios are depicted in Table 2.

Table 2: Marginal electricity mixes

Technology	Current policy	Net-Zero
Oil	0.0%	0.0%
Natural gas	5.6%	5.6%
Coal	0.0%	0.0%
Solar PV	72.6%	71.6%
Wind	17.4%	18.3%
Hydro	1.1%	1.1%
Biomass	1.4%	1.4%
Nuclear	1.7%	1.8%
Geothermal	0.0%	0.0%
Other	0.1%	0.1%
Hydrogen	0.0%	0.0%
Solar CSP	0.1%	0.1%

To discuss the results, the current policy mix will be the energy mix studied. Both scenarios present very similar technology distribution, therefore the final results are very similar.

4.8 Transport processes.

In every different scenario, the biomass is originated from different feedstock and in a different location. In order to deliver the torrefied biomass produced to the gasification plant, a transport strategy is needed. The strategies followed are visualized in Table 3 and in Figure 6, Figure 7 and Figure 8.

Table 3: Transport processes

Scenario	Transport step	Means of conveyance	Distance (Km)	Origin	Destination
Forest residues	Transport to torrefaction plant	Truck	100	Forest location in Estonia	Torrefaction plant in Vagari
	Transport to port	Truck	150	Torrefaction plant in Vagari	Port of Tallin
	Maritime transport to Rotterdam	Vessel	1772	Port of Tallin	Port of Rotterdam
	Transport to Westpoort, Amsterdam	Barge	120	Port of Rotterdam	Torranol plant
Demolition wood	Collection and transport to torrefaction unit	Truck	150	Various location in the Netherlands	Torrefaction unit (Pre-Zero) Westpoort, Amsterdam
	Transport to Torranol plant	Conveyor belt	0.8	Torrefaction unit (Pre-Zero) Westpoort, Amsterdam	Torranol plant
Barley straw	Transport to port	Truck	200	Various crop location in the north of France	Port of Le Havre
	Maritime transport to Rotterdam	Vessel	460	Port of Le Havre	Port of Rotterdam
	Transport to Amsterdam	Barge	120	Port of Rotterdam	Torranol plant. Westpoort, Amsterdam

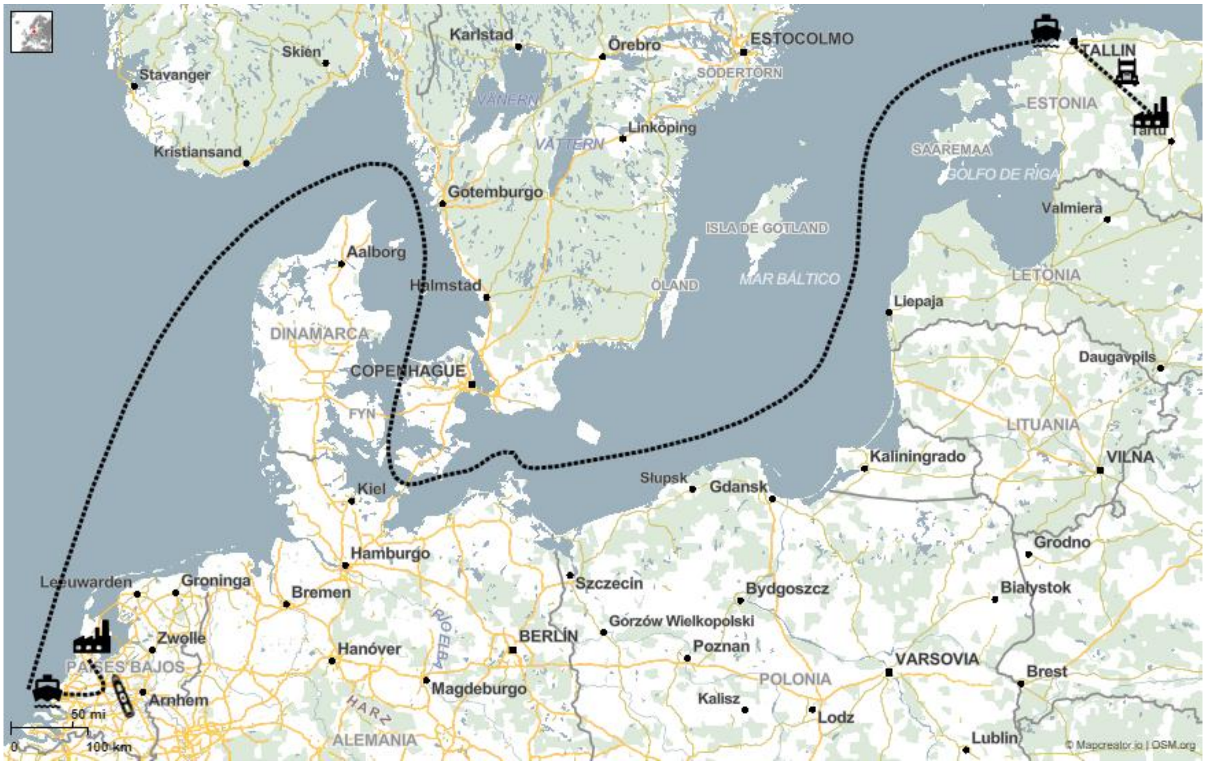

Figure 7: Forest residues transport processes.

Figure 6: Demolition wood transport processes.

Figure 8: Barley straw processes

4.9 Infrastructure materials processes

Data regarding the materials used were provided by Torrgas. The materials for the torrefaction plant correspond to a proposed future project by Torrcoal, outlining the necessary infrastructure for efficient torrefaction processes. Similarly, the materials for the gasification plant are aligned with the specifications for the future Torranol plant, designed to optimize the gasification process. The data regarding the materials used are shown in Table 4, providing a comprehensive overview of the infrastructure components for both plants.

Table 4: gasification and torrefaction plant materials

Plant	Material	Description
Torrefaction Plant	Chromium Steel	Stainless steel enriched with chromium.
	Rock Wool	Insulation material known for its thermal properties.
	Reinforced Concrete	Modelled as 98.5% concrete block and 1.5% reinforcing steel.
Gasification Plant	Chromium Steel	Stainless steel enriched with chromium.
	Rock Wool	Insulation material known for its thermal properties.
	Autoclaved Aerated Concrete	Concrete with numerous air voids, reducing density and providing good thermal insulation.
	Mastic Asphalt (ZOAB)	Material used for specific structural purposes in the gasification plant. Detailed process information provided by Torrgas.
Mobile Torrefaction Units	Stainless Steel	Material used for mobile torrefaction units, ensuring durability and resistance to environmental stresses.
	Mild Steel	Used alongside stainless steel in mobile units, providing necessary structural support.
	Concrete	Essential for the structural integrity of mobile torrefaction units.

4.10 Wood chipping

Data regarding the wood chipping process was obtained by assumptions based on literature, focusing on operational aspects such as energy consumption, chipper type, and output metrics like chip size and production rate. The efficiency of the chipping process and the quality of the output chips are crucial for optimizing subsequent stages like drying, torrefaction, and gasification (Spinelli et al., 2011).

4.11 Methane emissions

Methane emissions from biomass decomposition during storage are significantly influenced by the storage conditions. In anaerobic conditions, the absence of oxygen leads to the production of methane by microbial activity. These emissions are crucial for the environmental impact assessment of biomass storage (Kuptz et al., 2020).

Due to the uncertainty of storage conditions in each different raw biomass feedstock source scenario, the results will include both the impacts associated with this process and those without. This consideration is supported by Alakoski et al., (2016), who highlighted that storage conditions of woody biomass significantly impact the degradation process and the resulting gaseous emissions. Additionally, the duration of storage plays a crucial role, as longer storage times can lead to increased dry matter losses and higher emissions of gases such as methane, carbon dioxide, and volatile organic compounds (Kuptz et al., 2020).

4.12 Torrefaction processes

Quantifying the impacts of the torrefaction processes will include creating an LCI model that gathers every input entering the torrefaction plant and every output coming out after the torrefaction process was carried out. The data that was provided by Torrgas indicates the flow of torrefied biomass that enters to the gasification plant. Data regarding amount of natural gas used, raw biomass input, and flue gases output, were obtained depending on the way the feedstock is obtained. Torrefaction induces mass loss. This is primarily due to the drying and thermal decomposition of low-molecular weight components in wood biomass, such as hemicellulose, which decompose at lower temperatures compared to cellulose and lignin. The extent of this mass loss can vary significantly, ranging from 1.5% to 32.2% by weight, depending on the process temperature. For the forest residue species selected in this project, the torrefaction process at the chosen temperature results in an approximate dry mass loss of 10%(Ramos-Carmona et al., 2017).

All data concerning the torrefaction processes were provided by Torrgas, ensuring the accuracy and relevance of the inputs. The impacts of the Torrgreen torrefaction mobile units will be multiplied by 56, corresponding to the total units operating simultaneously in northern France to meet the biomass torrefaction demand.

In the Torrcoal system, natural gas is used as the heating fuel. In contrast, the Torrgreen mobile units utilize liquefied petroleum gas (LPG) as their fuel source. This distinction in fuel types and the operational scale highlights the variations in environmental impacts and efficiency between the two systems. By accounting for these factors, a comprehensive Life Cycle Impact Assessment (LCIA) can be performed, providing valuable insights into the overall sustainability of the biomass torrefaction and gasification processes. This approach ensures that the assessment captures the full range of operational scenarios, allowing for a detailed comparison of the environmental impacts associated with different technologies and methodologies employed by Torrgas. By leveraging the specific data provided, this study presents a robust and contextually relevant evaluation of the processes involved.

4.13 Gasification and methanol synthesis processes

Quantifying the gasification and methanol synthesis processes will involve creating an LCI comprehensive model that includes all the inputs and outputs. The data provided by Torrgas is depicted in Table 5, this includes the mass balances of the entire process, as well as electricity and fuel consumption. In this process, the synthesis of methanol is integrated with the gasification process under the Torranol technology.

The fuel used is assumed to be natural gas, utilizing approximately 200 hours each year for cold start heating. That according to a cold start heating in a gasification plant refers to the initial heating phase required to bring the gasifier up to its operating temperature from ambient conditions. The flue gases produced during the process, including NOx, SO_2, and dust emissions, are also considered in the analysis.

Table 5: Input and output data of the torrefaction and gasification processes.

Process	Torrcoal	Torrgreen	Torranol	Unit
Input				
Electricity use	2.9	1.68	6	MW
Cold start heating	0.2	0	0	GJ/h
Heating	2.3	7.5	2	GJ/h
Water	8.5	9	12	Tons/h
Biomass	18.9	20.1	17.2	Tons/h
Biomass (BS)	-	-	18.3	Tons/h
Output				
NOx	4.2	4.2	0.25	Kg/h
SO_2	2.4	2.4	0	Kg/h
Dust	0.21	0.21	0.13	Kg/h
CO_2	14.17	14.8	13	Tons/h
Wastewater	1.8	2	7.2	Tons/h
Torrefied biomass	17.2	18.3	-	Tons/h
MeOH	-	-	8.2	Tons/h
MeOH (BS)	-	-	9.1	Tons/h
Biochar	-	-	2.83	Tons/h
Biochar (BS)	-	-	2.7	Tons/h

4.14 Electrolyser

The electrolyser assumed to be used to produce additional hydrogen is PEM. Data regarding the PEM cell components, materials and manufacturing processes is shown in Table 6 were obtained from Krishnan et al. (2024).

Table 6: PEM stack components and materials (Krishnan et al., 2024)

Component	Material (Advanced 2030)	Weight (kg/kgH2)
CCM Membrane	Nafion 80 µm	3.7E-06
Coatings	Pt: 0.05 mg/cm2	1.17E-08
	Ir: 0.1 mg/cm2	2.34E-08
PTL Anode	Sintered porous 316 L Stainless steel	5.61E-04
	Nb (20 µm)	8.0E-05
Cathode	Carbon cloth	2.88E-06
Seals/Frames	PPS 40 % Glass Fiber	6.55E-05
Bipolar Plate	316 L Stainless steel	2.69E-04
	Nb (200 µm)	2.31E-04
End plate	A356 Al	9.9E-06

4.15 Biochar

The properties of the char originated in the gasification process were proportionated by Torrgas. Table 7 shows the properties of the Biochar as a byproduct of the gasification of the torrefied biomass originated from forest residues, demolition wood and barley straw scenarios.

Table 7: Biochar properties

Variable	FR and DW Biochar	BS biochar	Unit
C content	85.8%	65.4%	wt%
H content	1.0%	1.2%	wt%
Ash content	9.9%	32.8%	wt%
Moisture content	0.6%	0.6%	wt%

4.15.1 Pulverized coal replacement ratio

The replacement ratio refers to the quantity of coke substituted by the injected material. Essentially, it measures the efficiency of the injection process(Campos, Barbosa and Assis, 2021) (Campos, Barbosa and Assis, 2021). By understanding the properties of the biochar and applying the average of the result of both formulas outlined by Campos, Barbosa, and Assis article, we can compute the replacement ratio for the generated biochar. The ratio used for substituting pulverized coal with biochar in the steel industry is based on the carbon content and energy value of biochar compared to coal. This substitution ratio considers the differences in combustion properties and ensures that biochar can effectively replace coal without compromising the energy output and efficiency of the steel manufacturing process.

The biochar properties produced by Torrgas are summarized in the preceding table. Using these properties and the formulas below, the final replacement ratio is calculated.

The formulas are:

$$Replacement\ ratio\ (RR) = \frac{(2x\%Carbon + 2.5x\%Hydrogen + 0.9x\%ash - \%moisture - 86)}{100}$$

$$Replacement\ ratio\ (RR) = \frac{(-118.9 + 2.3\%Carbon + 4.5\%Hydrogen + 0.97\%ash)}{100}$$

5 Results

In this chapter, the results of the Life Cycle Impact Assessment (LCIA) are presented per GJ of methanol or hydrogen produced, with particular emphasis on potential impacts on global warming. This section includes a comparison of the results obtained for each impact category across three different feedstock source scenarios and an additional scenario based on data from a case study in Sweden. Additionally, the implications of integrating an electrolyser into the process and the allocation of biochar produced as a byproduct are examined.

5.1 GWP

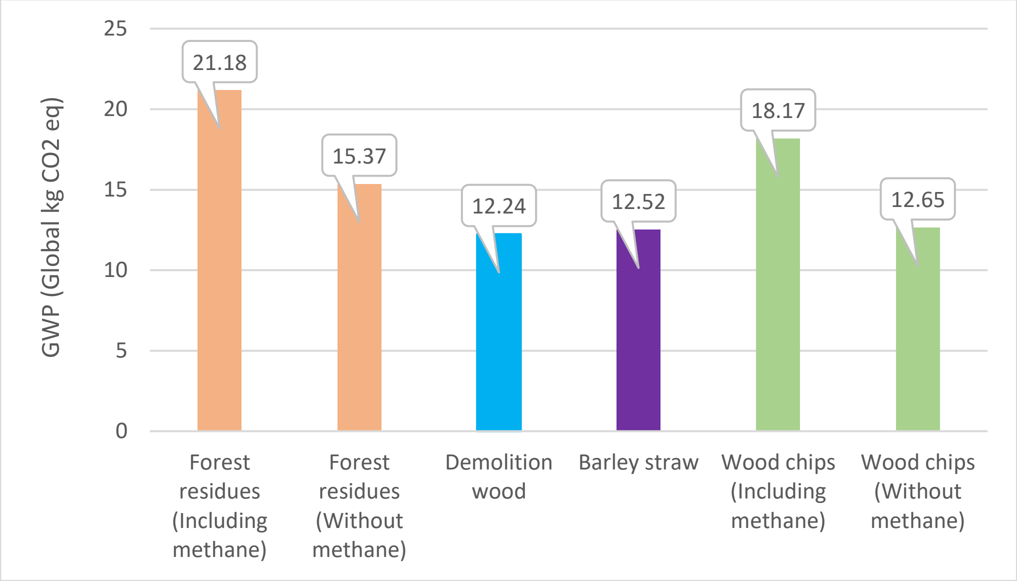

Figure 9: GWP impacts results of the different scenarios studied. Methane emissions are included in the scenarios where these emissions occur.

The Global Warming Potential (GWP) for each scenario varies significantly, highlighting the influence of methane emissions and the properties of the feedstock. For forest residues, the GWP including methane is 21.18 Kg CO_2 eq, while excluding methane it drops to 15.37 kg CO_2-eq. This demonstrates the substantial impact of methane emissions. For demolition wood, the GWP is 12.24 kg CO_2 eq. For the Swedish biomass scenario, the GWP is 18.17 kg CO_2 eq with methane and 12.65 kg CO_2 eq without methane. Barley straw shows a GWP of 12.52 kg CO_2 eq, as no methane emissions are considered. These results underscore the variability in environmental impacts based on feedstock properties and methane management.

5.2 Forest residues

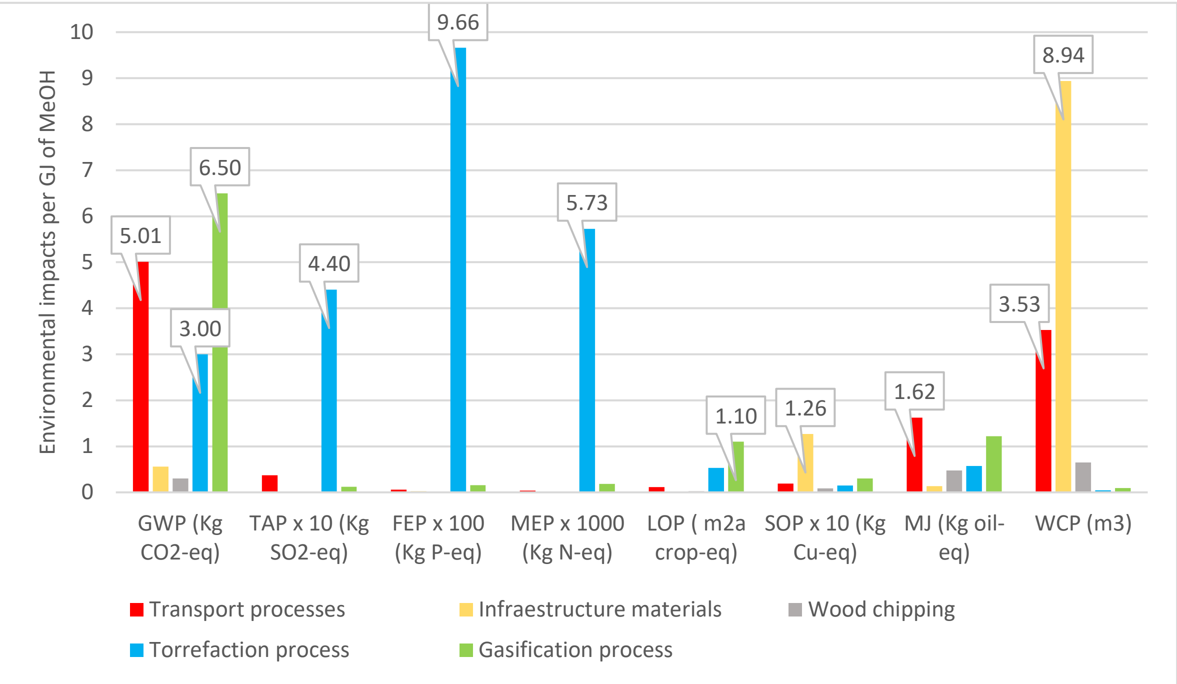

Figure 10: Environmental impacts results in the forest residues scenario.

The environmental impacts results in the forest residues scenario are represented in Figure 10. The GWP is primarily influenced by the gasification process (6.50 kg CO_2-eq) and transport processes (5.01 kg CO_2-eq). Terrestrial Acidification Potential (TAP) is the highest in the torrefaction process (4.40 kg SO_2-eq), while Freshwater Eutrophication Potential (FEP) is also dominated by the torrefaction process (9.66 kg P-eq). Marine Eutrophication Potential (MEP) shows significant impact from torrefaction (5.73 kg N-eq). Land

Occupation Potential (LOP) is most affected by gasification (1.10 m^2a crop-eq). Soil Organic Depletion Potential (SOP) is highest for infrastructure materials (1.26 kg Cu-eq). Fossil Resource Depletion Potential (MJ) is driven by transport (1.62 Kg oil-eq) and gasification (1.22 kg oil-eq). Water Consumption Potential (WCP) is highest for infrastructure materials (8.94 m^3).

5.3 Demolition wood

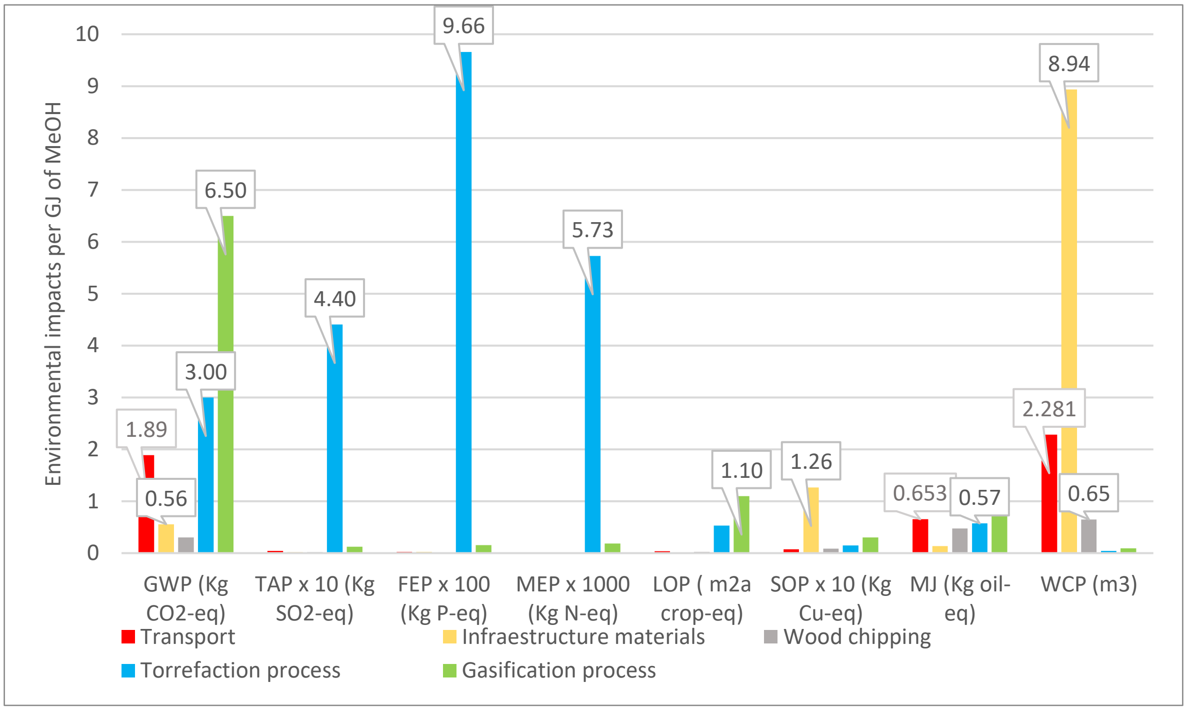

Figure 11: Demolition wood environmental impacts.

The environmental impacts derived from the demolition wood scenario are represented in Figure 11, where the GWP is predominantly influenced by the gasification process (6.50 kg CO_2-eq) and transport processes (1.89 kg CO_2-eq). TAP is highest in the torrefaction process (4.40 kg SO_2-eq). FEP shows the highest impact in the torrefaction process (9.66 kg P-eq), indicating significant nutrient release MEP also peaks in the torrefaction process (5.73 kg N-eq). LOP is most affected by gasification 1.1 m2a crop eq. SOP is highest for materials (1.26 kg Cu-eq). MJ is driven by gasification (1.22 kg oil eq) and transport (0.65 kg oil-eq). WCP is significantly influenced by materials (8.94 m3).

5.4 Barley straw

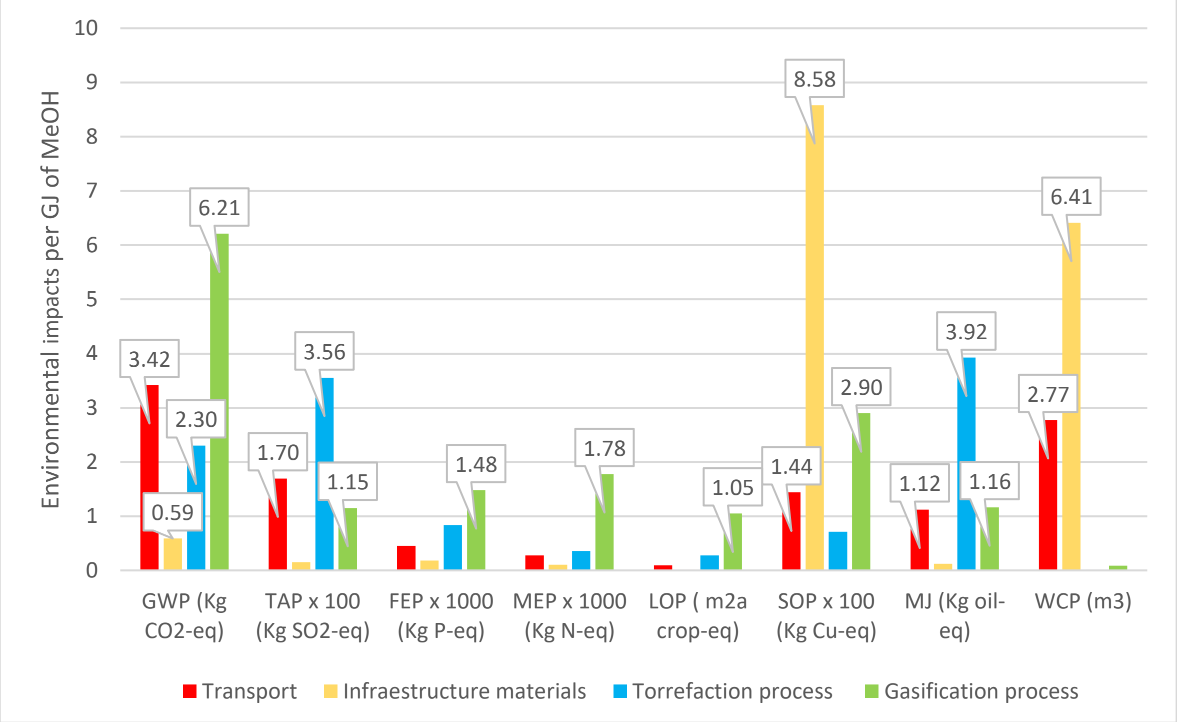

Figure 12: Barley straw scenario environmental impacts.

In Figure 12, the environmental impacts obtained in the barley straw scenario are represented. The GWP is mainly driven by the gasification process (6.21 kg CO_2 eq) and transport (3.42 kg CO_2-eq). (AP is highest in the torrefaction process (3.56 kg SO_2-eq). FEP is most affected by the gasification process (1.48 kg P-eq). MEP also peaks in the gasification process (1.78 kg N-eq). LOP is primarily influenced by the gasification process (1.05 m2a crop eq). SOP is highest for infrastructure materials (8.58 kg Cu eq/GJ MJ is driven by the torrefaction process (3.92 kg oil-eq). WCP is significantly influenced by infrastructure materials (6.41 m^3).

5.5 Wood chips scenario

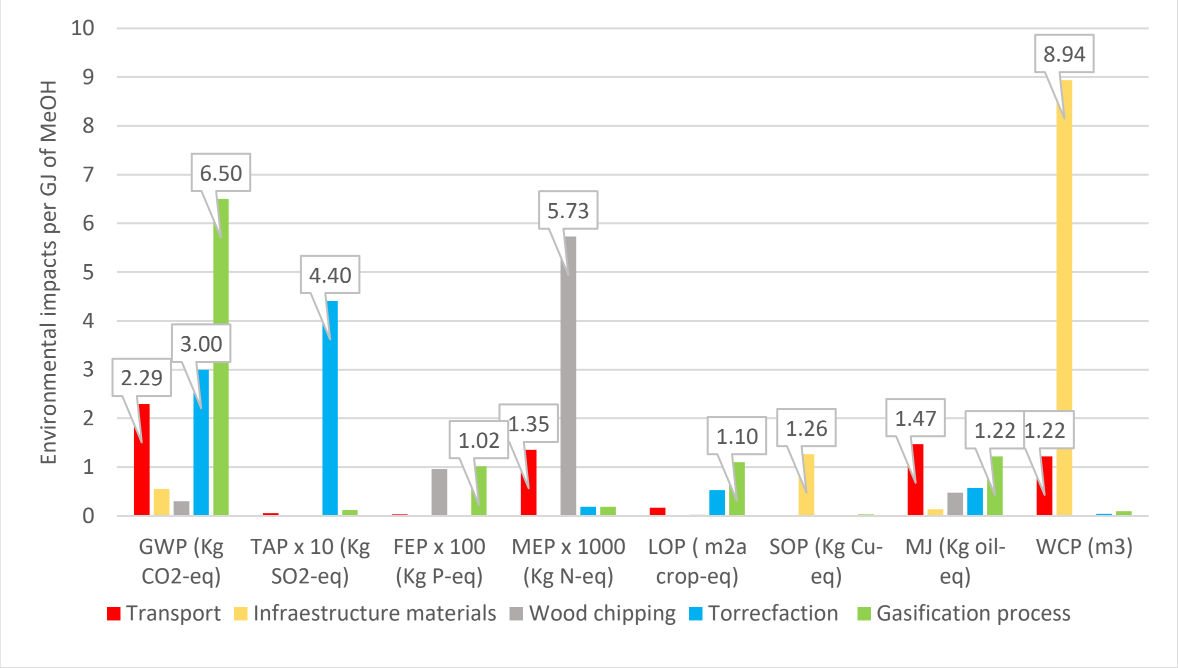

Figure 13: Wood chips scenario environmental impacts results.

The results obtained from the wood chips scenario are depicted in Figure 13 , the GWP is predominantly influenced by the gasification process (6.50 kg CO_2-eq) and transport processes (2.29 kg CO_2-eq). TAP shows the highest impact in the torrefaction process (4.40 kg SO_2 eq). FEP is most affected by the gasification process (1.02 kg P-eq). MEP peaks in the wood chipping process (5.73 kg N-eq). LOP is primarily influenced by the gasification process (1.10 m^2a crop-eq). SOP is highest for infrastructure materials (1.26 kg Cu-eq). MJ is driven by gasification (1.22 kg oil-eq) and transport (1.47 kg oil-eq) WCP is significantly influenced by infrastructure materials (8.94 m3).

5.6 Biochar

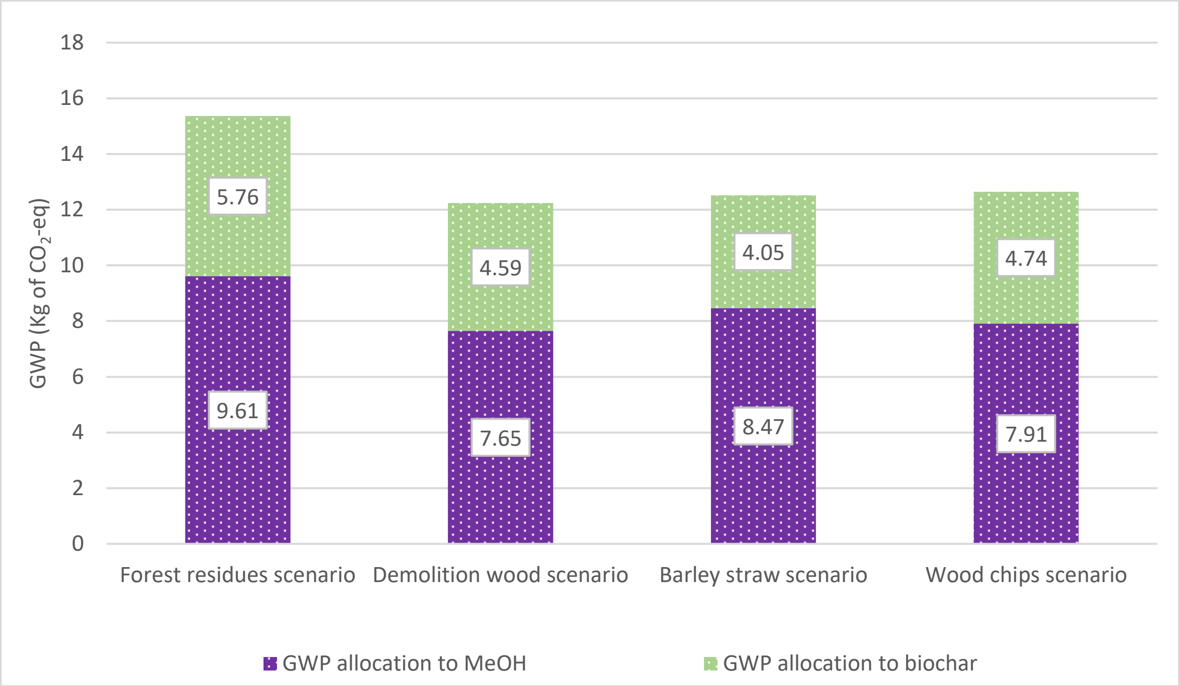

Figure 14: GWP impact results per scenario if the biochar impacts are allocated.

Figure 14 presents the GWP results for biochar across different feedstock sources, showing the total impacts of producing methanol from forest residues, demolition wood, barley straw, and the Swedish biomass scenario. The GWP values are allocated between methanol production and biochar. For methanol production, the GWP values are 9.61 kg CO_2 for forest residues, 7.65 kg CO_2 for demolition wood, 8.47 kg CO_2 for barley straw, and 7.91 kg CO_2 for the Swedish scenario. For biochar, the GWP values are 5.76 kg CO_2 for forest residues, 4.59 kg CO_2 for demolition wood, 4.05 kg CO_2 for barley straw, and 4.74 kg CO_2 for the wood chips scenario. The total GWP impacts, without allocation, are the sum of these values: 15.37 kg CO_2 for forest residues, 12.24 kg CO_2 for demolition wood, 12.52 kg CO_2 for barley straw, and 12.65 kg CO_2 for the Swedish scenario. This approach shows the significant carbon sequestration potential of biochar, as a notable portion of CO_2 is allocated to the biochar produced.

Biochar derived from forest residues, demolition wood, and the wood chips scenario shows similar carbon content and stability, enhancing its potential for carbon sequestration and use as a soil amendment. For barley straw, biochar properties differ slightly, primarily due to its higher ash content and lower carbon content, affecting its stability and carbon sequestration potential.

5.7 Electrolyser

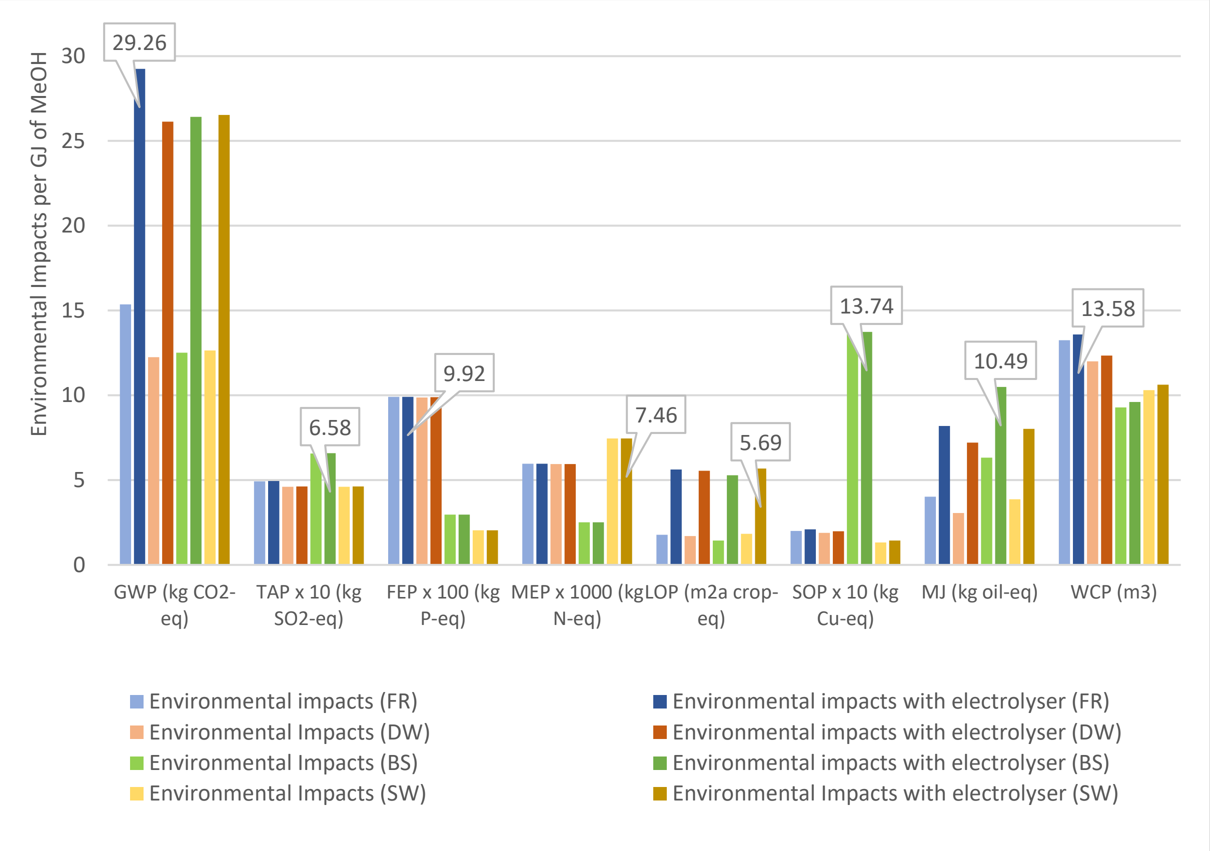

Figure 15: Environmental impacts comparison per scenario and including an electrolyser.

Figure 15 illustrates the environmental impacts calculated for each scenario, including the use of an electrolyser. The GWP doubles across all scenarios, indicating a substantial increase in CO_2 emissions due to the additional electricity required for electrolysis. Terrestrial acidification and freshwater eutrophication show minimal changes. However, the impact on land use increases markedly, reflecting the additional land area needed to produce the required electricity for electrolysis. Mineral resource scarcity and fossil resource scarcity also show notable increases, highlighting the higher demand for minerals like copper and fossil fuels for electricity generation. Water consumption increases slightly across all scenarios, pointing to the additional water needed for the electrolysis process. Additionally, the methanol yield increases by 57% with the inclusion of an electrolyser, which means a significant improvement in production efficiency.

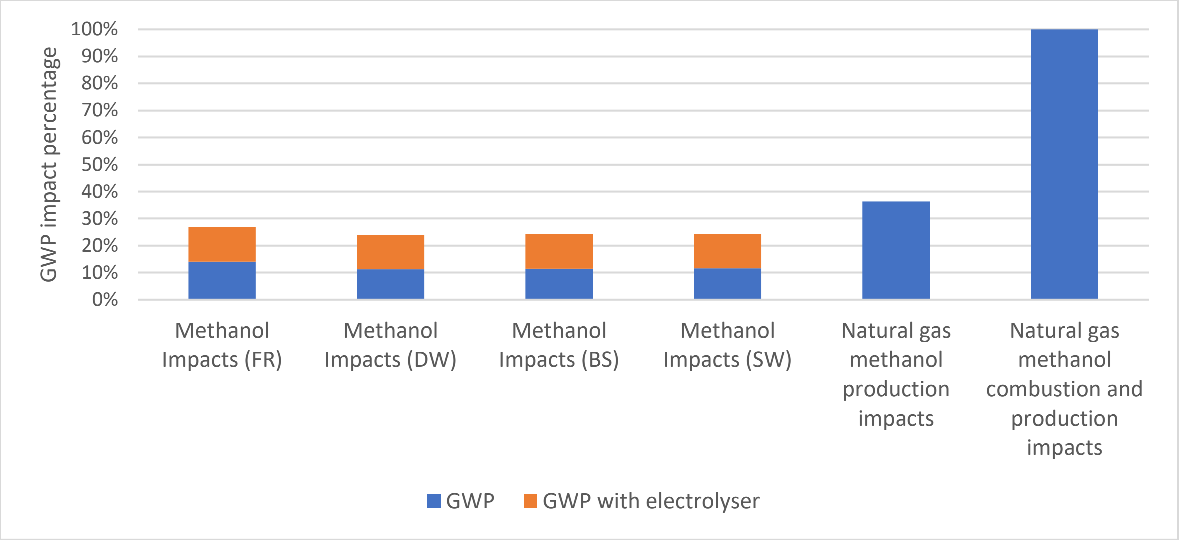

Figure 16: GWP comparison between the different scenarios including the production and use of fossil fuel methanol.

In Figure 16, the analysis of the GWP impacts provided scenarios reveals significant changes when an electrolyser is added to the methanol production process. For forest residues, the GWP impact increases from 14% to 27%, demonstrating a considerable rise in CO_2 emissions due to the additional electricity required for the electrolyser. Similarly, demolition wood sees an increase from 11% to 24%, barley straw from 12% to 25%, and the Swedish scenario from 12% to 25%. These percentages reflect the enhanced CO_2 footprint attributable to the electrolyser electricity consumption.

5.8 Hydrogen production

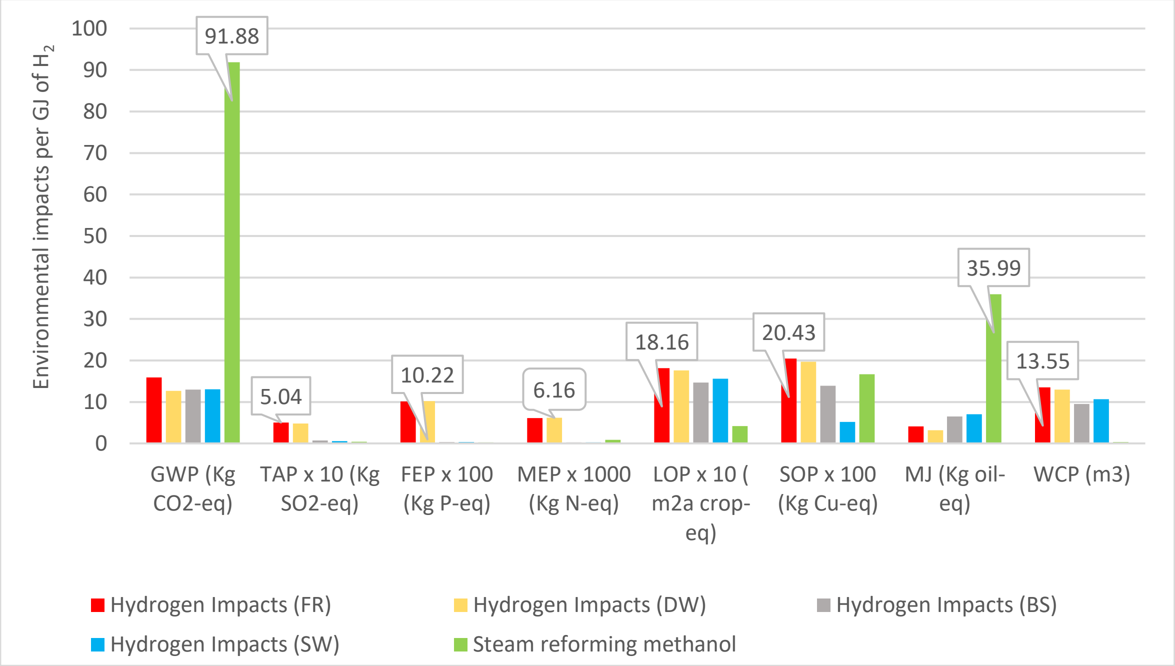

Figure 17: Environmental impacts of the production of one GJ of hydrogen.

Figure 17 depicts the environmental impacts of hydrogen production for each scenario studied, as well as hydrogen production through steam reforming of methane. the GWP is 15.88 kg CO_2 eq for forest residues, 12.65 kg CO_2 eq for demolition wood, 12.94 kg CO2 eq for barley straw, and 13.07 kg CO_2 eq for wood chips, with hydrogen from natural gas at 91.88 kg CO_2. The TAP (x 10) is 5.04 kg SO_2 eq for forest residues, 4.83 kg SO_2 eq for demolition wood, 0.67 kg SO_2 eq for barley straw, and 0.55 kg SO_2 eq for Swedish wood chips, with hydrogen from natural gas at 0.42 kg SO_2 eq. FEP (x 100) is 10.13 kg P eq for forest residues, 10.22 kg P eq for demolition wood, 0.30 kg P eq for barley straw, and 0.29 kg P eq for wood chips, with hydrogen from natural gas at 0.25 kg P eq.

MEP (x 1000) is 6.10 kg N eq for forest residues, 6.16 kg N eq for demolition wood, 0.26 kg N eq for barley straw, and 0.25 kg N eq for Swedish wood chips, with hydrogen from natural gas at 0.83 kg N eq. LOP (x 10) is 18.16 m2a crop eq for forest residues, 17.59 m2a crop eq for demolition wood, 14.67 m2a crop eq for barley straw, and 15.56 m2a crop eq for wood chips, with hydrogen from natural gas at 4.17 m2a crop eq. SOP (x 100) is 20.43 kg Cu eq for forest residues, 19.71 kg Cu eq for demolition wood, 13.93 kg Cu eq for barley straw, and 5.20 kg Cu eq for Swedish wood chips, with hydrogen from natural gas at 16.66 kg Cu eq. MJ is 4.12 kg oil eq for forest residues, 3.21 kg oil eq for demolition wood, 6.47 kg oil eq for barley straw, and 7.07 kg oil eq for Swedish wood chips, with hydrogen from natural gas at 35.99 kg oil eq. WCP is 13.55 m^3 for forest residues, 12.94 m^3 for demolition wood, 9.49 m^3 for barley straw, and 10.65 m^3 for wood chips scenario, with hydrogen from natural gas at 0.33 m^3.

Table 14, in appendix C, shows more detail information about the environmental impacts of the production of hydrogen from natural gas.

6 Discussion

In this section, the results of the Life Cycle Impact Assessment (LCIA) presented in the Results section, are discussed. First, a general overview synthesizes the comparison of the results obtained for each biomass feedstock scenario, focusing on the integration of a single electrolyser and its impact on the overall environmental performance. The discussion addresses the key results summary, followed by a sensitivity analysis to explore the influence of different assumptions and parameters on the study's outcomes. Next, the limitations and assumptions of the study are considered, including the specificity and interpretability of the results. The comparison with other studies is then discussed to contextualize the findings. The place of this research within the broader field of bio-methanol production is highlighted, and areas for further research are identified. Each impact category is analysed in detail to provide a comprehensive understanding of the environmental impacts associated with bio-methanol production.

6.1 Key results overview

In the Results section, the Forest Residues scenario shows the highest environmental impacts, primarily due to the significant contributions from transportation processes. The GWP for this scenario is 15.37 kg of CO_2, driven by transport and gasification processes. The higher transport impacts are due to the extensive distances the biomass must travel from Estonia to the Netherlands, involving multiple transport modes including trucks, maritime shipping, and barges.

For each of the four scenarios—forest residues, demolition wood, barley straw, and wood chips—the differences in environmental impacts are mainly attributed to the distinct transport processes involved. The demolition wood scenario, with a GWP of 12.24 kg of CO_2, benefits from shorter transport distances within the Netherlands. The barley straw scenario's environmental impacts are influenced by slightly different infrastructure materials and torrefaction and gasification processes, as the data provided by Torrgas for this feedstock differs from the other scenarios. The Swedish wood chips scenario, included to represent a common biomass feedstock for the IEA bioenergy intertask project, has a GWP of 12.65 kg of CO_2, assumed to have similar torrefaction and gasification impacts as the forest residues scenario for consistency.

The allocation of GWP impacts to biochar, when used as a replacement for pulverized coal in the steel manufacturing industry, shows significant carbon sequestration potential. For forest residues, biochar accounts for 5.76 kg of CO_2, for demolition wood 4.59 kg of CO_2, for barley straw 4.05 kg of CO_2, and for the Swedish scenario 4.74 kg of CO_2. This allocation demonstrates the environmental benefit of biochar in reducing overall GWP.

Adding an electrolyser increases the methanol yield by 57%, significantly enhancing production efficiency. However, it also raises environmental impacts across most categories, doubling the GWP in each scenario (14 Kg of CO_2 eq). Despite the higher GWP, the bio-methanol production with an electrolyser remains lower in GWP than conventional natural gas methanol production, which has a GWP of 39 Kg of CO_2 eq. When including the total GWP from production and combustion, natural gas methanol reaches 108 Kg of CO_2 eq, significantly higher than any biomass-based scenario. This is particularly important as bio-methanol has no emissions while being burned. From an environmental perspective, the impacts, especially the GWP, are considerably higher with an electrolyser. Nevertheless, considering the overall impacts of methanol production and combustion from fossil fuels, the increased methanol yield makes the addition of an electrolyser an interesting option to explore.

Finally, the environmental impacts of producing hydrogen instead of methanol are nearly identical. However, from an environmental perspective, producing methanol is preferable, especially when considering cradle-to-grave impacts. Hydrogen production is advantageous from a cradle-to-gate perspective, but for a company like Torrgas, the lower GWP of biomass-based methanol production and its lack of combustion emissions make it a more attractive option compared to fossil fuel-derived methanol.

Notably, adding an electrolyser also increases the methanol yield by 57%, significantly boosting production efficiency. Despite the rise in GWP, the improved methanol yield represents a substantial benefit in terms of output. For comparison, the GWP for methanol produced from natural gas is 36%. This highlights that even with the increased emissions when adding an electrolyser, biomass-based methanol production remains lower in GWP than conventional natural gas methanol production. When considering the total GWP, including combustion and production, natural gas methanol reaches 100%, significantly higher than any biomass-based scenario. This is particularly important as bio-methanol has no emissions while being burned.

6.2 Sensitivity analysis

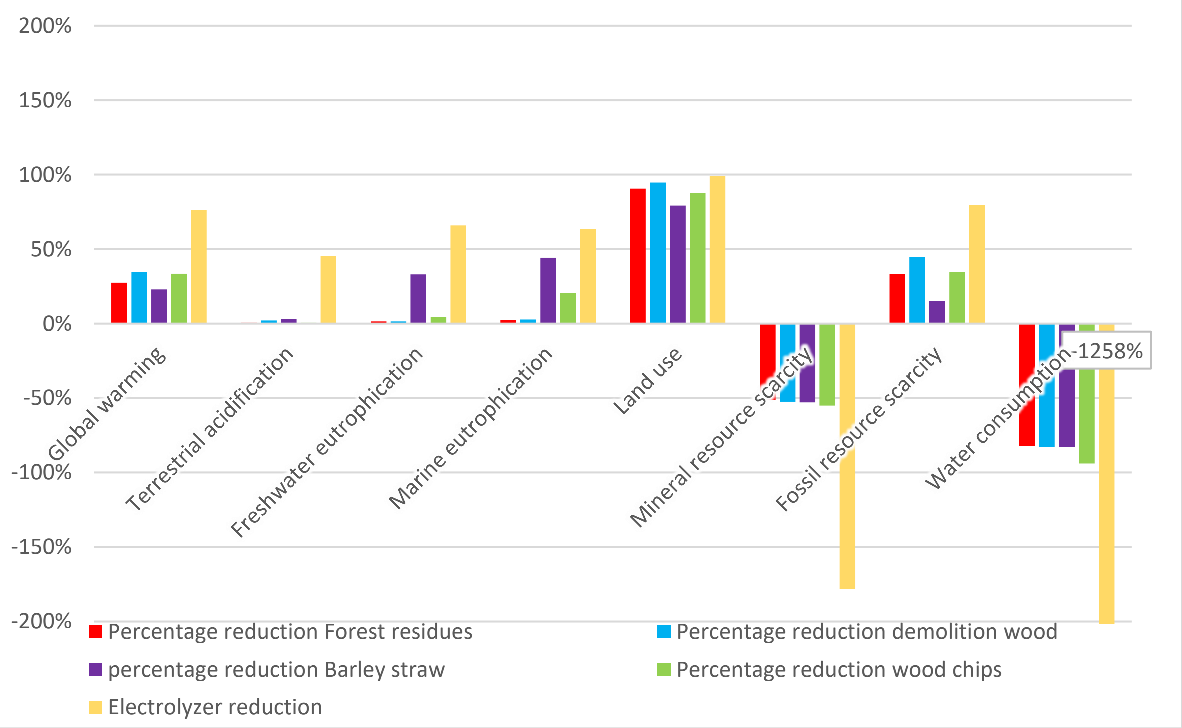

Figure 18: Sensitivity analysis results if the electricity mix used is substituted by wind energy.

Figure 18 presents the sensitivity analysis results, demonstrating changes in environmental impacts across various categories for all biomass feedstock scenarios when the electricity mix is changed to wind energy. Using wind energy instead of the marginal electricity mix results in substantial reductions in Global Warming Potential (GWP), with reductions of 27% for forest residues, 34% for demolition wood, 23% for barley straw, and 33% for wood chips. The most notable reduction is seen with the inclusion of an electrolyser, resulting in a 76% decrease in GWP. Terrestrial acidification shows modest reductions of 1% for forest residues, 2% for demolition wood, 3% for barley straw, and 1% for wood chips, with the electrolyser scenario showing a more substantial 45% reduction. Freshwater eutrophication and marine eutrophication also benefit from the switch to wind energy, with reductions of up to 66% and 63%, respectively, for the electrolyser scenario. Land use impact sees significant reductions across all scenarios, particularly with the electrolyser scenario achieving a 99% reduction, highlighting the substantial land use efficiency gained by utilizing wind energy. These impacts were quantified using the standard SimaPro process of a mix between offshore and onshore wind energy production in Europe.

Interestingly, the analysis reveals negative reductions in mineral resource scarcity, indicating an increased demand for minerals like copper due to the materials required for wind turbine construction and maintenance. Fossil resource scarcity shows positive reductions, with the electrolyser scenario achieving an 80% reduction, reflecting the decreased reliance on fossil fuels. Water consumption reductions are substantial, with reductions of up to 94% across the biomass scenarios and a dramatic 1258% reduction in the electrolyser scenario. This significant decrease is primarily due to the hydroelectric power component in wind energy production, which requires substantial water use during the manufacturing phase of wind turbines. Overall, this sensitivity analysis demonstrates that shifting to wind energy can lead to significant reductions in most environmental impact categories, particularly in GWP, fossil resource scarcity, and water consumption, while also highlighting the increased demand for certain minerals.

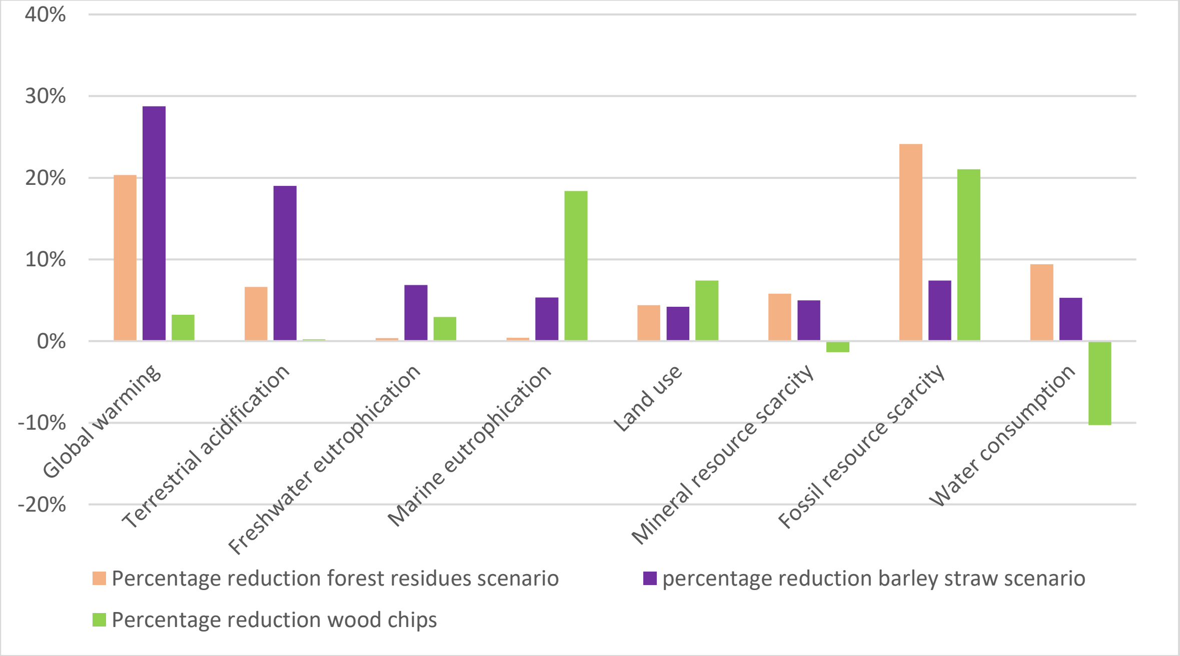

Figure 19: Sensitivity analysis results if the transport processes used are the DW transport processes for every scenario.

In Figure 19, the second sensitivity analysis examines how the environmental impacts change if the transport processes are uniform across all scenarios, using the lower-impact transport processes from the demolition wood scenario. For forest residues, there is a notable 20% reduction in GWP, a

7% reduction in terrestrial acidification, and a 24% reduction in fossil resource scarcity. Freshwater eutrophication and marine eutrophication remain unchanged, while land use and mineral resource scarcity see reductions of 4% and 6%, respectively. Water consumption is also reduced by 9%. In the barley straw scenario, GWP is reduced by 29%, terrestrial acidification by 19%, freshwater eutrophication by 7%, and marine eutrophication by 5%. Land use and mineral resource scarcity decrease by 4% and 5%, respectively. Fossil resource scarcity is reduced by 7%, and water consumption by 5%.

For the wood chips scenario, the reductions are less significant due to the similar transport processes already in use. GWP decreases by 3%, terrestrial acidification remains unchanged, freshwater eutrophication and marine eutrophication reduce by 3% and 18%, respectively. Land use sees a 7% reduction, while mineral resource scarcity slightly increases by 1%. Fossil resource scarcity decreases by 21%, but water consumption increases by 10%. Overall, standardizing transport processes to those of the demolition wood scenario leads to substantial environmental benefits, particularly for forest residues and barley straw. The wood chips scenario sees minimal impact reductions due to already similar transport conditions, demonstrating the importance of transport distances and methods in influencing the environmental impacts of methanol production

6.3 Comparison with other studies and place of this research

To place the results of this study in context, it is valuable to compare them with findings from other similar studies. The study by Galusnyak et al., 2023 assessed the environmental impacts of bio-methanol production from various raw materials, including woody biomass gasification and CO_2 hydrogenation using renewable electricity sources such as biomass, solar, wind, and hydroelectric power. Their results highlighted that using hydroelectric power for methanol production performed better in six out of nine environmental impact categories compared to other renewable sources, with wind power following closely behind. This aligns with the sensitivity analysis in this study, where using wind energy significantly reduced environmental impacts, particularly GWP.

Another relevant study by Kajaste, Hurme and Oinas, 2018 evaluated methanol production from multiple feedstocks, including biomass and CO_2 hydrogenation. They found that co-production of methanol with renewable corn ethanol had the lowest global warming impact, underscoring the benefits of integrating renewable sources in methanol production processes. This is consistent with the findings here, where integrating an electrolyser and using renewable energy sources like wind power can lead to substantial reductions in environmental impacts despite the higher GWP associated with the electrolyser.

Both studies support the conclusion that while biomass-based methanol production has higher GWP impacts when incorporating an electrolyser, it remains significantly lower than conventional natural gas methanol production, especially when considering the full lifecycle impacts. These comparisons emphasize the importance of renewable energy integration and efficient resource use in minimizing the environmental footprint of methanol production.

Due to the specificity of this study, comparing the results with other studies is complex. This complexity arises because this study performs a consequential LCA, while the majority of LCAs performed for bio methanol are attributional, leading to different results. Additionally, FU and the feedstock sources are highly specific to this study, further complicating direct comparisons.

The place of this study within the broader field of bio-methanol production research is significant due to its comprehensive approach, which includes multiple feedstock sources, the integration of advanced technologies such as electrolysers, and a cLCA. This study contributes valuable insights into the environmental impacts of bio-methanol production, emphasizing the trade-offs between increased production efficiency and sustainability. It highlights the potential of bio-methanol as a lower GWP alternative to fossil-based methanol and underscores the importance of renewable energy integration in reducing the overall environmental footprint. Additionally, the study's focus on different feedstock sources and the detailed analysis of biochar's role in carbon sequestration provide a robust framework for future research and industrial applications in sustainable biofuel production.

6.4 Limitations and assumptions

In this study, several assumptions were made regarding the background data to ensure the feasibility and accuracy of the LCA. These assumptions were necessary due to the specific detail required for certain parameters such as the type of vessel or truck used, the model of the woodchipper, and the methane emissions considered. These details were based on literature reviews and assumptions made by the proximity to other studies and applying similar processes in SimaPro. These assumptions were rigorously discussed and verified with other students participating in the "IEA Bioenergy Intertask 5" project to ensure consistency and reliability.

One significant limitation of this study is the specificity of the technology developed by Torrgas, especially concerning the Torrgreen mobile torrefaction unit. The technology for Torrgreen is not as advanced as that for Torrcoal or Torranol, resulting in some uncertainties in the environmental impact results for the torrefaction process. This study also assumes that the environmental impacts for the Swedish wood chips scenario are the same as those for the forest residues scenario to facilitate comparison, which might introduce some discrepancies.

Furthermore, the data for various background processes were based on assumptions or generic datasets from SimaPro due to the lack of specific data. These include assumptions about transport impacts, which varied across scenarios, and the impacts of infrastructure materials, which differed slightly for barley straw due to variations in the data provided by Torrgas. The uncertainties arising from these assumptions and limitations are acknowledged and suggest a degree of caution when interpreting the results.

6.5 Areas for further research

Given the findings and limitations of this study, several areas for further research have emerged to improve the understanding and optimization of bio-methanol production. Future studies should aim to obtain and use more precise data for all background processes, particularly concerning the technology used in the Torrgreen mobile torrefaction unit. Researching more on each background process will enhance the certainty and reliability of the results. Additionally, exploring different feedstock sources such as other agricultural residues, dedicated energy crops, or algae can provide a broader perspective on the sustainability of bio-methanol, identifying the most sustainable options through comparative studies. Examining the quality and specific characteristics of the raw biomass in greater detail could also help identify the best feedstock sources based on biomass quality.

Integrating advanced renewable energy sources like solar power, geothermal energy, or advanced bioenergy with carbon capture and storage (BECCS) could further reduce environmental impacts, as demonstrated by the sensitivity analysis highlighting the benefits of wind energy. Comparing bio-methanol with other renewable fuels like bioethanol, biodiesel, and hydrogen will highlight the relative advantages and disadvantages of each fuel type. This study briefly addresses the comparison with hydrogen, but with more detailed information, it could be interesting to develop a more comprehensive and thorough comparison. By addressing these areas, future research can build on this study's findings, providing deeper insights and more robust data to support sustainable bio-methanol production technologies.

7 Conclusion

This research investigated the environmental impact of bio-methanol production from various biomass feedstock sources, including forest residues, demolition wood, barley straw, and Swedish wood chips. Using LCA methodology, the study aimed to determine the environmental impacts of bio-methanol production from different biomass feedstocks and compare them to conventional methanol production from natural gas, as well as to assess the production of hydrogen and the potential benefits of biochar as a byproduct.

The study addressed several key questions: What are the environmental impacts of producing bio-methanol from forest residues, demolition wood, barley straw, and wood chips scenarios? How do these impacts vary between different feedstock sources? What are the benefits and trade-offs of incorporating an electrolyser in the methanol production process? What are the environmental impacts or benefits of biochar as a byproduct of bio-methanol production, particularly when used as a replacement for pulverized coal? How do the environmental impacts of producing hydrogen compare with those of producing methanol?

The GWP of bio-methanol production varies among the different feedstock scenarios. Forest residues have the highest GWP due to extensive transport impacts, while demolition wood has a lower GWP, primarily due to localized processing. Barley straw's impacts are influenced by specific torrefaction and gasification processes, and the wood chips scenario, used for comparability, shows similar impacts to forest residues. The inclusion of an electrolyser significantly increases the methanol yield by 57% but also raises the GWP and other environmental impacts due to higher electricity consumption.

Furthermore, biochar produced as a byproduct shows significant carbon sequestration potential, particularly when used as a replacement for pulverized coal in the steel manufacturing industry. Lastly, the environmental impacts of producing hydrogen instead of methanol were found to be nearly identical. However, bio-methanol production offers better overall environmental benefits when considering the cradle-to-grave perspective, especially regarding combustion emissions savings.

After analysing and discussing the results, the demolition wood scenario exhibits the lowest environmental impacts. However, this scenario requires the construction of a torrefaction plant in Amsterdam. The barley straw scenario presents a promising option, contingent upon advancements in the Torrgreen mobile torrefaction technology and further research. The forest residues scenario, while having the highest environmental impacts, benefits from an existing torrefaction unit. Therefore, in the short term, the forest residues scenario is the most viable alternative to meet the biomass demand for gasification.

In conclusion, this LCA provides a comprehensive evaluation of the environmental impacts of bio-methanol production from various biomass sources, highlighting the benefits and trade-offs of different feedstock scenarios and technological choices. The findings demonstrate the potential of bio-methanol as a lower GWP alternative to fossil-based methanol and underscore the importance of renewable energy integration in reducing the overall environmental footprint. Further research with more precise data and exploration of alternative feedstocks and renewable energy sources will improve the understanding and optimization of sustainable bio-methanol production technologies. Additionally, assessing the environmental impacts of biochar as a byproduct and comparing hydrogen production with bio-methanol production offer valuable insights for future technological developments

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Appendix

Appendix A Life cycle inventory data table

In this appendix the Inventory table for the background processes used is displayed, this is shown in Table 8

Table 8: Inventory table of the background processes

Process	SimaPro Process	Amount per unit	Unit	Amount per FU	Unit (X/FU)
Distance by truck (forest residues)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Conseq, U	687040000	TKm	26.2	TKm/GJ
Distance by truck (Demolition wood)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Conseq, U	412224000	TKm	15.72	TKm/GJ
Distance by truck (Barley straw)	Transport, freight, lorry >32 metric ton, euro5 {RER}| market for transport, freight, lorry >32 metric ton, EURO5 | Conseq, U	440799459	TKm	16.81	TKm/GJ
Distance by barge (Forest residues)	Transport, freight, inland waterways, barge {RER}| market for transport, freight, inland waterways, barge | Conseq, U	329779200	TKm	12.57	TKm/GJ
Distance by barge (Barley straw)	Transport, freight, inland waterways, barge {RER}| market for transport, freight, inland waterways, barge | Conseq, U	352639567	TKm	13.45	TKm/GJ
Distance by vessel (Forest residues)	transport, freight, sea, bulk carrier for dry goods {GLO}| market for transport, freight, sea, bulk carrier for dry goods | Conseq, U	4869739520	TKm	185.7	TKm/GJ
Distance by vessel	transport, freight, sea, bulk carrier for dry goods {GLO}| market for transport, freight, sea, bulk carrier for dry goods | Conseq, U	1357662334	TKm	51.78	TKm/GJ
Conveyor belt	Transport, freight, conveyor belt {GLO}| market for transport, freight, conveyor belt | Conseq, U	2198528	TKm	0.084	TKm/GJ
Reinforced concrete (Torrefaction plant)	concrete block {DE}| market for concrete block | Conseq, U. Reinforcing steel, at plant/RER U	8124	Ton	0.000309851	Ton/GJ
Steel (Torrefaction plant)	Chromium steel 18/8, at plant/RER U	905.2	Ton	3.45245E-05	Ton/GJ
Insulation material (Torrefaction plant)	Rock wool, at plant/CH U	99	Ton	3.77588E-06	Ton/GJ
Concrete (Torranol)	Autoclaved aerated concrete block, at plant/CH U	6120	Ton	0.000233418	Ton/GJ
Reinforced concrete (Torranol)	concrete block {DE}| market for concrete block | Conseq, U. Reinforcing steel, at plant/RER U	7256	Ton	0.000276746	Ton/GJ

Steel (Torranol)	Chromium steel 18/8, at plant/RER U	1046	Ton	3.98947E-05	Ton/GJ
Insulation material (Torranol)	Rock wool, at plant/CH U	26.6	Ton	0	Ton/GJ
Brick (Torranol)	Brick, at plant/RER U	210	Ton	1.01453E-06	Ton/GJ
Asphalt (Torranol)	Mastic asphalt, at plant/CH U	2625	Ton	8.00945E-06	Ton/GJ
Concrete (Torrgreen)	Concrete block, at plant/DE U	3600	Ton	0.000100118	Ton/GJ
Mild steel (Torrgreen)	Steel, low-alloyed, at plant/RER U	672	Ton	0.000137305	Ton/GJ
Stainless steel (Torrgreen)	Chromium steel 18/8, at plant/RER U	168	Ton	2.56302E-05	Ton/GJ
Wood chipping	Wood chopping, mobile chopper, in forest/RER U	3022950	Ton	0.104815496	Ton/GJ
Natural gas methanol	Methanol, at plant/GLO U	1310951	Ton	0.05	Ton/GJ

Appendix B Electricity mix modelling tables used.

In this appendix the installed electricity capacity, the contribution of each country to the marginal mix, the results for the marginal capacity and how is the mix implemented under the current policy scenario. This is depicted in Table 9,

Table 10, Table 11, Table 12.

Table 9: Installed electricity capacity (GW) in Western Europe by country in 2022.

Technology / Country	Austria	Belgium	Germany	Denmark	Spain	Finland	France	Ireland	Italy	Luxembourg	Netherlands	Norway	Portugal	Sweden	Switzerland	United Kingdom	Total
Oil	0.12	0.45	4.69	0.96	0.67	1.05	2.57	1.27	1.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	13.32
Natural gas	4.21	6.99	34.25	1.57	29.90	1.78	12.89	4.26	44.22	0.07	18.35	0.46	4.58	0.00	0.00	42.30	205.83
Coal	0.00	0.00	37.68	3.02	3.22	2.61	4.23	1.20	7.65	0.00	4.01	0.00	0.00	0.00	0.00	0.00	63.62
Solar PV	3.27	6.47	67.56	2.32	18.52	0.02	14.64	0.00	5.43	0.30	22.59	0.00	1.33	0.00	4.74	14.33	161.52
Wind	3.57	5.31	66.19	7.02	29.32	5.12	21.33	1.92	11.23	0.15	9.41	5.13	5.35	14.70	0.00	23.85	209.60
Hydro	12.03	1.50	14.64	0.01	20.34	3.17	25.54	0.51	22.25	0.03	0.04	34.46	8.20	16.30	14.98	2.10	176.10
Biomass	0.48	0.73	8.91	1.75	0.71	1.83	1.34	0.00	1.53	0.05	0.42	0.00	0.65	0.00	0.00	5.19	23.59
Nuclear	0.00	4.94	4.06	0.00	7.12	2.79	61.37	0.00	0.00	0.00	0.49	0.00	0.00	6.90	2.96	5.90	96.53
Geothermal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.89
Other	0.95	0.41	0.00	0.52	0.95	0.94	2.32	0.65	0.97	0.02	0.79	0.22	0.03	9.00	0.00	3.34	21.11
Hydrogen	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Solar CSP	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	24.63	26.80	237.98	17.17	110.75	19.31	146.23	9.83	95.69	0.62	56.10	40.27	20.14	46.90	22.68	97.00	972.10
Total (validation)	27.38	26.22	242.11	16.50	111.01	17.94	141.90	11.14	117.16	1.88	47.25	39.70	21.34	44.75	24.00	104.60	994.90
Variation vs EC statistics	10%	-2%	2%	-4%	0%	-8%	-3%	12%	18%	67%	-19%	-1%	6%	-5%	5%	7%	2%

Table 10: Relative contribution of each country to the marginal mix.

Country / Type of electricity	Natural gas	Solar PV	Wind	Hydro	Biomass	Nuclear	Other
Austria	2%	2%	2%	7%	2%		5%
Belgium	3%	4%	3%	1%	3%	5%	2%
Germany	17%	42%	32%	8%	38%	4%	
Denmark	1%	1%	3%	0%	7%		2%
Spain	15%	11%	14%	12%	3%	7%	5%
Finland	1%	0%	2%	2%	8%	3%	4%
France	6%	9%	10%	15%	6%	64%	11%
Ireland	2%		1%	0%			3%
Italy	21%	3%	5%	13%	6%		5%
Luxembourg	0%	0%	0%	0%	0%		0%
Netherlands	9%	14%	4%	0%	2%	1%	4%
Norway	0%		2%	20%			1%
Portugal	2%	1%	3%	5%	3%		0%
Sweden			7%	9%		7%	43%
Switzerland		3%		9%		3%	
United Kingdom	21%	9%	11%	1%	22%	6%	16%

Table 11: LCIA results for marginal electricity mix under current policy scenario using the Environmental Footprint method

Impact category	Unit	**Total**	Natural gas	Solar PV	Wind	Hydro	Biomass	Nuclear	Other	Solar CSP
Acidification	mol H+ eq	**2.9E-04**	2.3E-05	2.3E-04	9.3E-06	2.6E-07	3.0E-05	8.0E-07	4.7E-07	1.8E-07
Climate change	kg CO2 eq	**9.5E-02**	2.4E-02	7.5E-02	5.6E-03	2.5E-04	-1.0E-02	1.2E-04	1.4E-04	4.8E-05
Climate change – Biogenic	kg CO2 eq	**1.9E-04**	1.9E-06	1.5E-04	4.3E-06	2.4E-05	1.3E-05	2.1E-07	1.3E-07	2.1E-08
Climate change – Fossil	kg CO2 eq	**9.5E-02**	2.4E-02	7.5E-02	5.6E-03	7.0E-05	-1.0E-02	1.2E-04	1.4E-04	4.8E-05
Climate change – Land use and LU change	kg CO2 eq	**3.0E-04**	1.1E-06	9.9E-05	2.5E-05	1.6E-04	1.8E-05	2.6E-07	1.7E-07	5.6E-08
Ecotoxicity, freshwater – part 1	CTUe	**2.7E-01**	3.8E-03	2.8E-01	1.7E-02	1.3E-04	-3.8E-02	9.2E-04	1.5E-04	3.4E-04
Ecotoxicity, freshwater – part 2	CTUe	**1.6E-01**	5.8E-03	1.3E-01	2.4E-02	8.8E-05	-4.6E-03	2.9E-04	1.2E-04	4.7E-05
Ecotoxicity, freshwater – inorganics	CTUe	**4.1E-01**	9.3E-03	4.1E-01	3.8E-02	1.8E-04	-4.4E-02	1.2E-03	2.4E-04	2.6E-04
Ecotoxicity, freshwater – organics – p.1	CTUe	**1.9E-03**	1.4E-05	1.1E-03	3.3E-04	1.2E-05	2.3E-04	1.6E-06	3.0E-06	1.2E-04
Ecotoxicity, freshwater – organics – p.2	CTUe	**1.6E-02**	2.5E-04	1.2E-02	3.0E-03	2.3E-05	5.2E-04	3.0E-05	1.5E-05	9.9E-06
Particulate matter	disease inc.	**6.1E-09**	5.5E-11	5.0E-09	5.0E-10	7.0E-12	5.2E-10	5.7E-11	6.4E-12	1.9E-12
Eutrophication, marine	kg N eq	**1.1E-04**	7.1E-06	8.6E-05	8.0E-06	7.8E-08	9.7E-06	9.5E-07	1.6E-07	5.3E-08
Eutrophication, freshwater	kg P eq	**3.8E-05**	2.6E-07	3.4E-05	3.5E-06	2.2E-08	3.3E-07	7.6E-08	1.5E-08	8.4E-09
Eutrophication, terrestrial	mol N eq	**1.3E-03**	7.7E-05	9.0E-04	8.8E-05	8.4E-07	1.8E-04	2.6E-06	2.2E-06	5.4E-07
Human toxicity, cancer	CTUh	**1.9E-10**	1.6E-12	1.6E-10	2.4E-11	1.8E-13	3.3E-12	3.5E-13	1.3E-13	7.4E-14
Human toxicity, cancer – inorganics	CTUh	**5.3E-11**	2.6E-13	4.1E-11	8.9E-12	7.8E-14	1.6E-12	2.5E-13	4.9E-14	9.7E-15
Human toxicity, cancer – organics	CTUh	**1.4E-10**	1.3E-12	1.2E-10	1.5E-11	9.8E-14	1.7E-12	1.1E-13	7.8E-14	6.4E-14
Human toxicity, non-cancer	CTUh	**2.6E-09**	1.7E-11	2.1E-09	3.5E-10	8.0E-13	1.2E-10	3.8E-12	2.0E-12	3.2E-13
Human toxicity, non-cancer – inorganics	CTUh	**2.4E-09**	1.5E-11	2.0E-09	3.1E-10	7.5E-13	1.2E-10	3.7E-12	1.9E-12	2.9E-13
Human toxicity, non-cancer – organics	CTUh	**1.8E-10**	2.7E-12	1.3E-10	4.5E-11	5.1E-14	-2.4E-12	1.4E-13	1.4E-13	2.5E-14
Ionising radiation	kBq U-235 eq	**1.5E-02**	1.8E-04	2.4E-03	1.4E-04	2.2E-06	8.6E-05	1.2E-02	5.5E-05	2.4E-07
Land use	Pt	**1.0E+01**	6.6E-03	9.4E+00	7.5E-02	-2.7E-03	6.5E-01	9.9E-04	1.2E-02	1.7E-03
Ozone depletion	kg CFC11 eq	**1.2E-08**	3.9E-09	8.3E-09	4.0E-10	4.9E-12	-8.0E-10	1.6E-11	2.0E-11	5.9E-12
Photochemical ozone formation	kg NMVOC eq	**3.9E-04**	2.6E-05	3.1E-04	2.8E-05	2.8E-07	2.6E-05	7.4E-07	4.7E-07	1.7E-07
Resource use, fossils	MJ	**1.5E+00**	4.0E-01	9.2E-01	6.3E-02	5.7E-04	-1.5E-01	2.3E-01	3.1E-03	6.6E-04
Resource use, minerals and metals	kg Sb eq	**1.2E-05**	9.2E-09	9.4E-06	2.7E-06	-7.7E-10	-2.6E-08	6.9E-09	7.5E-09	1.7E-10
Water use	m3 depriv.	**7.0E-02**	1.4E-03	5.9E-02	2.3E-03	6.1E-03	6.2E-05	9.1E-04	2.8E-05	1.2E-05

Table 12:Implementation of the marginal mix for Western Europe under current policy scenario

Technology	Marginal mix	Unit	Dataset
Oil		kWh	
Natural gas	0.05581	kWh	Electricity - Natural gas - High voltage - Western Europe Mix
Coal		kWh	
Solar PV	0.72606	kWh	Electricity - Solar PV - High voltage - Western Europe Mix
Wind	0.17448	kWh	Electricity - Wind - High voltage - Western Europe Mix
Hydro	0.01113	kWh	Electricity - Hydro - High voltage - Western Europe Mix
Biomass	0.01363	kWh	Electricity - Biomass - High voltage - Western Europe Mix
Nuclear	0.01689	kWh	Electricity - Nuclear - High voltage - Western Europe Mix
Geothermal		kWh	
Other	0.00108	kWh	Electricity - Other - High voltage - Western Europe Mix
Hydrogen		kWh	
Solar CSP	CS	kWh	Electricity - Solar CSP - High voltage - Western Europe Mix

Appendix C Methodology applied to calculate the impacts associated to the production of methanol and hydrogen using natural gas.

Comparing the results regarding impact categories for every different feedstock source route and the production of methanol using fossil fuels, in this case, natural gas will proportionate perspective, and a more complex analysis of the results obtained. The most prominent industrial processes for synthesizing methanol rely on traditional fossil fuels, specifically natural gas and coal, most methanol is currently produced from natural gas, which serves both as a feedstock and a process fuel. The facility's CO_2 emissions are calculated using a carbon mass balance methodology (Rumayor, Dominguez-Ramos and Irabien, 2019).

This process includes activities involving raw materials, processing energy, estimates on catalyst use, emissions to air and water from the process, and plant infrastructure. It describes the production of methanol from natural gas, utilizing a steam reforming process to obtain syngas. The process assumes no CO_2 use and no hydrogen production, with hydrogen being burned in the furnace instead. The geographical data comes from various plants in different locations and is primarily sourced from literature and articles related to plant design. The technology data pertains to the steam reforming of natural gas, with other reforming technologies used to determine uncertainty. Only production from natural gas is included (EcoInvent, 2020).

Table 13: EcoInvent results of the production of methanol using natural gas

Impact category	Unit	Total impacts
Global warming	kg CO2 eq/GJ methanol	39.53
Terrestrial acidification	kg SO2 eq/GJ methanol	0.05
Freshwater eutrophication	kg P eq/GJ methanol	5×10^{-3}
Marine eutrophication	kg N eq/GJ methanol	2.2×10^{-4}
Land use	m2a crop eq/GJ methanol	0.53
Mineral resource scarcity	kg Cu eq/GJ methanol	0.07
Fossil resource scarcity	kg oil eq/GJ methanol	40.45
Water consumption	m3/GJ methanol	27.38

Comparing the GWP emissions of the methanol processes (cradle to gate) is one of the main goals of this research. However, one of the key aspects of bio-methanol is that no CO_2 emissions are released once is it is burned and used as a biofuel. The GWP emissions of the combustion and the use of the biofuel were calculated according to the chemical properties of the methanol.

The impacts of producing hydrogen via steam methane reforming were calculated using the EcoInvent dataset. The table below presents the total environmental impacts per functional unit (FU) for various impact categories:

The impacts of producing hydrogen via steam methane reforming were calculated using the EcoInvent dataset. In Table 14 below, presents the total environmental impacts per functional unit for the chosen impact categories

Table 14: EcoInvent results of the production of hydrogen using natural gas

Impact category	Unit	Total impacts
Global warming	kg CO2 eq/GJ methanol	91.88
Terrestrial acidification	kg SO2 eq/GJ methanol	0.05
Freshwater eutrophication	kg P eq/GJ methanol	2.50E-03
Marine eutrophication	kg N eq/GJ methanol	8.33E-04
Land use	m2a crop eq/GJ methanol	0.42
Mineral resource scarcity	kg Cu eq/GJ methanol	0.17
Fossil resource scarcity	kg oil eq/GJ methanol	36
Water consumption	m3/GJ methanol	0.33