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Life Cycle Assessment and Techno-economic Analysis of eFuels used in Heavy-duty Vehicle

Master's thesis in Innovative and Sustainable Energy Engineering

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Abstract

Road freight is indispensable to business and trade in Europe, with trucks responsible for moving 77% of all freight on the continent. Finland, known for its strong forest industry, is a leading exporter of timber and forest products, relying heavily on Heavy-duty vehicles (HDVs) to support its operations. However, in 2019, the HDV sector in Finland accounted for 4.3 million tonnes of carbon dioxide equivalent emissions, representing 40% of the country's total road transport CO₂ emissions.

To meet the EU's requirement of reducing domestic transport emissions by at least 50% by 2030, Finland must decarbonize its transport sector completely by 2045. Therefore, the modernization and decarbonization of the heavy-duty sector are crucial for achieving these targets.

This research aims to evaluate the environmental impact of decarbonizing the heavy-duty sector using alternative fuels, specifically hydrogen, methanol, and ammonia-based electrofuels (eFuels). By integrating life cycle assessment (LCA) and techno-economic analysis (TEA), the study examines the relationship between technical, economic, and environmental performance. Two scenarios are considered, with different electricity sources (grid and biopower plant) supplying the eFuel production process.

The LCA results, adopting a well-to-wheel approach, indicate that all eFuel options provide significant greenhouse gas (GHG) savings of over 50% compared to conventional diesel fuel, particularly when low carbon intensity (CI) electricity is employed. Among the eFuels, methanol fuel exhibits the lowest global warming impact (GWP) at 0.155 kgCO₂-eq/km, while ammonia (+diesel) fuel has the highest impact at 1.33 kgCO₂-eq/km. The findings consistently demonstrate that the biopower plant scenario results in lower climate impacts than the grid scenario.

Additionally, the production costs of all eFuels fall within the current market price range. Hydrogen fuel is the most cost-effective option at 0.58 € per kilometer, while ammonia (+diesel) fuel is the most expensive at 1.11 € per kilometer. The study emphasizes that electricity prices significantly influence the cost of eFuels, highlighting the importance of renewable electricity sources and supportive policies.

However, the production and availability of eFuels are currently limited, hampering large-scale pilot projects. Exploring alternative technological solutions becomes essential to meet decarbonization goals, considering the infrastructure challenges associated with electrification scenarios. This research underscores the potential of eFuels to reduce GHG emissions in the heavy-duty sector, emphasizing the importance of renewable energy sources and supportive policies.

Keywords eFuels, hydrogen, methanol, ammonia, HDV, global warming potential, production cost

Preface and acknowledgements

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Symbols and abbreviations

Symbols

<i>a</i>	Scaling factor
C	Equipment cost
g	gram
K	kelvin
kWh	Kilo-watt per hour
m ³	Meter cubic
MJ	Mega joule
MW	Mega watt
ppm	Part per million
V	Capacity

Abbreviations

AEA	Ammonia Energy Association
AEC	Alkaline electrolysis cell
BECCS	Bioenergy with carbon capture and storage
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CEPCI	Chemical Engineering Plant Cost Index
CML	Center of Environmental Science of Leiden University
DAC	Direct air capture
DDC	Detroit Diesel Company
EU	European Union
FCI	Fixed capital investment
FCV	Fuel cell vehicle
GHG	Greenhouse gas emission
GLO	Global
REET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWP	Global warming potential
HDV	Heavy-duty vehicle
HER	Hydrogen evolution reaction
ICE	Internal combustion engine
IEA	International Energy Agency
ILCD	International Life Cycle Data
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
KOH	Potassium hydroxide
LCA	Life cycle assessment

LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LPG	Liquid petroleum gas
MEA	Monoethanolamine
MSW	Municipal solid waste
OER	Oxygen evolution reaction
OPEX	Operational expenditure
PEMEC	Proton exchange membrane electrolysis cell
PEMFC	Proton exchange membrane fuel cell
PSA	Pressure swing adsorption
PV	Photovoltaic
ROW	Rest of the world
SMR	Steam methane reforming
SOEC	Solid oxide electrolysis cell
TEA	Techno-economic analysis
TTW	Tank-to-wheel
WTT	Well-to-tank
WTW	Well-to-wheel
YSZ	Yttria stabilised zirconia

1 Introduction

1.1 Background

In the continent of Europe, road freight is essential to business and trade. 77% of all freight moved in land in the European Union is moved by trucks, which are a part of a logistics chain that also includes inland waterways, shipping, air, and train transportation. Finland has a robust economy especially in forest industry making it leading exporter of timber and forest products due to its significant forest and freshwater resources. Heavy-duty vehicles' (HDVs) play a big role in supporting the operation of this corporation.

Currently, the transport industry is responsible for 37% of all CO₂ emissions. In Finland, the heavy-duty sector is responsible for 4.3 million tonnes of carbon dioxide equivalent of greenhouse gas emissions in 2019. The International Energy Agency (IEA) claims that when international marine traffic and road heavy-duty (HD) traffic are combined, the resulting quantity of global emissions is equivalent to that of road passenger travel.

According to the EU legislation, Finland needs to curb the domestic transport emissions in the effort sharing sector by at least 50% by 2030. In addition, Finland also has a government programme of being a carbon-neutral in 2035. This means that the transport sector should have zero emissions by 2045 at the latest. In order to achieve the target, modernization and decarbonization of the heavy-duty sector are necessary.

1.2 Goal and Scope

The main objectives in this thesis project are evaluating how does decarbonization of heavy-duty sector by using alternatives fuel impact the environment. The alternative fuels being assessed are hydrogen, methanol, and ammonia based fuel. The assessment is based on Life Cycle Assessment (LCA) method for research purposes in research group of energy conversion, Department of Mechanical Engineering in Aalto University. In addition, the techno economic analysis for the eFuels would be also analyzed to gain the cost estimation for production of such eFuels. Integration of life cycle assessment (LCA) and techno economic analysis (TEA) enables systematic analysis of the relationships between technical, economic, and environmental performance. The audience targeted for this thesis mainly are companies interested in building eFuel plants, government on building road infrastructure and technology developers.

The scope of LCA in this thesis is limited to Well-to-Wheel (WTW) approach where the data are taken from literature review and databases published in the last five years. It also has a firm focus on heavy duty vehicle fleet using combustion engine, specifically group 4 based on EU regulation (Regulation (EU) 2019/1242).

2 Literature review

2.1 Current status of fuel usage in heavy-duty sector

The European Commission recently released its revised proposal for the CO₂ requirements for buses, trailers, and trucks. The proposal includes a 90% CO₂ reduction target for trucks for 2040 (ICCT, 2023). There are currently around 92 633 total truck fleet in Finland (2022) based on Netwheels Ltd, Finnish Transport and Communications Agency data. Today's fleet commonly are fueled with diesel whereas it counts 89 691 trucks fueled by diesel in Finland (Tiedotuskeskus, 2023). Figure 2.1 depicts the amount of truck fleet by fuel type in Finland.

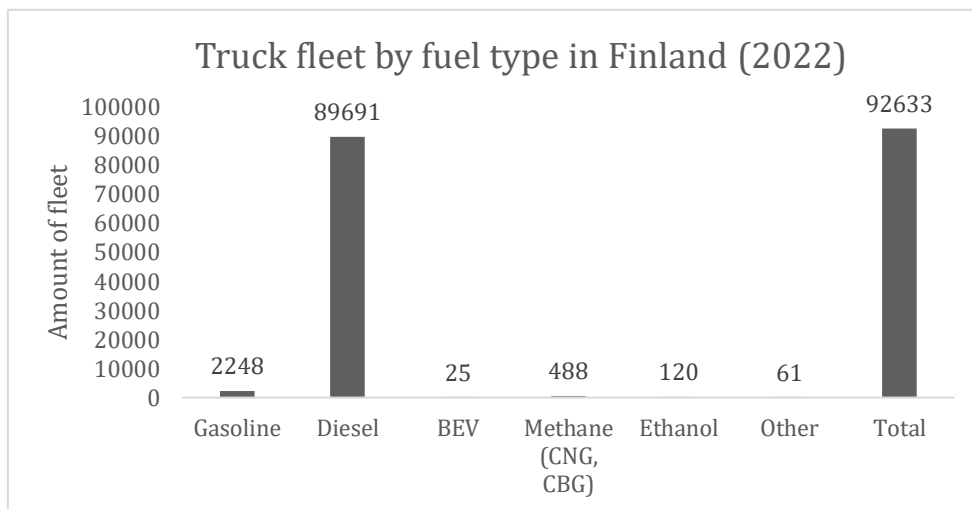


Figure 2.1 Truck fleet by fuel type in Finland on 2022 (Tiedotuskeskus, 2023)

Diesel engines are frequently used in heavy-duty transport, agricultural applications, and power generation. Increased torque, power and improved thermal efficiency and reduced fuel usage are a few of their perks. It is worth to mention that diesel engine is ideal for heavy vehicles performance since they offer better fuel economy, where they can provide a significant amount of force to run even at the slow speed. Regrettably, diesel engines produce higher levels of carbon monoxide, unburned hydrocarbons, nitrogen oxides, and soot problems (Gill, Tsolakis, Herreros, & York, 2012). Table 2.1 shows the characteristic of diesel fuel.

Table 2.1 Characteristic of diesel fuel (Ramirez, Aggarwal, Som, Rutter, & Longman, 2014) (Shadidi, Najafi, & Yusaf, 2021)

Properties	Value
Carbon content (mass percent)	86.64
Hydrogen content (mass percent)	13.01
Oxygen content (mass percent)	0
Molecular weight (g/mol)	~170
Sulfur content (ppm)	11.2
Lower heating value per kilogram (MJ/kg)	42.31
Cetane number	47.7
Density @ 25°C (kg/m ³)	849.2
A/F stoichiometric ratio	17
Temperature of ignition (K)	483
Temperature of adiabatic flame (K)	2300

As we know the diesel fuel usage has caused a significant fraction of the global fossil oil production, numerous strategies have been prepared worldwide to encourage the development of alternative fuels for heavy-duty sector. Policies have been issued and discussed aiming at reducing greenhouse gasses emission within this sector. For example, the Ministry of Transport and Communications of Finland has a roadmap targets and measures to halve greenhouse gas emissions by 2030 by replacing fossil fuels with alternative transport fuels. It aims to make at least 30% of the fuel consumption in transportation sector be covered by renewable fuels (i.e. eFuels) produced from sustainable raw materials, such as hydrogen and/or electrofuels made hydrogen (Ministry of Transport and Communications, 2021).

2.2 Hydrogen as alternative fuel

Hydrogen is one of the promising energy carrier that can be produced by renewable energy source. As a fuel that contains no carbon, hydrogen has several advantages. Compared to petroleum fuel based, hydrogen has three times higher of heating value while also emit markedly fewer hazardous tailpipe emissions (Fayaz, Saidur, Anuar, Saleman, & Islam, 2012). Hydrogen combustion process is free from carbon dioxide (CO₂), nitrogen oxides (NO_x), and sulfur oxides (SO_x) since hydrogen combustion emits

water vapour (Acar & Dincer, 2018). Contrary to hydrocarbon fuels including natural gas, gasoline, and diesel, using hydrogen as a fuel for internal combustion engines can increase thermal efficiency while lowering carbon emissions. Increasing our dependence on renewable sources while decreasing our use of non-renewable fossil fuels usage is one of the main advantages of utilizing hydrogen for transportation (Shivaprasad, Kumar, & Guruprasad, 2012).

Physical properties of hydrogen are flammable, tasteless, odourless, colourless and contain high content of energy value. Hydrogen is in gas state at standard pressure and temperature conditions. In addition, hydrogen also can be converted into liquid and solid state for energy carrier purposes. There have been a number of studies on the use of hydrogen in spark ignition engines that address issues like poor volumetric efficiency and decreased power density (Li & Karim, 2005) (Duan, Liu, & Sun, 2014). Table 2.2 shows the characteristic of hydrogen.

Table 2.2 Characteristic of hydrogen (Shadidi, Najafi, & Yusaf, 2021)

Properties	Value
Chemical formula	H ₂
Carbon content (mass percent)	0
Molecular weight (g/mol)	2.015
A/F stoichiometric ratio (kg/kg)	34.3
Temperature of ignition (K)	858
Temperature of adiabatic flame (K)	2384
Flammability limits (vol percent in air)	4.1-75
Density @ 25°C (kg/m ³)	0.08375
Lower heating value per kilogram (MJ/kg)	120
Volumetric energy content (MJ/m ³)	9.60

2.2.1 Present status hydrogen fuel production process

Hydrogen production technology can be accomplished based on various energy resources. There are four significant categories classifying the production of hydrogen, namely green (renewable energy-based hydrogen production), grey (coal gasification and natural gas-based hydrogen production without integration with carbon capture and storage process), blue (coal gasification and natural gas-based hydrogen production integrated

with carbon capture and storage process), and black or brown hydrogen (coal or lignite based in the hydrogen-making process). Table 2.3 arranges the overview different pathway of hydrogen production within their performance features.

Table 2.3 Overview different pathway of hydrogen production within their performance features (Ishaq, Dincer, & Crawford, 2022)

Process	Energy sources	Maturity level	Efficiency (%)
Steam methane reforming (SMR)	Light hydrocarbons	Mature	70-80
Methane/natural gas pyrolysis	Hydrocarbons	R&D to mature	72-54
H ₂ S methane reforming	Light hydrocarbons	R&D	50
Landfill gas dry reformation		R&D	47-58
Partial oxidation of heavy oil	Heavy fuel oil	Mature	70
Thermochemical water splitting	Heat	Early R&D	35-45
Coal gasification	Coal	Mature	60
Partial oxidation of coal	Coal	Mature	55
Grid electrolysis of water	Electricity	R&D	27
High temperature electrolysis of water	Electricity	R&D	48
Biomass gasification	Biomass	R&D	45-50
Solar and PV-electrolysis of water	Solar	R&D to mature	10

Currently, the common technology for hydrogen production is based on the fossil fuels. It could be introduced as an established commercial technology that can be used to achieve high efficiency at lower expense. Specifically, steam methane reforming and partial oxidation of methane gas processes still lead the market by 40%, following by reforming of oil and naptha process

by 30%, coal gasification process by 18%, electrolysis of water by 3.9%, and the rest is others (Shrestha, 2020).

The technologies for producing hydrogen from fossil fuels and renewable biomass sources, such as reforming (steam, partial oxidation, autothermal, plasma, and aqueous phase) and pyrolysis, were evaluated by Holladay et al. (Holladay, Hu, King, & Wang, 2009). The study shows that countries can generate hydrogen in the long run from a variety of local feedstock. According to another study by Ozbilen et al. (2011), the sulfur-iodine cycle, high temperature water electrolysis, conventional steam reforming of natural gas, and the production of hydrogen from renewable resources all have different environmental impacts. The study shows that steam reforming of natural gas has the highest impact. Accordingly, there is a need in shift for hydrogen production process into another process, pointedly with renewable energy resources based.

2.2.2 Decarbonization of hydrogen fuel production

Reducing the greenhouse gas emissions and accomplish the climate goals can be achieved by decarbonizing the industry, transport, and electricity generation. One of them is decarbonizing the hydrogen fuel production. The idea of generating hydrogen utilizing renewable energy technologies to tackle environmental pollution and decrease dependence on fossil fuel is not new, but it has recently gained more attention (IEA, Technology roadmap hydrogen and fuel cells, 2015). The hydrogen production methods evaluated in the selected hydrogen-based power generation for this project comprised electrochemical technology.

Electrochemical technology, namely electrolysis, are generally classified into three types according to the electrolyte they are using: Alkaline Electrolysis Cell (AEC) is based on an aqueous alkaline electrolyte, Proton Exchange Membrane Electrolysis Cell (PEMEC) is named after the polymeric proton exchange membranes used, and Solid Oxide Electrolysis Cell (SOEC) is based on solid ceramic membranes that conduct oxygen. Those technologies vary greatly in concept and materials, as well as the conducted ionic species, and the corresponding reaction details. Table 2.4 demonstrates comparison between AEC, PEMEC and SOEC in some comparable framework within primary categories.

Table 2.4 Main characteristics of AEC, PEMEC, and SOEC

	AEC		PEMEC	SOEC	Source
Electrolyte	Aqueous potassium hydroxide (20-30 wt% KOH)		Polymer membrane	Ytria stabilised zirconia (YSZ)	(Schmidt, et al., 2017)
Cathode	Ni, alloys	Ni-Mo	Pt, Pt-Pd	Ni/YSZ	(Schmidt, et al., 2017)
Anode	Ni, alloys	Ni-Co	RuO ₂ , IrO ₂	LSM/YSZ	(Schmidt, et al., 2017)
Operating Temp. (°C)	60-80		50-80	650-1000	(Schmidt, et al., 2017)
Operating Pressure (bar)	<30		<200	<25	(Schmidt, et al., 2017)
Electricity demand (kWh/kgH ₂)	50-78		50-83	45-55	(IRENA, 2020)
System efficiency (%)	65		60	85	(Zhao, et al., 2020)
Gas H ₂ purity (%)	>99.5		99.99	99.9	(IRENA, 2020)
Stack Lifetime (thousand hours)	60-90		20-60	<10	(Schmidt, et al., 2017)
Maturity	Commercial		Commercial	Demonstration	(IRENA, 2020)
Capital cost range - stack only (€/kW _{el})	240		356	>1780	(IRENA, 2020)

However, the fundamental building blocks of each technology are the same: an electrolyte for ionic transmission, an oxygen electrode for the oxygen evolution reaction (OER), and a hydrogen electrode for the hydrogen evolution reaction (HER). The basic layout of AEC, PEMEC and SOEC electrolyzer are showed in Figure 2.2a, 2.2b, and 2.2c, respectively. In addition, the general equation reactions happened on each type of electrolyzer during the electrolysis process are also written on Table 2.5.

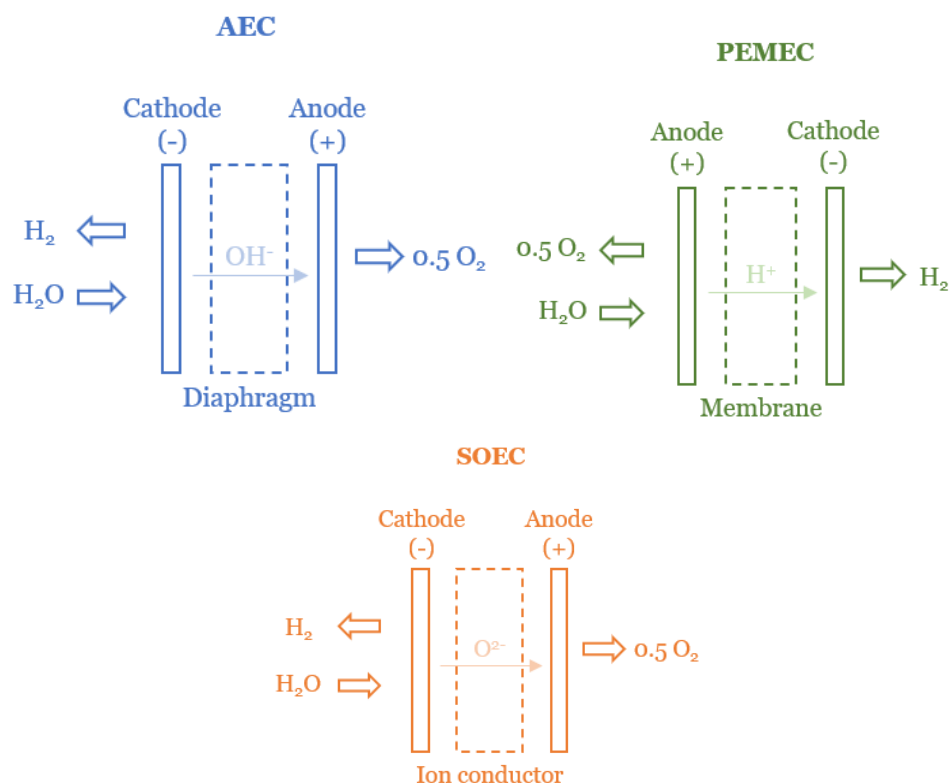


Figure 2.2 Basic layout of AEC (left), PEMEC (right), and SOEC (middle) electrolyzer

Table 2.5 Cathode and anode reaction of AEC, PEMEC and SOEC electrolysis technologies

	Cathode reaction	Anode reaction
AEC	$2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$	$2\text{OH}^- \rightarrow \text{H}_2\text{O} + 0.5\text{O}_2 + 2\text{e}^-$
PEMEC	$2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$	$\text{H}_2\text{O} \rightarrow 2\text{H}^+ + 0.5\text{O}_2 + 2\text{e}^-$
SOEC	$\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + \text{O}^{2-}$	$\text{O}^{2-} \rightarrow 0.5\text{O}_2 + 2\text{e}^-$

As mentioned earlier on Table 2.4, AEC and PEMEC are already on the commercial stage based on their maturity level of technology. Currently, AEC is the most developed electrolyzer and has the lowest capital cost (Luo, Shi, & Cai, 2021). Based on the comparative values of environmental assessment

by Gerloff (2021), AEC electrolyzer technology has lower global warming potential result than PEMEC within the 2050 energy scenario where it counts 17.4 kg-CO₂-eq/kg H₂ and 18.1 kg-CO₂-eq/kg H₂, respectively. Study by Zhao et al. (2020) also shows the same trend where PEMEC has 9 times higher climate change impact compared to AEC. The typical design configuration and balance of plant for an AEC electrolyser is depicted on Figure 2.3.

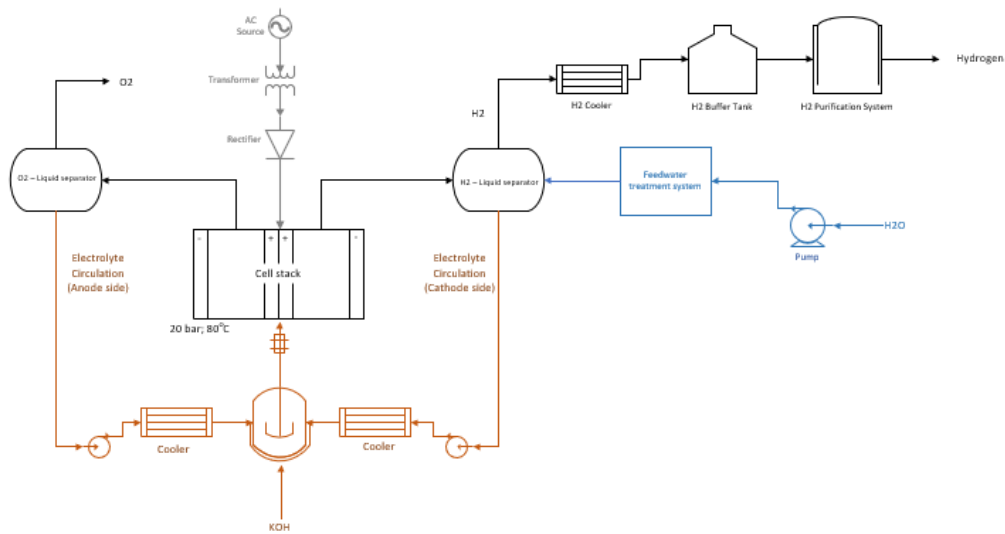


Figure 2.3 Typical design configuration and balance of plant for an AEC electrolyser (Sakas, et al., 2022)

2.2.3 Hydrogen fuel transport and delivery

Hydrogen has the lowest energy content by volume but the highest energy content by weight of any fuel. Hence, the delivery method of hydrogen is an essential consideration for the implementation of this hydrogen fuel utilization. Infrastructure is needed to distribute the hydrogen from the point of production to the refuelling station. There are three probable hydrogen-delivery methods: compressed tube trailers, cryogenic liquid trucks, and compressed gas pipelines. Hydrogen delivery is a major factor in the cost, energy consumption, and emissions of hydrogen pathways incorporating hydrogen central plant production. Scale (hydrogen flow rate), number of refuelling station, and delivery distance are crucial factors that influence delivery costs (Yang, Nicholas, & Ogden, 2006). On the other hand, the most cost-effective delivery method will be selected based on particular market and geographic factors (Yang & Ogden, 2007). Table 2.6 summarizes the overview of H₂ delivery methods.

Table 2.6 Overview of hydrogen delivery methods (Qureshi, et al., 2023)

Parameters	Pipeline	Tube trailer	Liquid (road)
Capacity	≥100,000 kg/h	≤400 kg delivered/truck	≤4000 kg /truck
Total cost (€/kg/100 km)	0.1-1.0	0.5-2.0	0.3-0.5
Efficiency	99.2% per 100 km	94% per 100 km	99% per 100 km for transport
Energy required	Pipeline compressors	Transport fuel	Transport fuel
Suitable for	- Large and very large quantities of gas - Where pipeline storage is used	- Small quantities of gas - Small distances	- Large quantities of gas - Where liquid storage is used

2.2.4 Hydrogen engine for heavy-duty sector

A promising path for the transportation industry's future is the use of hydrogen as a fuel in vehicles that are powered by internal combustion engine (ICE) or fuel cell (FC). Fuel cell vehicle is running based on electrochemical reactions to production electricity from hydrogen and oxygen. High efficiency, no harmful emissions (FC only emits water vapor that is safe compared to the emissions produced by the combustion of fossil fuels), quiet operation, and modularity are all advantages of hydrogen FCVs (Dicks & Rand, 2018). However, given that the production of fuel cell, which requires the use of uncommon and occasionally toxic raw materials and challenges with recycling, the widespread use of FCVs places a significant burden on the environment and limit the spread of this technology (DOE, 2017).

On the other hand, the advantages of Hydrogen-fueled ICEs (H₂-ICEs) include their reliance on a developed industry with a sizable production infrastructure, their ability to provide "flex-fuel" to help during transitional

period (from diesel fuel into eFuel) - which could support in the deployment of the hydrogen infrastructure, lower requirements for hydrogen compared to HFCs (hydrogen fuel cell), ultra-low emissions, raised peak and part load efficiencies, and lack of reliance on rare materials (Verhelst, 2014). H₂-ICEs have a poor achievable efficiency of 20-25% which poses issues when taking into account the present hydrogen storage capacities in both gas and liquid states (Hosseini & Butler, 2020).

2.3 Methanol as alternative fuel

Methanol is a famous chemical in the world that conventionally used by chemical industries such as paints, pharmaceuticals, adhesives, and automotive. In recent years, methanol demand has been firmly increasing for energy usage as a component of fuel blends or a fuel itself. Even though it emits hydrocarbons at a level comparable to gasoline (albeit of different species), due to the way it burns and the fact that it only contains a single carbon molecule, it emits much less nitrogen oxide and particulate matter than complex hydrocarbon fuels do (Verhelst, Turner, Sileghem, & Vancoillie, 2019).

One of the major justifications for considering methanol as a fuel for transportation is its scalability. It is a strong candidate for a sustainable fuel with the potential to greatly reduce the fossil fuel carbon footprint of transportation due to its simplicity of synthesis and wide range of source feedstocks. From Volvo (2008) study in Climate Issue in Focus, methanol performs exceptionally well in contrast to other renewable fuels. It has high scores for most of the criteria (i.e. climate impact, energy efficiency, and fuel potential) being employed in heavy-duty vehicle.

Methanol has many aspects which promotes it as an attractive fuel. It has high heat of vaporization, low stoichiometric air-fuel ratio, high specific energy ratio, low combustion temperature, etc. Table 2.7 shows the characteristic of methanol.

Table 2.7 Characteristic of methanol

Properties	Value
Chemical formula	CH ₃ OH
Carbon content (mass percent)	37.48
Molecular weight (g/mol)	32.04
A/F stoichiometric ratio (kg/kg)	6.50
Temperature of ignition (K)	738

Temperature of adiabatic flame (K)	2143
Flammability limits (vol percent in air)	6.0 to 36.5
Density @ 25°C (kg/m ³)	790
Lower heating value per kilogram (MJ/kg)	20.09
Volumetric energy content (MJ/m ³)	15871

2.3.1 Present status methanol fuel production process

As mentioned earlier, methanol is already extensively used chemicals since it is utilized as a primary feedstock for a large variety of chemicals such as formaldehyde, acetic acid, and dimethyl ether. There are four significant categories classifying the production of methanol, namely green (renewable energy-based methanol production), grey (natural gas-based syngas production without integration with carbon capture and storage process), and blue (natural gas-based syngas production integrated with carbon capture and storage process or green hydrogen with non-renewable CO₂ source), and brown hydrogen (coal gasification syngas making process). Figure 2.4 shows the overview different pathway of methanol production within their feedstock source.

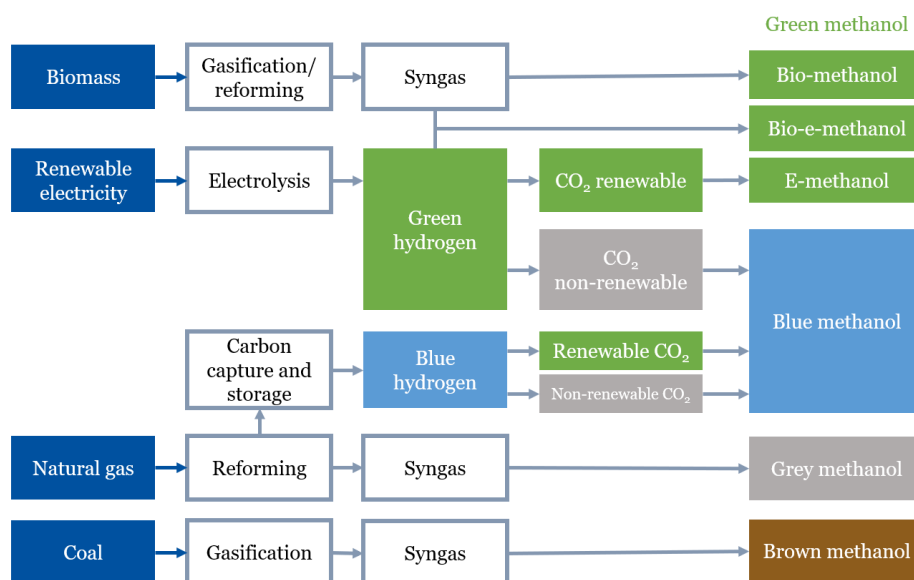


Figure 2.4 Overview different pathway of methanol production (IRENA, Innovation Outlook: Renewable Methanol, 2021)

Currently, the common technology for hydrogen production is based on the fossil fuels. The production of methanol is a comparatively straightforward industrial process. It entails three fundamentals' steps: synthesis gas production, synthesis gas conversion to methanol, and distillation of the reactor effluent (to separate the methanol from the by-products). For the synthesis gas production (a mixture of H₂, CO, and CO₂) dominantly is done by reforming of natural gas (Bozzano & Manenti, 2016). Nevertheless, it can also conceivably be produced from reforming or partial oxidation of petroleum, heavy-oil, coal, or biogas. Coal also can be gasified within gasification process to produce syngas.

Meanwhile to produce methanol, there are only a few different process variations accessible. Based on Bozzano and Manenti (2016) study, 60% of the methanol synthesis in the world employs Johnson Matthey process while 27% of the rest implements Lurgi process. As pure methanol cannot be obtained solely after the conversion process, distillation process is needed to separate the substances as methanol is a polar molecule (hence miscible with water).

Syngas synthesis requires several steps such as steam reforming, partial oxidation dry reforming, autothermal reforming, or a combination of those. These are an energy intensive process since it is operated in a high temperature condition (>800°C). Furthermore, since there are more impurities and contaminants in the syngas produced by coal gasification, it needs much more pre-treatment, conditioning, and adjustment which requires much more energy. Hence, it is essential to reduce the carbon intensity of methanol production.

2.3.2 Decarbonization of methanol fuel production

Low-emission methanol, especially when used as a fuel in land or sea transportation, could play a bigger role in decarbonizing some industries where choices are currently scarce. There are two pathways to produce green methanol using renewable energy and renewable feedstocks, namely bio-methanol and e-methanol. Biomass is the key aspect for bio-methanol production. Important possible sustainable biomass feedstocks include sewage, municipal solid waste (MSW), by-products of agriculture and forestry, biogas from landfills, and black liquor from the pulp and paper industry. On the other hand, e-methanol is produced by combining CO₂ captured from renewable sources (either from air capture [DAC] or bioenergy with carbon capture and storage [BECCS]) with green hydrogen (hydrogen made with renewable electricity). The synthesis process is called catalytic

conversion of CO₂ or CO₂ hydrogenation over Cu/ZnO/Al₂O₃ catalysts (Jiang, 2020).

The majority of the renewable methanol generated each year, less than 0.2 Mt, is produced as bio-methanol (IRENA, Innovation Outlook: Renewable Methanol, 2021). Finland has a big opportunity from its power generation system to produce green hydrogen since it has a comparatively low carbon intensity and a reliable national electricity transmission grid. In addition, renewable CO₂ source is readily available since around 85% of renewable energy is originated from biomass whereas the primary use is for renewable heat application (IEA Bioenergy, 2021). These favourable circumstances make e-methanol as an attractive product.

E-methanol is a type of electrofuel (e-fuel) and electrochemical that is created using Power-to-X technology. Electrochemical processes can produce e-methanol in a variety of methods. The most established and straightforward way of producing hydrogen is by electrolyzing water with a renewable source of energy electricity. Various pathway to produce green hydrogen can be referred to section 2.2. In addition, there are also other approaches to e-methanol production through electrolysis and electrochemical processes as shown on Figure 2.5.

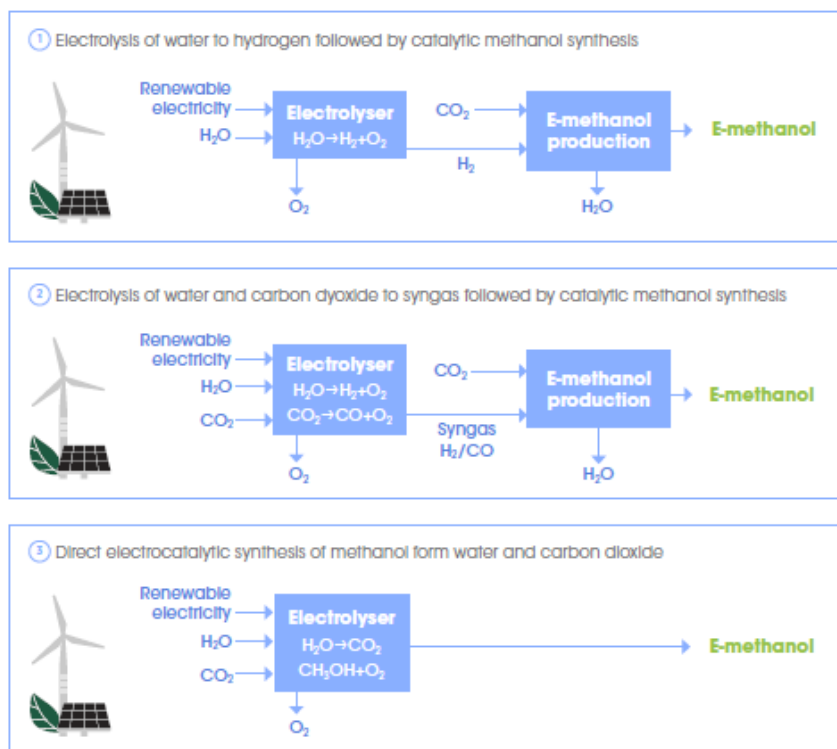


Figure 2.5 Various ways to produce e-methanol through electrolysis and electrochemical processes

By 2050, it is anticipated that concentrated CO₂ point sources in steel production, ammonia production, natural gas processing, and hydrogen production through steam reforming will be reduced and eventually eliminated as part of the shift to a greenhouse gas neutral economy (gGmbH, 2021). In theory, CO₂ capture from the air is feasible everywhere and even required for all prospective sites where there are no other options. However, concentrated sources are always brought up in relation to the creation of synthetic energy carriers, particularly those from industry and biogas generation. The options for capturing the CO₂ from concentrated sources are shown on Figure 2.6.

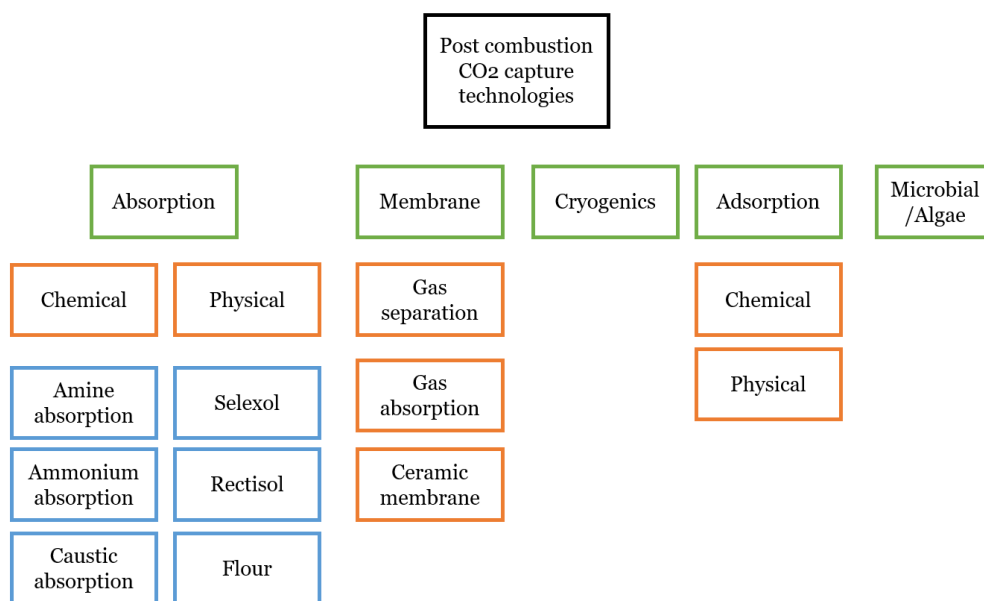
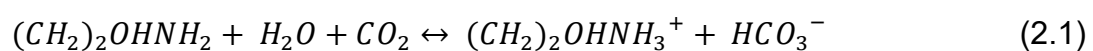


Figure 2.6 Options for carbon capture technologies (Ekanayaka, Ruvishani, Jinasoma, Piyathilaka, & Pathirana, 2020)

Amine absorption technique is the most advanced method, and it has clear benefits over other approaches, including maturity, cost-effectiveness, the potential for industrialization, and the ability to handle large exhaust streams (Afkhamipour & Mofarahi, 2017). One of the most commercialized one is absorption with Monoethanolamine (MEA). MEA has a large capacity for absorption. MEA interacts with CO₂ in the gas stream to form MEA solution with CO₂ where the reheated stripper is used to discharge the MEA solution. Equation 2.1 shows the reaction taken within the MEA and CO₂ absorbed. The schematic diagram of the absorption process is depicted on Figure 2.7.



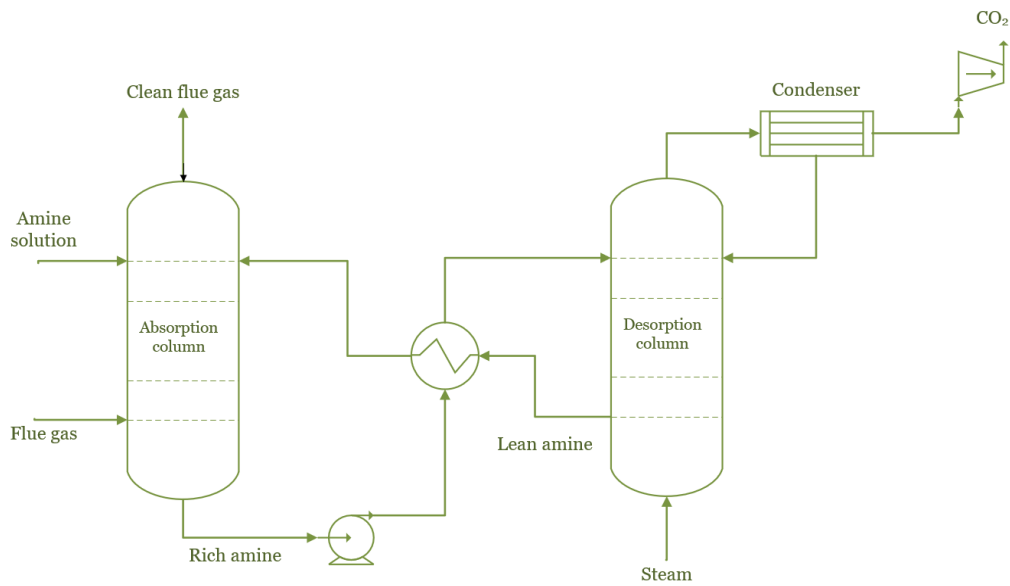


Figure 2.7 Carbon capture process schematic flow diagram (Chisalita, et al., 2019)

There are two general types of carbon source that can be captured for the process, namely biogenic and fossil carbon. Biogenic carbon common feedstocks include organisms that take up carbon throughout the course of their lives, such as soil, plants, and trees. Emissions related to the biological processes, such as burning, harvesting, digestion, fermentation, decomposition, or processing of biological materials are “biogenic emissions” and are included in the natural carbon cycle. And through the removal of CO₂ from the atmosphere during photosynthesis, the organisms contribute to the reduction of climate change.

On the other hand, fossil carbon is established when living things die and are deposited on the ground. This substance is eventually buried, where it is exposed to intense heat, a lack of oxygen, and air pressure. This acute environment leads the material to deteriorate and becoming a fossil fuel. As fossil fuels are used, more carbon from the geologic pool is liberated, which has never been exposed to the biosphere-atmosphere system previously. The different between the two types of carbon source can be visualized from Figure 2.8.

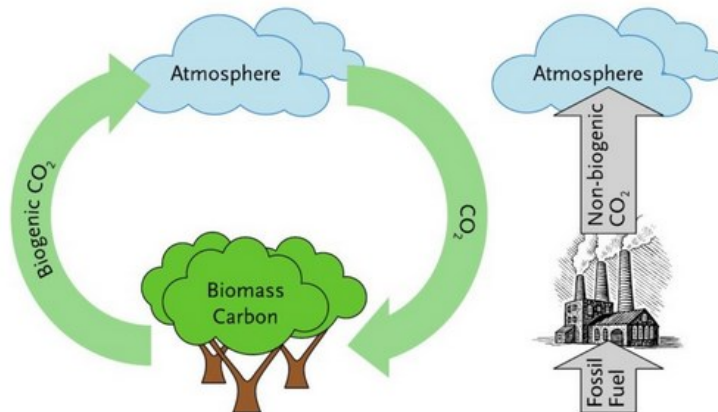


Figure 2.8 Biogenic vs fossil-based carbon cycle

As previously stated, the methanol synthesis is called carbon dioxide hydrogenation process. The process flow diagram such process is shown on Figure 2.9.

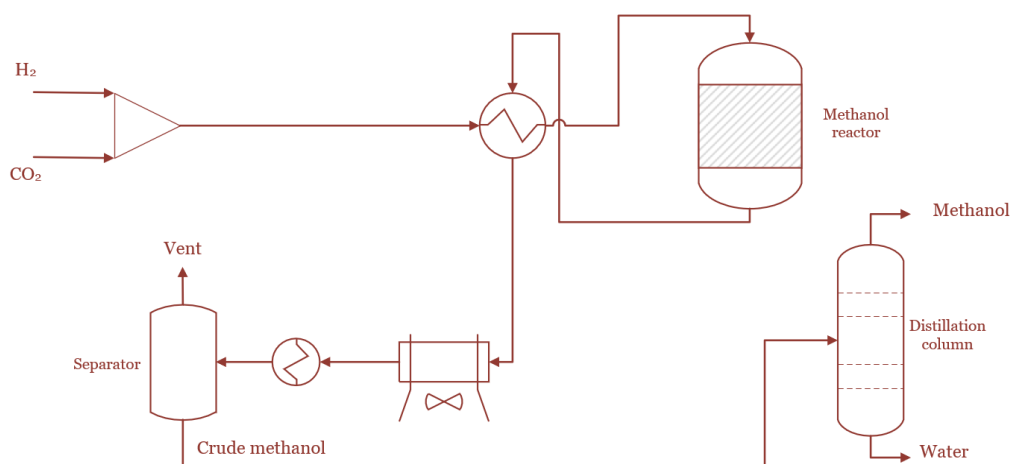


Figure 2.9 Carbon dioxide hydrogenation process schematic flow diagram (Samimi, Rahimpour, & Shariati, 2017)

The primary obstacles to the adoption of renewable methanol at the moment is its higher price compared to alternatives derived from fossil fuels, and this price difference will continue for some time. However, compared to other alternatives, its value lies in its ability to help abate emissions.

2.3.3 Methanol fuel transport and delivery

Methanol has already become a commodity that is widely accessible and has established distribution and storage networks. Since methanol typically

distributed in liquid form, shifting from apparent liquid fossil fuel-derived products (such as gasoline, diesel fuel, kerosene, etc) to a renewable and sustainable liquid fuel would be highly appealing in the transportation sector in particular.

Each month, methanol is shipped by ship, barge, train, and truck to a wide range of dispersed users. Like gasoline and other petroleum products, methanol can also be transported through pipelines. Smaller quantities and distribution to local markets typically utilize tanker trucks with up to 30 tons of capacity. Pipeline is another method of moving a lot of liquid, and they are also widely used to distribute oil, natural gas, and other derivatives. Technically speaking, there are no issues with transporting methanol through pipelines, as has been effectively shown in Canada with crude oil and LPG pipelines (Canada Energy Regulator, 2021). When methanol is produced in isolated areas, it is transported around the globe by specialized methanol ocean tankers, which vary in size from 15,000 to around 100,000 dead weight tons (Methanex, 2023). The expense of shipping methanol will become comparable to that of crude oil when it is transported in such large containers.

2.3.4 Methanol engine for heavy-duty sector

Methanol is attractive as a substitute for diesel fuel due to its combustion characteristic of does not produce smoke, soot, or particulates. However, Methanol has a high-octane rating of 119 (combined octane rating) compared to regular gasoline of 87 (Bromberg & Cohn, 2008). This promotes methanol to be more efficient than using gasoline as a fuel within the same engine —spark ignition engine. It is also should be noted that all gasoline-powered vehicles presently on the market can run on low-level methanol blends. However, gasoline or spark ignition engine mostly is made up for light duty vehicle.

Most heavy-duty vehicles use compression ignition engines. Diesel engines and gasoline engines are distinct to each other. Diesel engines depend on the fuel's inherent ability to self-ignite under specific high-temperature and high-pressure conditions to ignite the fuel/air mixture in the cylinders rather than spark plugs. In addition, due to the high-octane number of the methanol —which demonstrate a low cetane number, it is incompatible to be used with conventional compression-ignition engine. However, ignition improver or additives can be added to leverage the cetane ratings of the methanol. The Detroit Diesel Company (DDC) designed adjusted versions of their “ignition-improved” methanol-fueled compressions ignition engines which was implemented on heavy-duty vehicles (M, S, C, & R, 1985). Throughout the

1990s, the engines were tested in various locations across the United States. Particularly in Los Angeles, the Metropolitan Transit Authority maintained a sizable fleet of about 330 methanol-powered transit buses. It is also noteworthy that Methanol's characteristic, especially its polarity, bring a common issue regarding material compatibility of the current engine. Hence, it necessitates adjustment for such engines.

Many strategies have proposed using hydrogen-rich liquids like gasoline or methanol as a source of hydrogen via on-board reformers within fuel cell engine application in an effort to surmount the issues related to hydrogen storage and distribution. Several examples have shown that on-board methanol reformers are capable of powering fuel cell vehicles. In 2001, the Ballard Power System built the first local transit bus powered by methanol-fueled with 100 kW PEMFC (Proton-exchange membrane fuel cells) system (Ballard Power System, 2001). On the other side, significant research has to be done to further refine the processes for converting methanol to hydrogen because the hydrogen produced by these processes currently consistently has more than 100 ppm CO, which is poisonous for PEM fuel cell catalysts operating at temperatures below 100°C.

2.4 Ammonia as alternative fuel

Ammonia has been used extensively for many years as a refrigerant in refrigeration systems and in the manufacture of fertilizers, household cleaning products, and disinfectants. However, due to its carbon-free nature and potential use as a fuel to lower CO₂ emissions, ammonia has recently obtained the attention from experts.

Ammonia has been used in internal combustion engines and gas turbines in various recent developments. For example, the California Public Utilities Commission is taking a consideration to substitute the diesel generator with ammonia-driven ones (The California Public Utilities Commission, 2020). In another part of the world, a project to develop ammonia-fueled ship has been revealed by a Japanese marine corporation (Brown, 2020). This also could act as one of the actors in developing the hydrogen economy.

Some of the notable benefits of ammonia as a possible fuel are; it is a carbon-free fuel; it might perhaps be employed as a hydrogen carrier; its production, storage, transportation and distribution are already developed since many decades ago; and it offers a significant advantage in terms of the specific energy cost (Erdemir & Ibrahim, 2021). Table 2.8 shows the characteristic of ammonia.

Table 2.8 Characteristic of ammonia (Erdemir & Ibrahim, 2021)

Properties	Value
Chemical formula	NH ₃
Carbon content (mass percent)	0
Molecular weight (g/mol)	32.04
A/F stoichiometric ratio (kg/kg)	6.05
Temperature of ignition (K)	924
Temperature of adiabatic flame (K)	2073
Flammability limits (vol percent in air)	16.25
Density @ 25°C (kg/m ³)	602.8
Lower heating value per kilogram (MJ/kg)	18.80
Volumetric energy content (MJ/m ³)	11333

2.4.1 Present status ammonia fuel production process

Different fossil-based hydrogen sources, including natural gas, coal, naphtha, and heavy fuel oil, can be used to produce ammonia. Biomass and water are sources of decarbonized hydrogen. Nitrogen is obtained by purifying air. With the help of an iron catalyst, hydrogen and nitrogen are mixed to produce ammonia using the Haber-Bosch process at high temperatures (350-500°C) and pressures (100-400 bar) (Brightling, 2018). The production pathways of ammonia can be seen from Figure 2.10.

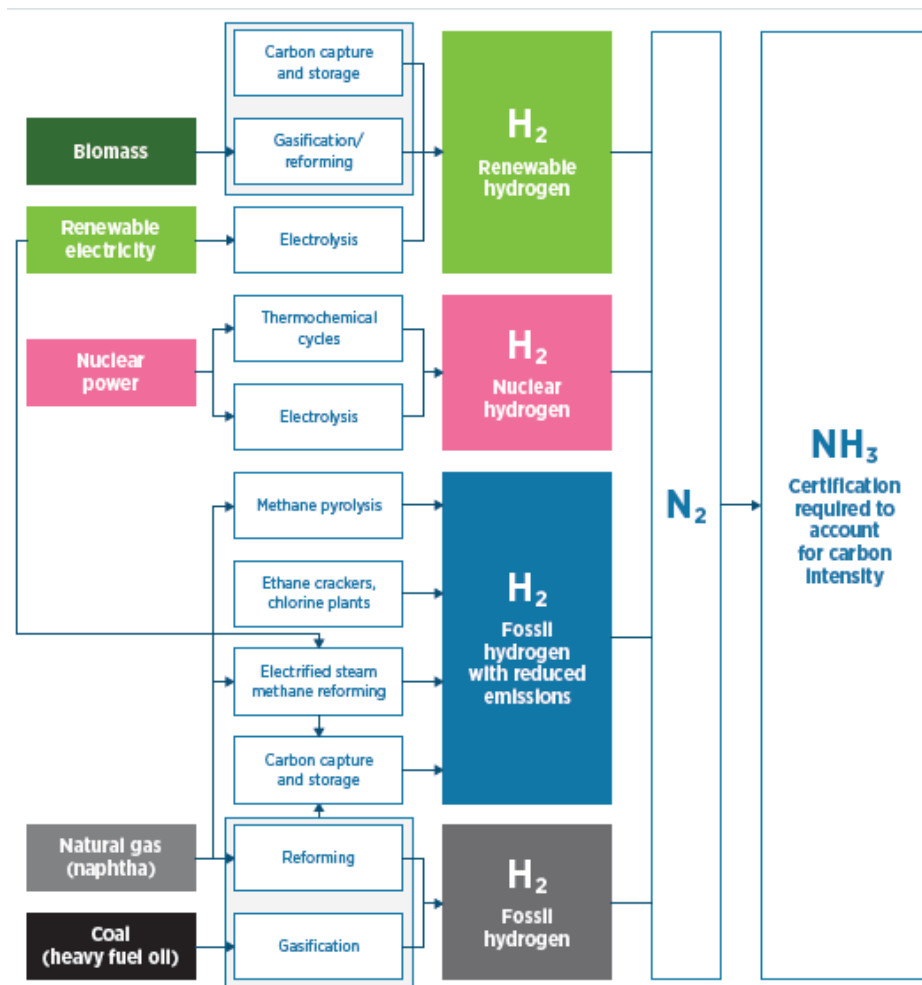


Figure 2.10 Various pathways for ammonia production (IRENA & AEA, 2022)

The production of hydrogen as a feedstock for ammonia nowadays is mostly driven by economic considerations. The Haber-Bosch process is used in big facilities to manufacture ammonia (Soloveichik, 2017). Globally, more than 95% of ammonia production utilizes fossil fuels (which is dominated by natural gas of 72% share) (Bicer & et al, 2016).

Moreover, the ammonia production process is responsible for about 1% of the world's CO₂ emissions, or around 420 Mt of CO₂ emissions, which making ammonia emits the most CO₂ in the chemical industry sector (Lim, ym., 2022). Hence, to comply with net zero carbon emission goals, a decarbonization plan and its implementation are required. By switching ammonia feedstocks from fossil-based to renewable hydrogen, this decarbonization may be realized.

2.4.2 Decarbonization of ammonia fuel production

As it can be seen from Figure 2.10, ammonia can be produced with renewable energy sources like biomass, solar, and wind, to make it as a carbon-neutral fuel. A Haber-Bosch based process facility that obtains nitrogen from an air separation plant and hydrogen from a water electrolysis plant (which supplies hydrogen), will most likely be the future of decarbonization of ammonia production. This green ammonia is produced where all of these electrical processes will be driven by renewable energy sources. The detailed explanation about the various electrolysis options is already written on Section 2.2.2. The schematic overview of green ammonia synthesis is depicted on Figure 2.11.

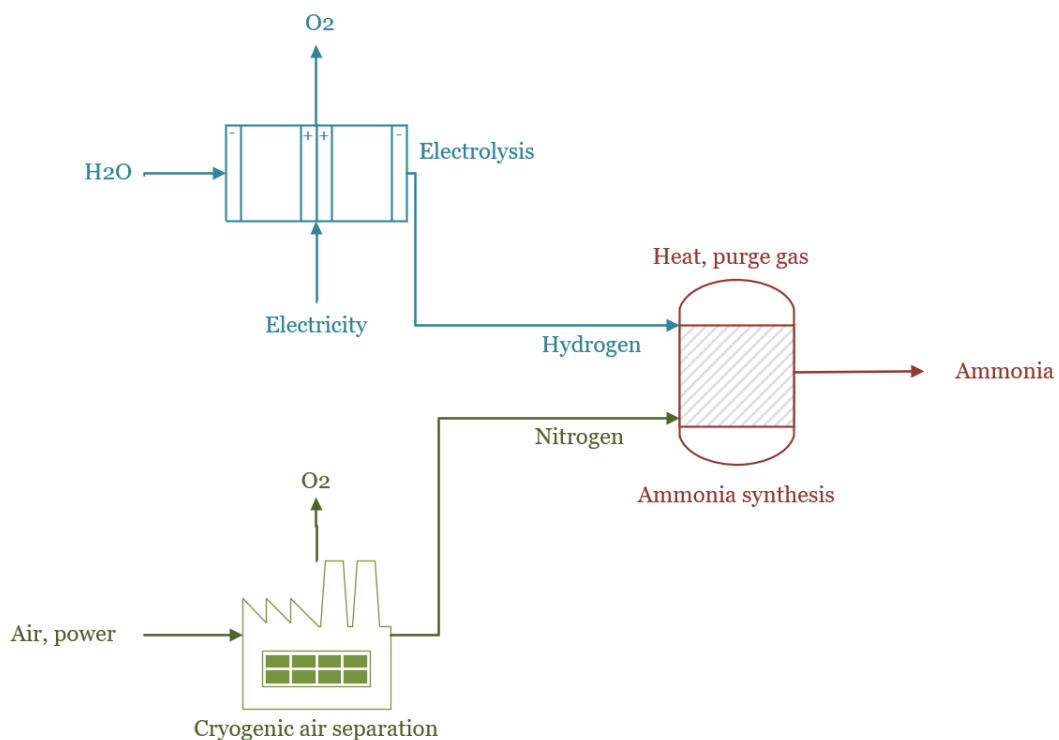


Figure 2.11 Schematic overview of green ammonia synthesis

Renewable ammonia can also be produced from biomass. This technology pathway is also already established, much like renewable ammonia produced by electrolysis. Several pathways can be used to convert biomass into ammonia as can be seen from Figure 2.12. However, only a small share of the world's ammonia production is anticipated to switch to biomass (IRENA & AEA, 2022). The insufficient supply of sustainable biomass is considered act as a challenge for producing ammonia for biofuel as well as the feedstocks for the chemical industry.

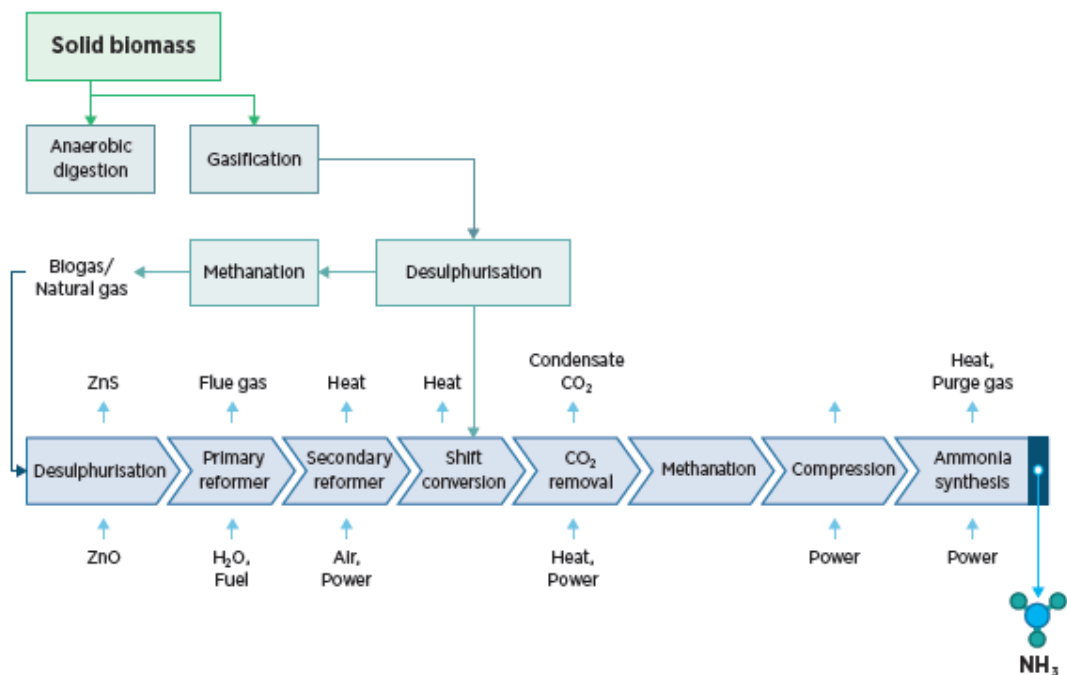


Figure 2.12 Overview of the process flow diagram for producing ammonia from solid biomass and biogas (IRENA & AEA, 2022)

The process of separating nitrogen from air is carried out to meet the nitrogen needs for ammonia production. There are several types of air separation processes for nitrogen aimed. Their comparison on production rates and purities are written on Table 2.9.

Table 2.9 Overview of air separation processes (Häring, 2008)

Separation method	Capacity (Nm ³ /h)	Purity mol (%)
Membrane	1-1000	<99.5
Pressure swing adsorption	5-5000	<99.99
Cryogenic air separation	200-400 000	Any with residual concentrations down to ppb 1 range
Vacuum pressure swing adsorption	100-5000	<95

Pressure Swing Adsorption (PSA) uses air under atmospheric conditions as its feed and uses carbon molecular sieve to undergo adsorption process. The adsorption process occurs due to differences in molecular size or polarity because some molecules bind stronger to the surface of the adsorber than other molecules (Purnamasari;Yerizam;& Junaidi, 2019). This technology is

usually used for purification process or a nitrogen supplier who does not need a high purity outcome.

A completely established method for breaking down air into its constituent parts at high production rates and purity is cryogenic air separation. The air compression and purification, primary heat exchanger, and cryogenic distillation column are the minimum processes that make up the system (Figure 2.13)

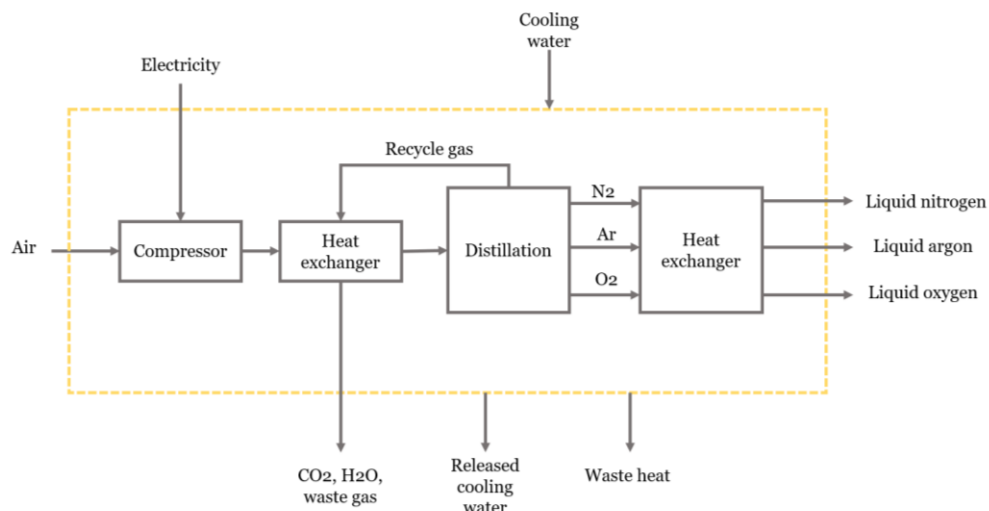


Figure 2.13 General process flow diagram of cryogenic air separation unit (Althaus, ym., 2007)

2.4.3 Ammonia fuel transport and delivery

Since many years ago, liquid ammonia has been transported via ships and pipelines for use in the fertiliser industry. Ammonia's intercontinental transportation is likewise highly established, and it mostly uses semi-refrigerated liquefied petroleum gas tankers. On land, ammonia is often carried with a pressurized liquefied gas through pipelines that pass through inhabited areas, by railroad in tank cars, by highway in tankers trucks, and also by rail in tank cars.

Ammonia storage is required at both the local and the final port. At large volumes, it is most economical to store ammonia in insulated tanks at -33°C and atmospheric pressure. However, storage at atmospheric pressure and temperature is more expensive since it takes more steel to resist the fluid's static pressure.

2.4.4 Ammonia engine for heavy-duty sector

Due in part to the relatively high NO_x emissions and flame instability, a pure (100%) ammonia engine has not yet been developed for utilization in road transportation (Herbinet, Bartocci, & Dana, 2022). According to Starkman et al., the modification of a spark plug to ignite the injected fuel is the only way to burn liquid ammonia satisfactorily in a diesel engine at nominal compression ratios (Starkman, James, & Newhall, 1967).

The benefits of utilizing ammonia as a fuel in internal combustion engines have generally proven that high torque can be produced with fuel mixing, albeit there is a danger of acquiring high NO_x emissions at high temperatures and high unburned NH₃ emissions at low temperatures (Dimitriou & Javaid, 2020). In detail, some ammonia is first injected with air early intake, known as pilot injection, to generate a homogeneous mixture with equivalency ratios of 0.1 – 0.3 due to the low ignite tendency of ammonia-air mixtures under lean circumstances. The primary ammonia spray might be sparked more readily as a result of the premixed mixture's combustion, which raises the temperature within the cylinder. (Kalghatgi, Agarwal, & Leach, 2022)

Despite the particular benefits of ammonia, its toxicity, flammability, and combustion in conventional engines, turbines, and power generators present significant challenges. Such challenges are high ignition temperature, low flame velocity, and slow chemical kinetics. The autoignition temperature of ammonia is about more than 200°C compared to gasoline and diesel. This high ignition temperature induces low combustion temperature and reduction of the power in the engine.

3 Research material and methods

3.1 Life Cycle Assessment

Life cycle assessment (LCA) is an important and comprehensive method for analysis of the environmental impact of products and services. It addresses the potential environmental impacts over a product's entire lifetime which is from the extraction and processing of raw materials to the manufacturing, operation, and marketing procedures, as well as the use, reusing, and the maintenance of the product, and finally to its eventual recycling or disposal as waste (ISO 14040, 2006). At every step of the life cycle, emissions and the use of resources (raw materials, energy) are assessed. There are several procedure to conduct such study, starting from specifying the purpose of the LCA and scoping about the modelling of the system analyzed in the goal and scope definition. Inventory analysis entails the creation of the life cycle model and calculation of the emissions generated and the resources utilized during the life cycle. In the impact assessment phase, the emissions and resources are associated to various environmental issue through the step of classification and characterisation. The schematic diagram of LCA methodology can be seen in Figure 3.1.

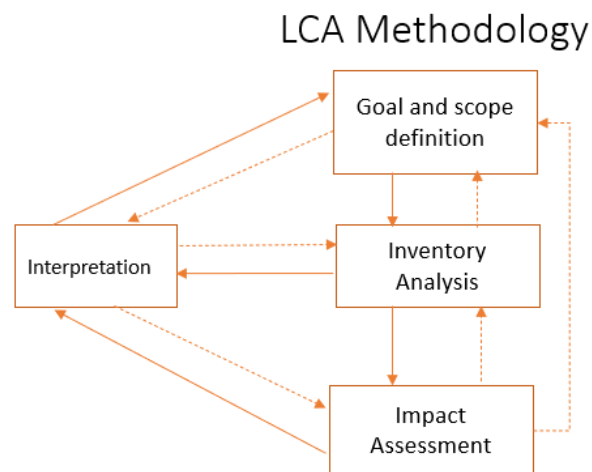


Figure 3.1 Schematic diagram of LCA methodology

3.1.1 Goal and scope definition

The purpose of the LCA study is determined in the goal definition. According to the ISO standard (ISO 14040 1997), the goal definition comprises stating the intended application of the study, the consideration for carrying the study, and to whom the results are intended to be reported. The goal and context

might be formulated as a question posed to the LCA study. For this project, the goal and context are:

- Subject of study: eFuels (H₂, methanol, and ammonia) production for heavy duty vehicle
- Research question: What is the environmental impact of using eFuels in heavy duty vehicle?
- Audience: Companies interested in building eFuel plants, government on building road infrastructure and technology developers

The scope of the study is related to the modelling to be carried out. It includes the choice of which options to model, functional unit, choice of impact categories and method for impact assessment, system boundaries and principles for allocation and data quality requirements. The scope of this study is written on Table 3.1. In addition, the manufacturing of production plants components is also considered while the land use is not included in the study. The scope of study can be visualized by Figure 3.2.

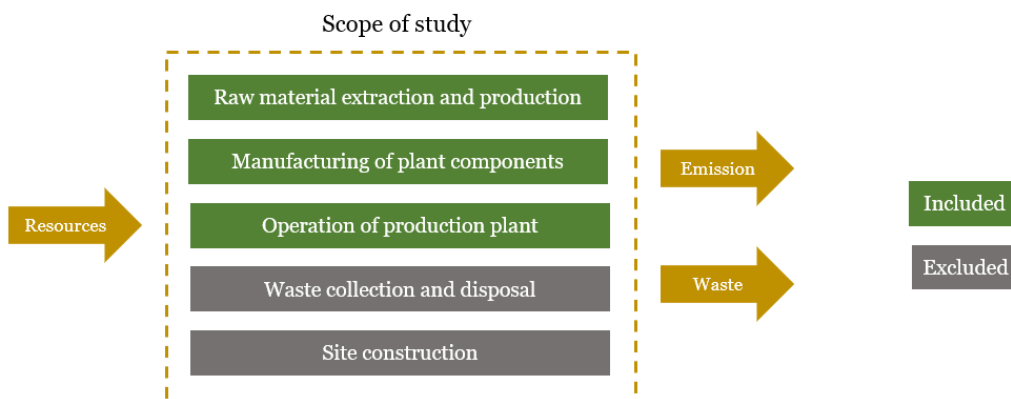


Figure 3.2 Visualization the scope of this study

Table 3.1 Scope and modelling requirement for this study

Scope and modelling requirement			
Functional unit	One kilometer driven		
Type of LCA	Attributional		
Choice of impact categories	Global warming		
System boundaries	Well-to-wheel (extraction of resources to the final use in a vehicle). Grouped into two parts: WTT (stages of production and distribution of the fuel) and TTW (tailpipe emissions resulting from the end-use of the fuel)		
	Hydrogen	Production technology	Alkaline Electrolysis Cell

		Delivery technology	Pipeline
		Vehicle engine	Internal combustion engine
	Methanol	Production technology	Hydrogenation of CO ₂ and H ₂
		Delivery technology	Tube trailers truck
		Vehicle engine	Internal combustion engine
	Ammonia	Production technology	Haber-Bosch
		Delivery technology	Tube trailers truck
		Vehicle engine	Compression ignition engine
	Geographical boundaries: Finland		
	Vehicle reference: Truck group 4. 18 t HGV (Heavy goods vehicles)		
Data quality requirement	Temporal data quality		Recent data from last 5 years
	Geographical data quality		National level
	Technological data quality		Specific to technology
	Completeness data quality		As complete as possible from what is available in literature
Inventory analysis			
Data sources	<ol style="list-style-type: none"> 1. GaBi database 2. Ecoinvent database 3. Literature review 		
Impact assessment			
LCA Software	GaBi Software		
Method	CML v4.8 2016		

In the context of well-to-wheel (WTW) LCA analysis for transportation, the functional unit of one kilometer driven is used to ensure consistent and meaningful comparisons between different vehicle technologies and fuels. One kilometer driven is a tangible and easily understandable unit for assessing the performance of vehicles. It corresponds to a common measure of transportation distance, making the results of the LCA analysis more relatable and applicable to real-world scenarios. Attributional LCA is chosen because the simplification, data-driven, and direct approach to assess the environmental impacts of products and processes, especially when detailed data or resources for more complex methodologies are limited. Global warming impact category is one of the most widely recognized impact

categories in LCA. It has gained significant attention from policymakers, businesses, and the general public due to their potential long-term consequences. In addition, carbon emissions and global warming impacts are relatively easy to communicate to a broad audience.

These are the assumptions implied in this study:

1. Port Kotka-Hamina (The relation between port Kotka-Hamina and heavy-duty sector) for the refuelling station
2. Kouvola for the plant location with total area of 13000 m²
3. Cut-off criteria
 - Filling station infrastructure is not considered on the study
 - Capital goods (machinery, buildings, etc)
 - Contribution of mass: >5% of the overall weight
 - Vehicle (the truck) powertrain is not considered on the study
4. The facilities for carbon capture, hydrogen production, air separation, are in the same area within an industrial cluster for all eFuels scenario, meaning that distances are short and synergies are harnessed.
5. Lifetime of 20 years and operating hours of 8000 h per year
6. There will be 150 trucks fueled per day which done two trips a day with transportation distance generalization of 350 km
7. Freshwater consumption or land use were excluded due to the lack of primary data or missing reference values in the datasets for feasible comparability (paraphrase)
8. Production infrastructure is considered in the study
9. Byproducts produced are not going to be valorized, hence it will be considered as only a purge out of the system

These are the limitations implied in this study:

1. Finland has been chosen for this study geographical reference. Processes with the geographic references Europe, RoW (Rest of the World), or GLO (Global) have been used if processes with the geographical reference of Finland were not available.
2. This study does not include the recycling of materials and utilization of by-products as well as the waste handling

3.1.2 Life Cycle Inventory (LCI)

Inventory analysis implies to construct a system model according to the requirements of the goal and scope definition. The model is an incomplete mass and energy balance over the system, which include the use of scarce resources and emissions of substances considered harmful (Baumann & Tillman, 2004). Environmentally indifferent flows such as water vapour

emissions from combustion process and industrial surplus heat are not considered. Activities included in the life cycle inventory analysis (LCI) are

1. Building a flow model based on the system boundaries that were determined during the goal and scope definition phase. A flowchart that depicts the actions included in the analysed system (production, processes, transports, use and waste management) and the flows between them serves as the standard form of documentation for the flow model.
2. Data collection for each step of the product system's process. The information gathered covers all activities' inputs and outputs, such as supplies, goods, and solid waste, as well as emissions into the air and water.
3. Calculation of the amount of resource use and pollutant emission of the system in relation to the functional unit.

In accordance to the definition of the LCI itself, the flowchart showing flow model of the alternative fuels (hydrogen, methanol and ammonia) based on the Well-to-Wheel approach can be seen on Figure 3.3, 3.4. and 3.5, respectively. Table 3.2, Table 3.3 and Table 3.4 also shows the summary of components data used for each eFuels. The complete data of the components are attached in the Appendix. In addition, aggregated data is chosen for every process types.

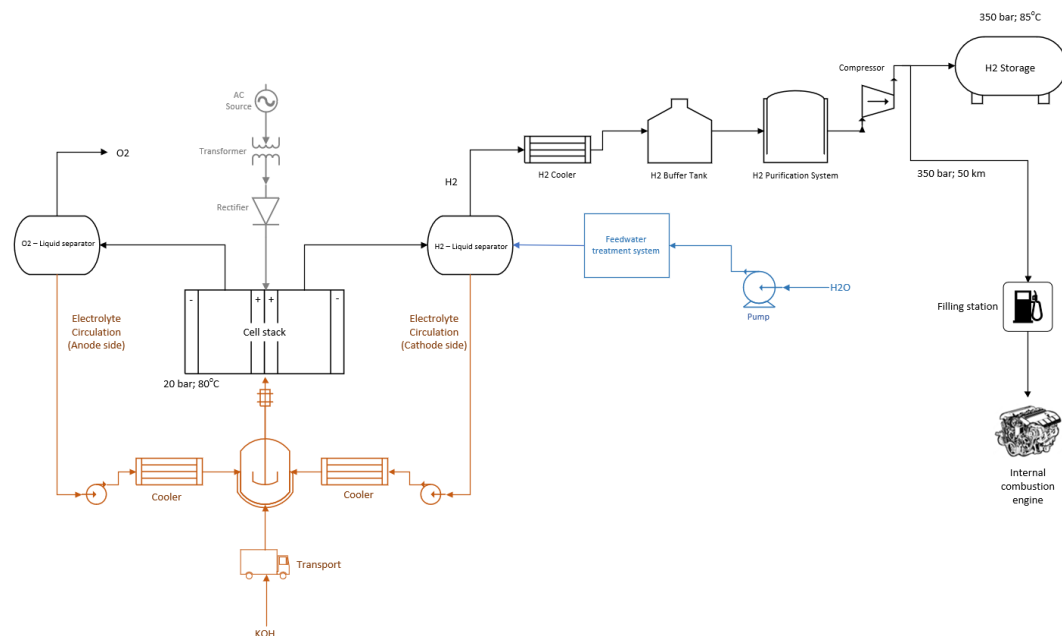


Figure 3.3 Flowchart of hydrogen fuel production

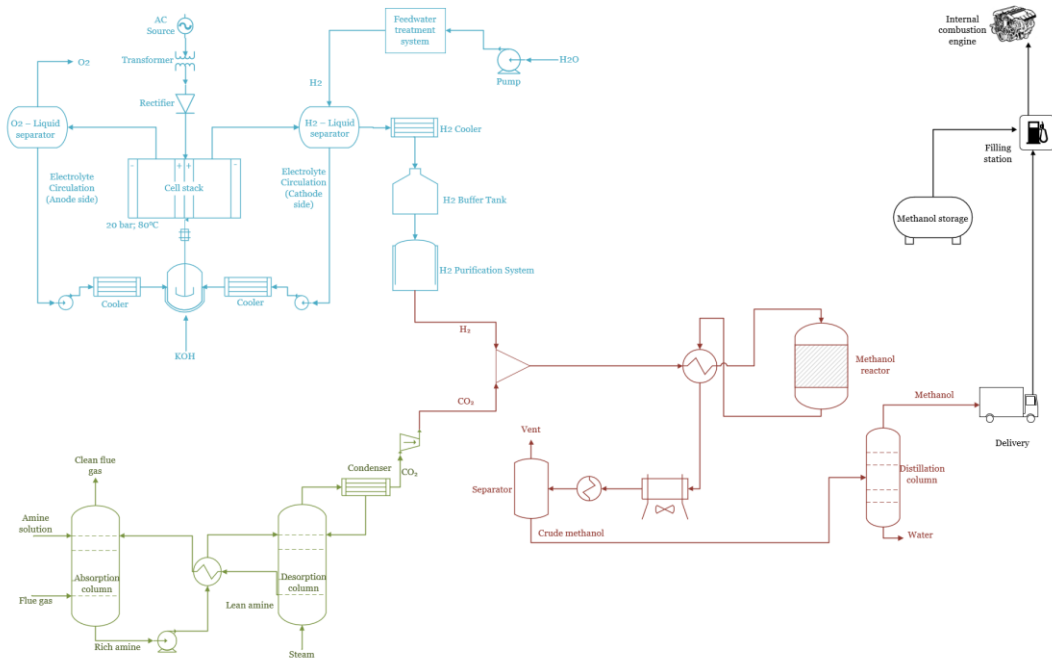


Figure 3.4 Flowchart of methanol fuel production

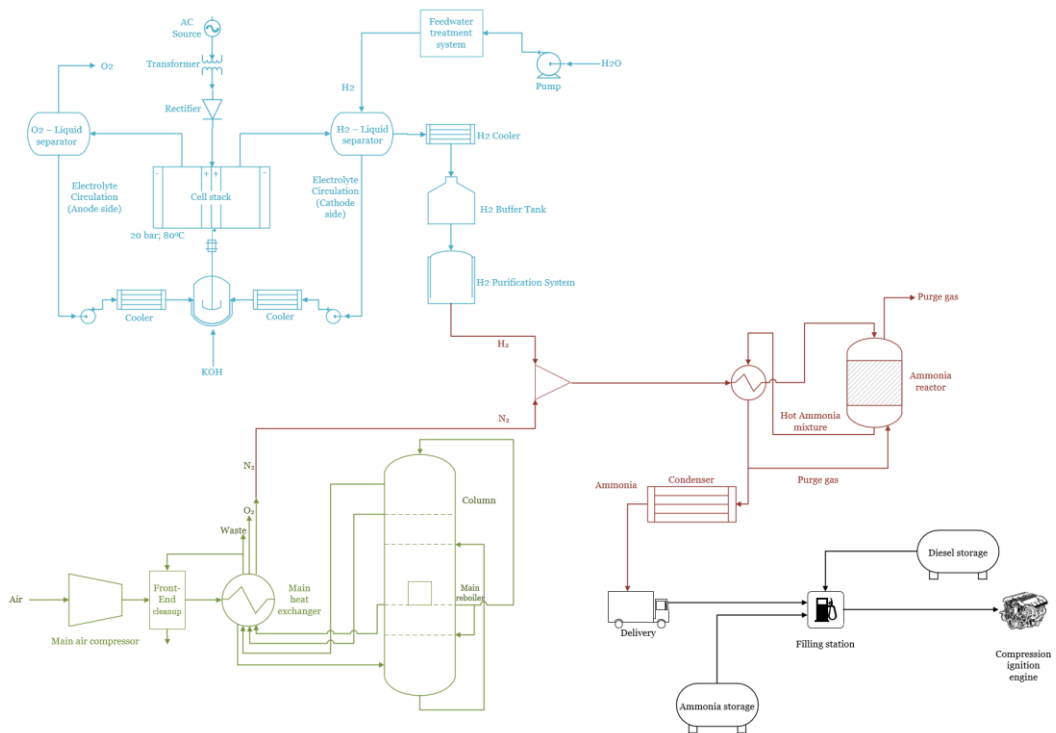


Figure 3.5 Flowchart of ammonia fuel production

The components data of the hydrogen production technology originate from Gerloff (2021) study, based on a 1 MW system, while scaled-up to 25 MW by scaling factor mentioned earlier. The total production of the hydrogen using 25 MW electrolyzer is 3 861 ton H₂ per year based on the working hours of 8000 h per year. The inventory data for Tank-to-Wheel approach of all eFuels engine is obtained from GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model developed by Argonne National Laboratory with own estimation result.

Table 3.2 Components data for hydrogen fuel production

AEC Stack	Balance of Plant	Delivery	Storage
Anode and cathode with frame	Water purifier and feed tank	Pipeline (steel)	Storage tank
Gasket	Control panel/electronics	Frequency converter diaphragm compressor	
Diaphragm, zircon	Transformer and rectifier	Diaphragm, for diaphragm compressor	
	Hydrogen dryer and deoxidiser		
	Buffer tank		
	Tubing and cables		
	Water cooling plant for electrolyzer		
	Pumps and colers		
	Heat exchanger		
	Gas separator (2x)		
	Alkali-resistant rotary pump		
	Steel tank for KOH		
	Container		
	Foundation (concrete)		

The components data of the methanol production technology originate from Zhu et al. (2022) study with some additional information from other literatures and own data. The total production of the methanol using 25 MW electrolyzer and carbon capture process with MEA (monoethanolamine) is 20 314 ton methanol per year based on the working hours of 8000 h per year. Since the methanol production is assumed to be carried out between 300°C to 550°C, the heat required to heat up the feed for the methanol synthesis process is going to be assumed to be met by the waste heat released from the synthesis process itself. In addition, the delivery/shipment process of the methanol from the plant to the filling station is going to utilize the methanol produced by the plant.

Table 3.3 Components data for methanol fuel production

Carbon Capture	Hydrogen production	Methanol synthesis	Storage
Absorber	Refer to Table 3.2	Methanol factory construction	Storage tank
Stripper			
Compressor			
Pipeline for CO ₂ delivery			

The components data of the ammonia production technology originate from Zhu et al. (2022) study with some additional information from other literatures and own data. The total production of the ammonia using 20 MW electrolyzer and cryogenic air separation technology is 17 275 ton ammonia per year based on the working hours of 8000 h per year. In this study, the ammonia fuel is a fuel-mix blend with diesel with 70% and 30% ratio of ammonia and diesel, respectfully. It will be written Ammonia (+Diesel) until stated otherwise (a pure ammonia, 100% Ammonia).

Table 3.4 Components data for ammonia fuel production

Cryogenic air separation	Hydrogen production	Ammonia synthesis	Storage
Compressor	Refer to Table 3.2	Ammonia factory construction	Storage tank
Heat exchangers			

Distillation tower
Cryogenic air separation plant construction

3.1.3 Life Cycle Impact Assessment (LCIA)

Another phase in LCA is called Life Cycle Impact Assessment (LCIA). LCIA aims at translating the impacts of the environmental loads calculated in the inventory analysis. Thus, one goal of the LCIA is to transform the inventory results into knowledge that is more pertinent to the environment – information on how the environment impacted rather than only the amount of emissions and resource use within the process. One of LCIA perks is making results more comparable.

There are two main steps of LCIA, namely classification and characterisation. The LCIA based on ISO standard (ISO 14042) is shown in Figure 3.6. Classification is the first step of arranging the inventory parameters according to the type of environmental impact they responsible to. Characterisation as the second step is calculating the relative contributions of the emissions and resource consumptions to each type of environmental impact.

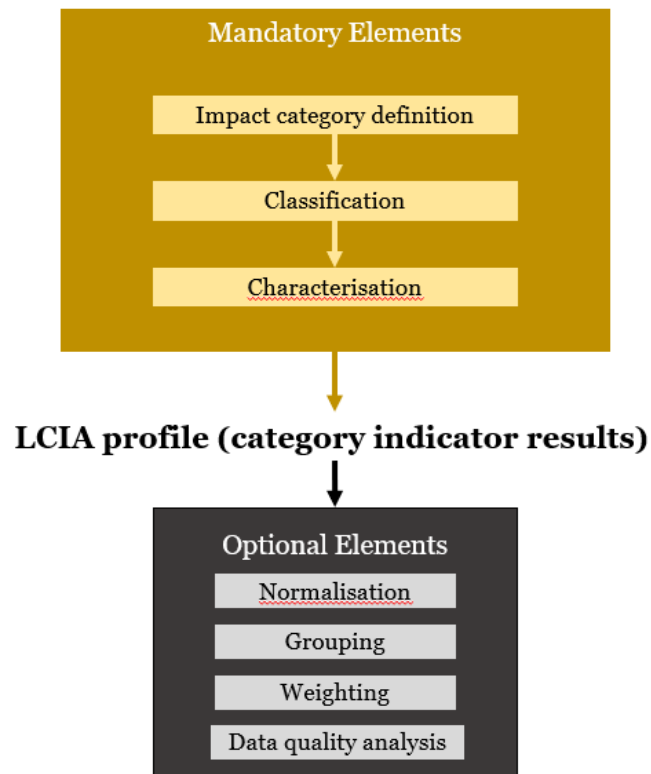


Figure 3.6 LCIA phases according to ISO 14042

The usual categories of environmental impacts underlie in an LCA include resource use, human health, and ecological consequences (Baumann & Tillman, 2004). Yet, environmental problems are complex and still not fully understood since a pollutant's primary impact may result in a number of secondary effects, or vice versa. Hence, it is viable to define environmental impacts at different levels while also means that the potential rather than the actual effects of the pollutants are determined.

There are several methodologies to define a complete set of impact categories. They account the differences in describing environmental impacts at various levels. For example, GaBi LCIA Method is Environmental Footprint (EF) 2.0. In this study, the LCIA methodology chosen is CML 2016 (Center of Environmental Science of Leiden University). In addition, CML is also based on the recommendations of the International Life Cycle Data system (ILCD), which is a review study for LCIA methods performed by The Institute for Environment and Sustainability in the Center of European Union Joint Research.

CML 2016 is chosen because it operates based on the ISO14040 series of standards and recommended methods for normalization. It also aligns with

this study scope where impacts of land use is not evaluated. The midpoint assessment is covered with CML method where it complies indicators at the level between the emission and the areas of protection. In addition, CML 2016 method has the highest number of factors within Ecoinvent pack (i.e. The database that used in this study) (Acero & Cristina Rodriguez, 2015). The selected impact category and indicators are shown in Table 3.5.

Table 3.5 Impact categories and impact factors

Impact category	Characterization facotr	Areas of protection	Abbreviation
Global warming	Global Warming Potential 100	Human health	GWP100

The most significant indicator is the potential for global warming. The Global Warming Potential (GWP) was created to enable comparisons between the effects of various gases on global warming. In more detail, it is a measurement of the energy that 1 ton of gas emissions will absorb over a certain amount of time in comparison to 1 ton of carbon dioxide (CO₂) emissions. A given gas warms the Earth more in comparison to CO₂ during a certain time period the higher the GWP. The typical time frame for GWPs is 100 years. With the help of GWPs, analysts may sum up estimates of the emissions of various gases (for example, to create a national GHG inventory) and policymakers can assess different sectors' and gases' potential for emissions reduction.

3.1.4 GaBi Software

GaBi LCA (Life Cycle Assessment) software used in this study is an effective tool for assessing the environmental effects of different products, services, technology, and systems. GaBi LCA users can create unique models and procedures for their projects and case studies. The GaBi LCA application has a distinctive GUI and is user-friendly. Because of the software's user-friendly design, users may browse through its numerous components and features.

The GaBi system is modular. This translates to the idea that modules are made up of plans, processes, and flows together with their functions. As a result, the GaBi system has a visible and easy-to-understand structure. Data on life cycle impact assessment, life cycle inventory and evaluation, and weighting models are meticulously kept apart from one another. As a result, the separate models continue to be simple to manage and are only used for calculating balance

GaBi software system has a principle of life cycle balances. It offers assistance for modeling product life cycles and managing massive data volumes. GaBi performs many sorts of balancing calculations and aids with the analysis and interpretation of the findings with several impact assessment methodology options. The example of how the life cycle balance model is built in the software can be seen from Figure 3.7 (while this study life cycle balance model is attached in the appendix).

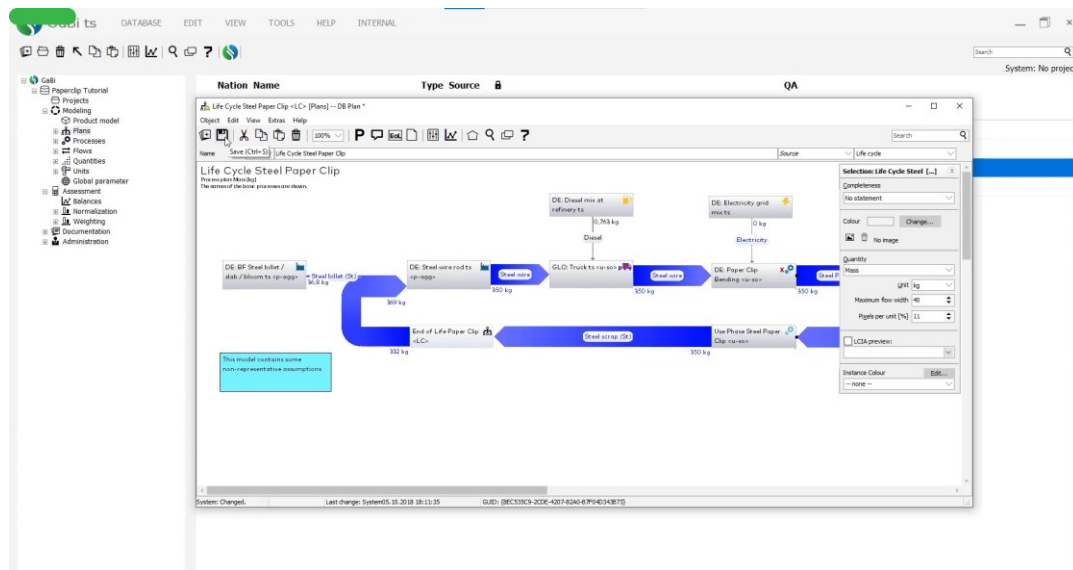


Figure 3.7 Example of life cycle balance model built in GaBi software (Sphera, 2023)

The life cycle inventory data is filled into each block processes (each rectangle shaped showed in Figure 3.7) attempting to portray the real-life scenario as accurately as possible. The visualization of the inventory data input to the software is depicted in Figure 3.8. In addition to the ability to import database to the software, there is a sizable database of Life Cycle Inventory (LCI) data available from GaBi itself in other industries, including electronics, chemicals, plastic, and construction. These databases help assess how operations and products affect the environment.

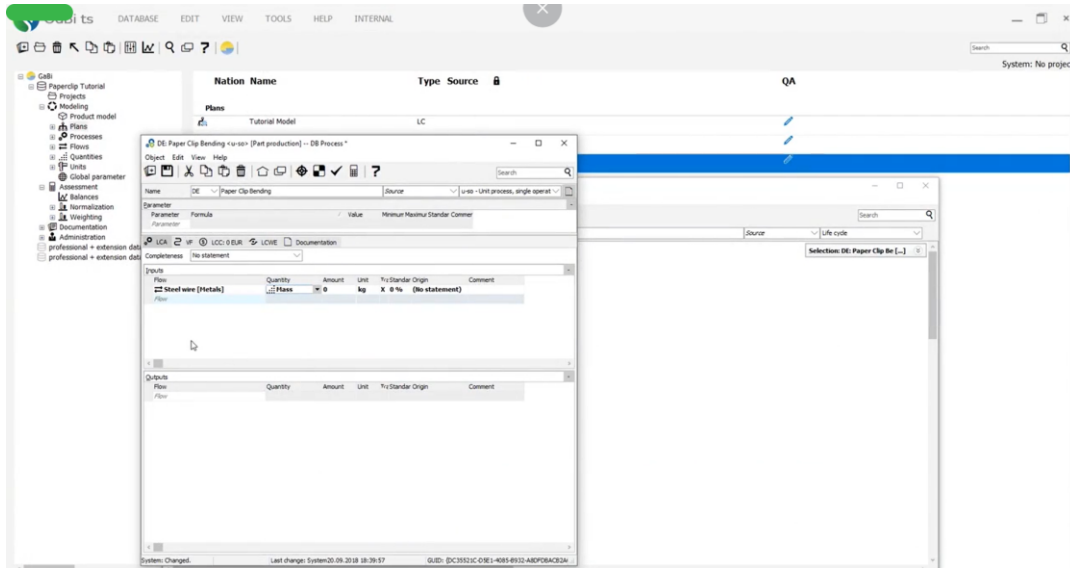


Figure 3.8 Inventory data input to the single block process in GaBi software

Finally, the impact assessment result calculated automatically in GaBi based on the general impact categories (e.g. acidification, global warming) with several provided impact methodologies (e.g. TRACI, ReCiPe, CML, etc). The available impact methodologies approach in GaBi is based on the International Reference Life Cycle Data System (ILCD) which suggests the approach deemed to be the best within the impact category, especially in Europe. The example LCIA result dashboard of the model built in the software can be seen in Figure 3.9.

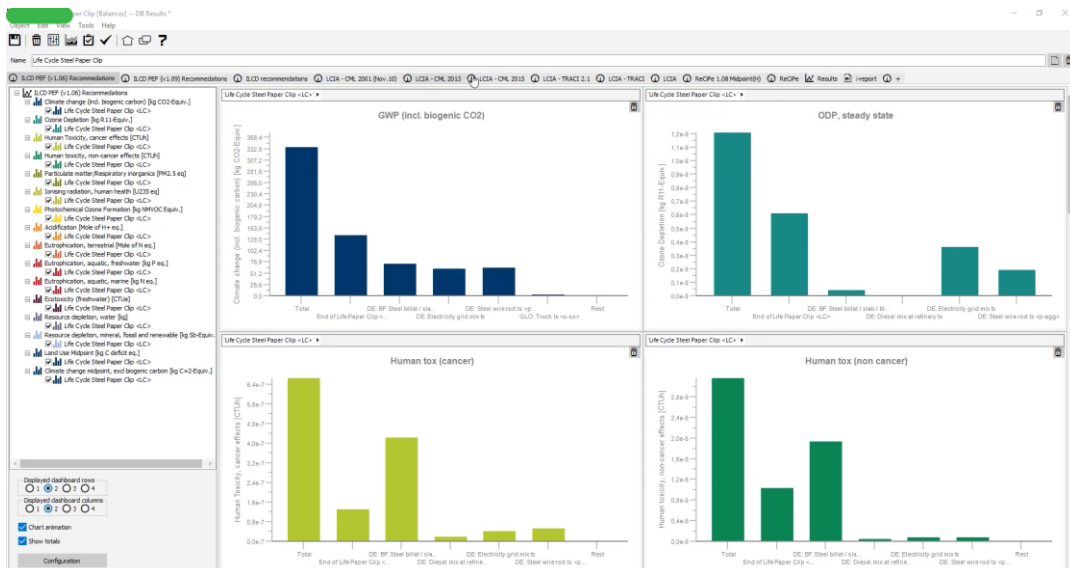


Figure 3.9 Result dashboard of LCIA in GaBi software

ISO 14040 series standardizes the eco-balancing process. Please be aware, however, that employing GaBi does not guarantee that your balance complies with other standards like ISO 14040, we should choose subjectively the method available in GaBi that aligns with ISO 14040.

3.2 Techno-economic Analysis

The alternative fuels must be produced that will be sold at a profit. Techno economic analysis (TEA) evaluates the technical performance and economic feasibility of a technology. TEA is an essential assessment tool for evaluating economic feasibility and it has been widely used to assess systems across different industries. The assessment for the study will be based on cash flows related to investment and operating cost for the production of the eFuels. The resulted product costs will provide comparison of fuel production rates, capital costs, and product selling prices between eFuels. The model input-output of the TEA methodology can be seen on Figure 3.7.

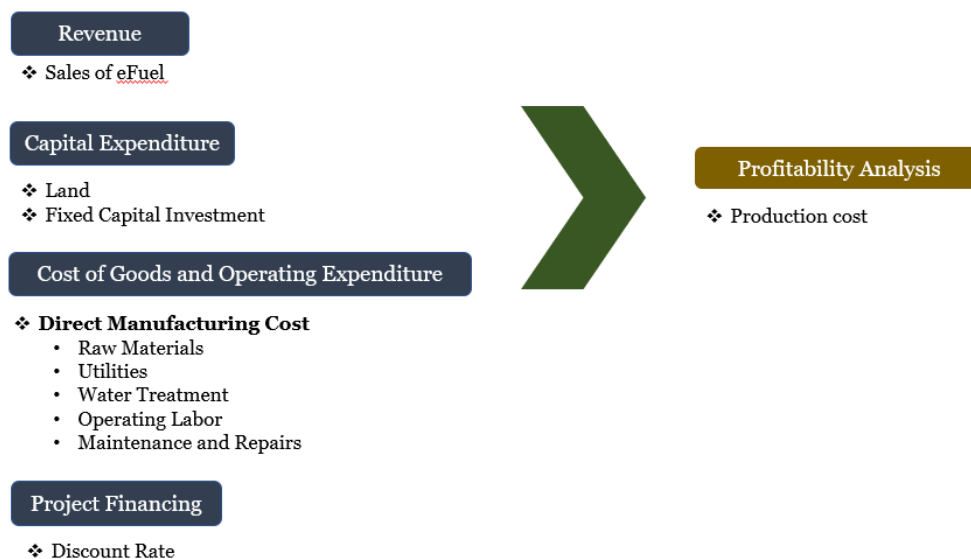


Figure 3.7 Input-output model for the techno-economic analysis implemented in this study

3.2.1 Capital Investment (CAPEX)

Capital investment, or CAPEX, is the total amount of money required to purchase and install the necessary machinery and equipment related to plant processes. To assess a capital investment cost, it is essential to consider the following costs: purchased equipment, instrumentation, electrical, piping, service facilities, building. Land also must be acquired, in addition to the mentioned costs before. The basis for calculating the capital investment is

the expense of the purchased equipment. Process equipment, raw material handling and storage equipment, and finished product handling and storage equipment are the three categories into which the various kinds of equipment can be divided. CAPEX costs calculation in this project is estimated to include costs for its installation and all construction work such as piping, civil and architectural work.

Where there are some studies already done for estimating the cost of major equipment, capacity factored methods can be applied to estimate the purchase cost in this study. This method requires a scaling factor which is different case by case. There is a rule of thumb for the scaling factor, which is 0.6, used mostly in the basic equipment such as pipes and tanks (Tribe, 1986). Equation 3.1 is used to calculate the cost by the capacity factored methods.

$$\frac{C_1}{C_2} = \left(\frac{V_1}{V_2}\right)^a \quad (3.1)$$

Where a is the scaling factor, C is the equipment cost and V is the capacity. The scaling factor used in this study is written on Table 3.6.

Table 3.6 Scaling factor for several unit or processes

Unit/Process	Scaling Factor	Source
Electrolyzer – Stack	0.88	(Gerloff, 2021)
Electrolyzer – BoP	0.70	(Gerloff, 2021)
Ammonia synthesis unit	0.67	(Jain;Muthalathu;& Wu, 2022)
Ammonia storage tank	0.67	(Jain;Muthalathu;& Wu, 2022)
Cryogenic air separation unit	0.65	(Zhang;Wang;Van herle;Marechal;& Desideri, 2020)

In addition, to have a better accuracy on estimating the capital costs of process engineering, updating process plant construction costs from one period to another as a function of historical data is essential. Chemical Engineering Plant Cost Index (CEPCI) is used to help indicate the equipment costs to the latest period. The index was composed of the weighted average of 12 labor cost indices and 44 industry and commodity indices. Chemical process industry professionals have been adjusting process plant

construction expenditures from one period to another for more than 37 years using the CEPCI (Vatavuk, 2002). Equation 3.2 is used to apply the updated equipment cost from period A to period B using CEPCI.

$$Cost\ at\ B = Cost\ at\ A \times \left(\frac{CEPCI\ Index\ at\ B}{CEPCI\ Index\ at\ A} \right) \quad (3.2)$$

3.2.2 Operational Cost (OPEX)

Manufacturing cost, or commonly called operational cost (OPEX), is the total expenses that is correlated with the manufacturing operation. These expenses include the variable production costs and fixed charges of the plant processes. Variable production cost consists of cost directly connected to the manufacturing operation, such as raw materials, direct operating labor, utilities, plant maintenance and repairs, operating supplies, catalysts, and solvents. Fixed charges are cost which are unconnected to the production rate. The examples are property taxes, insurance, financing (loan interest), and depreciation. This study does not consider fixed charges as operational cost.

Maintenance and repairs cost considered for the manufacturing cost is calculated depend on the fixed-capital investment (FCI). FCI can be estimated from CAPEX with the following Equation 3.1 (Nyari, Magdeldin, Larmi, Järvinen, & Santasalo-Aarnio, 2020)-

$$FCI\ (\text{€}) = \frac{CAPEX\ (\text{€})}{1.47} \quad (3.1)$$

In addition, calculation of the labour cost for all of the cases uses the same assumption where there are 30 people working in the plant and the rate per person is 25 €/hour.

3.2.3 Cost analysis

The main components of the economic analysis are the total of all costs of running the plant, generating revenue from selling the products, and recovering the capital investment. As mentioned earlier, the cost analysis done in this study is estimating the production cost of the alternative fuel by considering the capital investment (CAPEX) and operational cost (OPEX). The total cost will be allocated per total production of the alternative fuel each year with a discount rate of 10%. Hence, the capital investment cost is calculated based on a financial function that returns within the periodic payment. Equation 3.2 shows how the production cost is estimated.

$$\text{Production cost} \left(\frac{\text{€}}{\text{kg of product}} \right) = \frac{\text{Total CAPEX} \left(\frac{\text{€}}{\text{year}} \right) + \text{Total OPEX} \left(\frac{\text{€}}{\text{year}} \right)}{\text{Total product produced} \left(\frac{\text{kg}}{\text{year}} \right)} \quad (3.2)$$

3.3 Electricity source

Electricity is one of the energy sources that is important for the processes. In this study, there are two sources for supplying the electricity, namely biopower plant and the national electricity grid. Finland is one of the pioneers in the utilization of renewable energy sources, notably bioenergy. The deployment of renewable energy is affected by Finland's own energy and climate policies as well as the commitments and policy choices made by the European Union under its energy and climate legislation, which requires the EU to become climate neutral by 2050.

According to International Energy Agency (IEA), Finland generated 71,711 GWh of electricity from various sources in 2021. Figure 3.8 shows the Finnish electricity grid mix in 2021. Furthermore, in this study, each of the power plant employed for the Finland's electricity grid is using aggregated data where it accounts the whole life cycle inventory of its process.

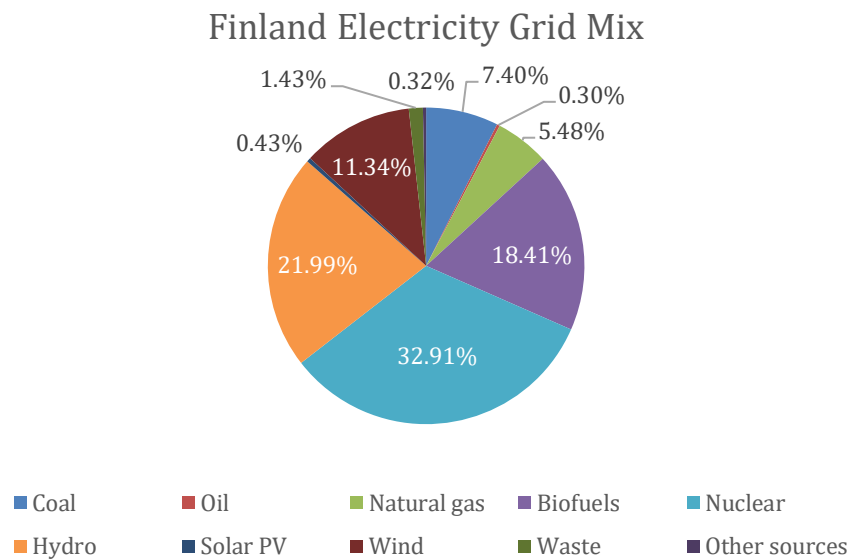


Figure 3.8 Finnish electricity grid mix (2021) (IEA, Electricity Information, 2022)

4 Results and Discussions

4.1 Life Cycle Assessment Results

In this section, the previously presented methodology and its database is used to calculate the impacts for the different scenarios in terms of global warming potential (it was mentioned as Global Warming Potential or GWP100 in Section 3.1.3) for the different scenarios in each alternative fuels. The outlook for all eFuels is still on two scenarios, namely grid and biopower scenario whereas they are the electricity source. Consequently, the CO₂-eq emitted from utilizing the alternative fuels are reported. Finally, the numerous approaches are assessed in accordance with the stated technical and non-technical enablers and challenges.

4.1.1 LCA result of hydrogen as fuel

The global warming potential of the hydrogen production is analysed in more detail respected to the process parameters. In addition to compare the hydrogen fuel production in heavy-duty vehicle utilization, the GWP results are compared with the results from other study. The overall result comparison between the hydrogen utilization for both scenarios with a reference in well-to-wheel approach is shown on Figure 4.1. The reference for this study is based on a renewable electricity source study in Germany by Sens et al. (2021) which has 0.024 kg- CO₂-eq/kWh GWP. For comparison, biomass power plant in Finland has 0.020 kg CO₂-eq/kWh GWP.

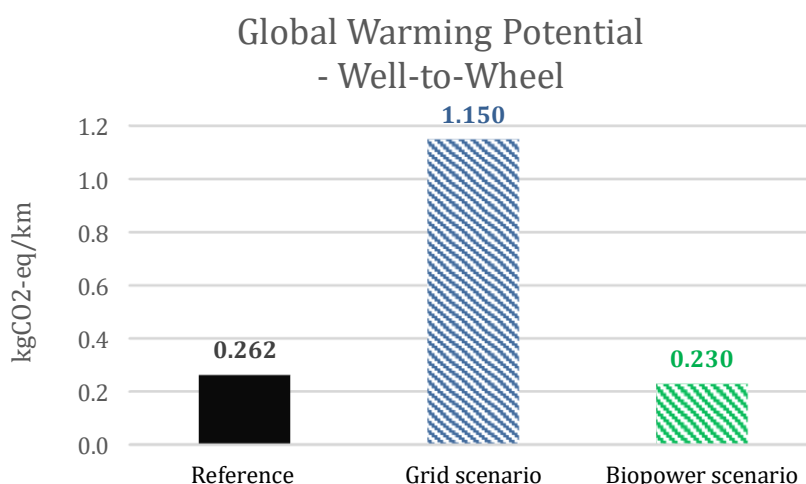


Figure 4.1 GWP result for hydrogen fuel compared with a reference for well-to-wheel approach

The GWP of the hydrogen fuel utilization for heavy-duty vehicle increases by 1% for grid scenario from the reference study meanwhile it decreases by 80% for biopower scenario. The breakdown of the resulting well-to-wheel LCA for hydrogen production is reported in Figure 4.2.

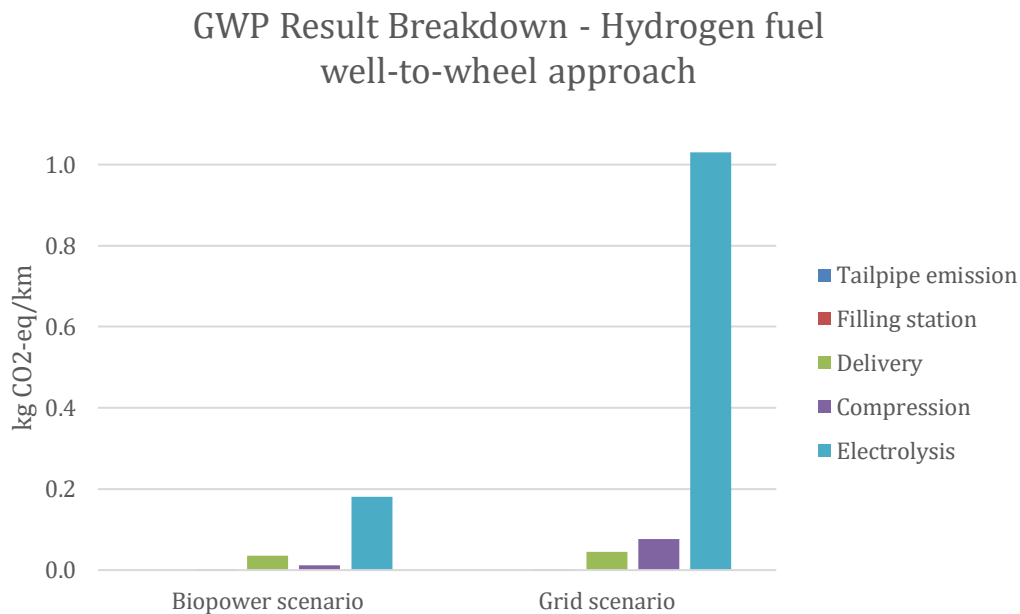


Figure 4.2 GWP result breakdown for well-to-wheel approach in hydrogen fuel utilization

Figure 4.2 shows the main driver of CO₂-eq emission is electrolysis process. This is also because the electrolyzer operates with 51.8 kWh per kg H₂ produced. Comparing grid and biopower scenario, the global warming potential from delivery process has a negligible difference since in both cases, delivery is done within pipeline where the pipe length and material is remained the same.

As mentioned earlier, the main driver for the global warming potential is electrolysis. It accounts of 97% GWP for electricity usage if the electricity source is from the grid while it accounts 84% if it is from biopower plant. By altering the electricity source from grid into biopower plant, we can achieve a reduction of 83% of CO₂-eq emission from electrolysis process. It is also worth to mention where water treatment electricity usage is the second highest contribution in the electrolysis process.

The global warming potential of hydrogen production within well-to-tank approach also evaluated (see Figure 4.3 and Figure 4.4). The reference used for this study us based on German grid mix 2050 whereas consists of 40%

natural gas, 39% wind, 21% solar PV source. As we can see from the figures, when we shift the electricity source to the more renewable energy source, we can achieve a reduction of GHG emission significantly. In this case, we can reduce 82% of CO₂-eq emission by utilizing electricity from biopower plant. These results as well help to emphasize that electrolysis is still the main contributors for the GWP.

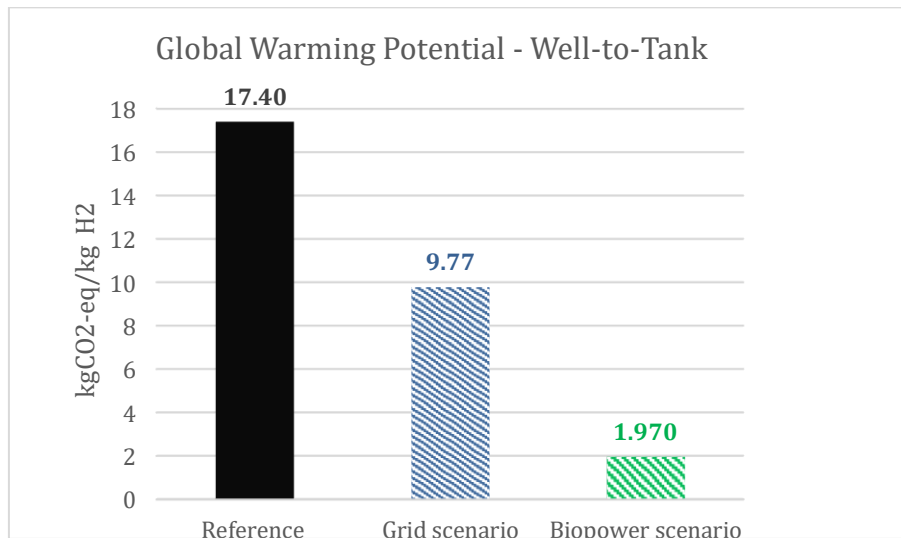


Figure 4.3 GWP result for hydrogen fuel compared with a reference for well-to-tank approach

GWP Result Breakdown - Hydrogen production well-to-tank approach

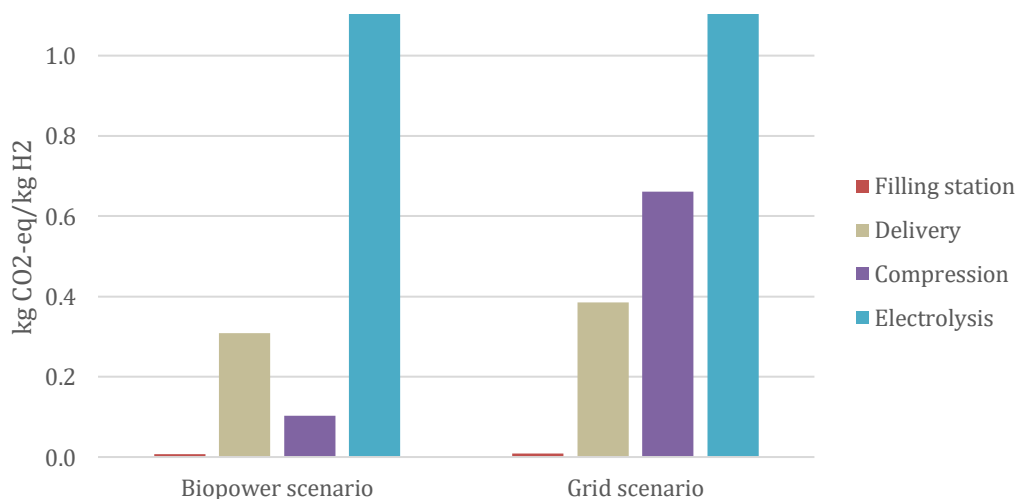


Figure 4.4 GWP result breakdown for well-to-tank approach in hydrogen fuel utilization

4.1.2 LCA result of methanol as fuel

The life cycle assessment result of methanol fuel utilization in heavy-duty vehicle is also done both for well-to-wheel approach and well-to-tank approach. The overall result comparison between the methanol production from both scenarios (grid and biopower plant scenario) in well-to-wheel approach is shown on Figure 4.5.

The GHG saving from obtaining electricity from biopower plant reaches 81% with a reference of grid source. The main contributor for the emission is hydrogen production process as shown in Figure 4.6. As it mentioned earlier on how big share of electricity usage in electrolyzer, it accounts 98% and 90% GWP in grid and biopower plant scenario, respectively. It achieves a huge amount of reduction of GWP, namely 83%, if we change the electricity source from grid to biopower plant. Meanwhile, the rest of the process has a slight reduction since they do not use electricity as main energy as electrolysis process does. Note to state that carbon capture unit is the second highest carbon intensive process due to the steam required for the process.

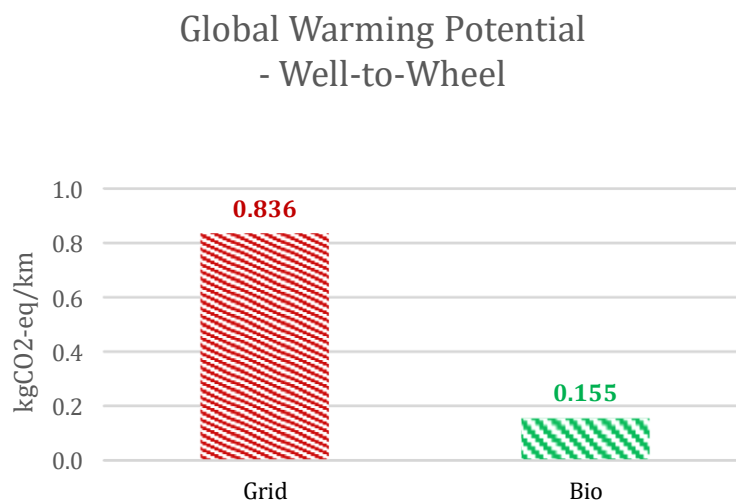


Figure 4.5 GWP result for methanol fuel for well-to-wheel approach

GWP Result Breakdown - Methanol fuel well-to-wheel approach

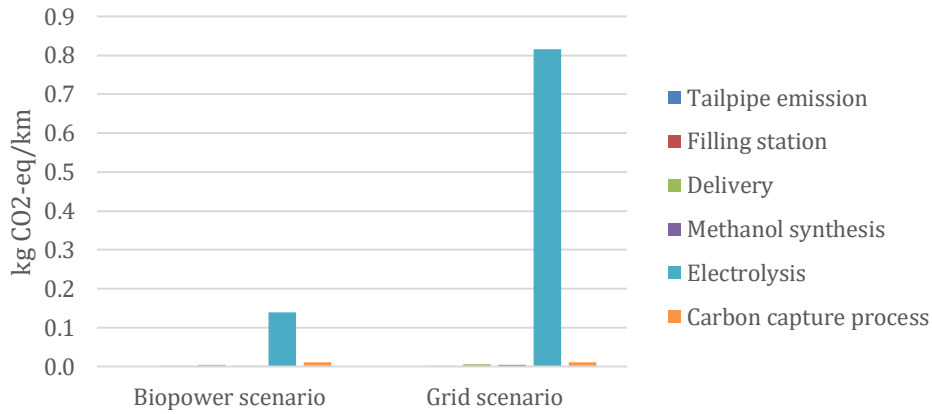


Figure 4.6 GWP result breakdown for well-to-wheel approach in methanol fuel utilization

The LCA result within well-to-tank approach under the grid and biopower plant scenario are compared with a previous study (Figure 4.7). Comparing the calculated results in this study with those in the literatures would help to confirm the validity of the current methodology. The reference for this case is based on PV powered source study by Zhu et al. (2022).

From Figure 4.6 and Figure 4.8, we can see the result helps to emphasize hydrogen production still dominate the GWP. It also has a consistency where by altering the electricity source from grid into biopower plant, we can achieve a reduction of 83% of CO₂-eq emission from electrolysis process.

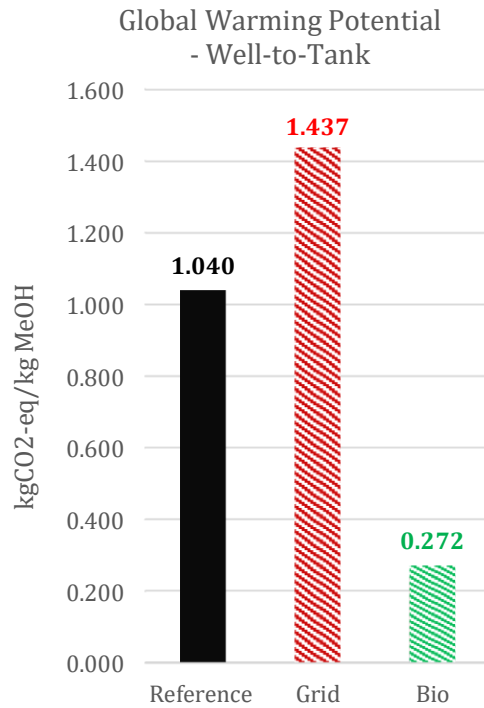


Figure 4.7 GWP result for methanol fuel compared with a reference for well-to-tank approach

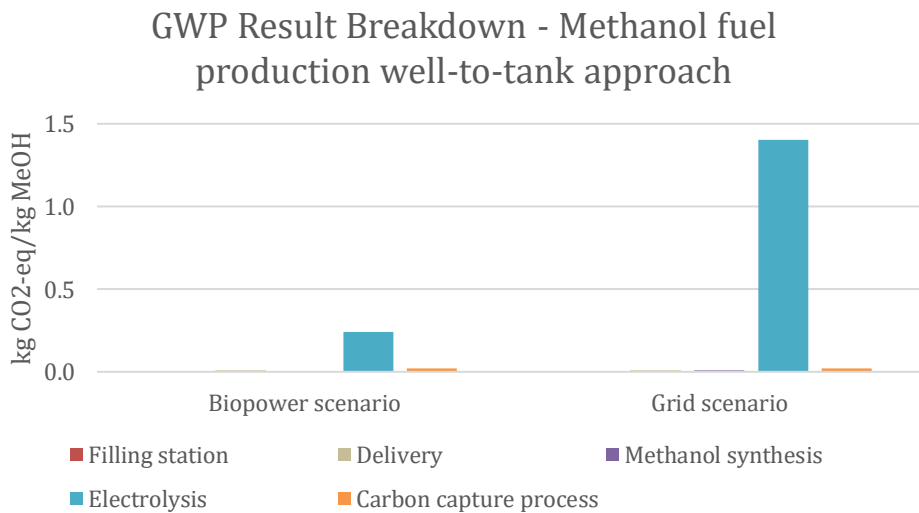


Figure 4.8 GWP result breakdown for well-to-tank approach in methanol fuel production

Producing methanol requires carbon dioxide as a feedstock where it was explained on Figure 3.4 earlier. It was also mentioned there are two general type of carbon source to be captured, biogenic and fossil-based carbon source. In this part, we will compare their difference on global warming impact

both in well-to-wheel (Figure 4.9) and well-to-tank (Figure 4.10) approach. As it can be seen from both figures, the CO₂ uptake and tailpipe emission accounting is zero for biogenic source. This is due to the characterisation factor of zero assumed for the study. The fundamental idea is a climate neutrality of any biogenic CO₂ realised during the harvest and use of biomass would eventually be absorbed by plants during their development, producing zero emissions. On the other hand, for fossil-based carbon, the CO₂ that should not be emitted (by fossil fuel, which should be remained sequestered) is absorbed – That is why it is accounted negative. And the tailpipe emission is positive because it is considered as a normal process of emitting carbon. Since after it releases CO₂, it will stay in the atmosphere.

There is a reduction of 53% GWP if we use biogenic source in well-to-wheel approach. But if we are just going to not considering utilization of the fuel (well-to-tank approach), it won't make any reductions for the GWP, instead of an increment of 99%. This is due the fact that the fuel act as the carbon sequestration unit. Although carbon capture technology can capture CO₂ and use it as a raw material for products with added value, it cannot be regarded as a reliable method for long-term CO₂ storage. These CO₂-based products will release their integrated CO₂ back into the environment when they are utilized for a brief time, such as when they are burned in internal combustion engines.

From Zhu et al. (2022) study, it shows that methanol combustion in the tank-to-wheel phase contributes up to 61.71% of the total GHG emissions through the whole life cycle. While in this study, regarding to the result of fossil-based carbon source, the methanol combustion accounts 53% of the whole GHG emissions throughout the well-to-wheel approach life cycle.

It worth to note that climate neutrality nevertheless results in a biased comparison of emissions from bioenergy to fossil energy since photosynthesis may take some time to completely remove these emissions, depending on the pace at which plants grow. Theoretically, the characterisation factor of the biogenic carbon will vary based on different complex indicators since it is reliant on time and specifically takes the timing of biogenic CO₂ emissions and absorption within a rotational period into account. But for simplicity in this study, the characterisation factor of the climate impact for biogenic carbon fossil-based carbon is zero and one, respectively.

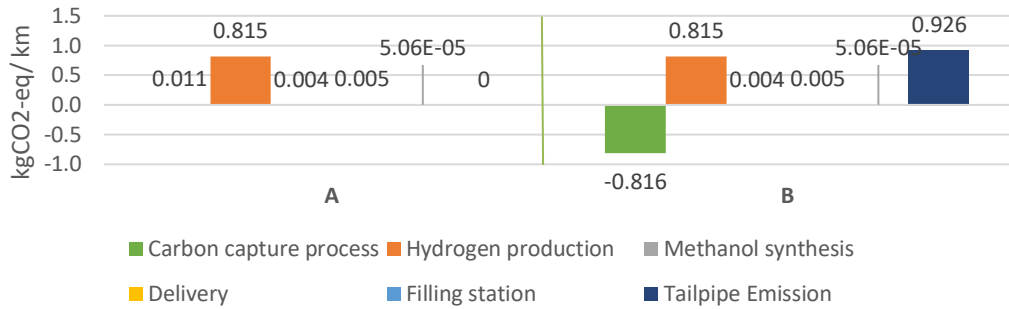


Figure 4.9 The GWP result of methanol fuel utilization with biogenic and fossil-based carbon source based on grid scenario in well-to-wheel approach

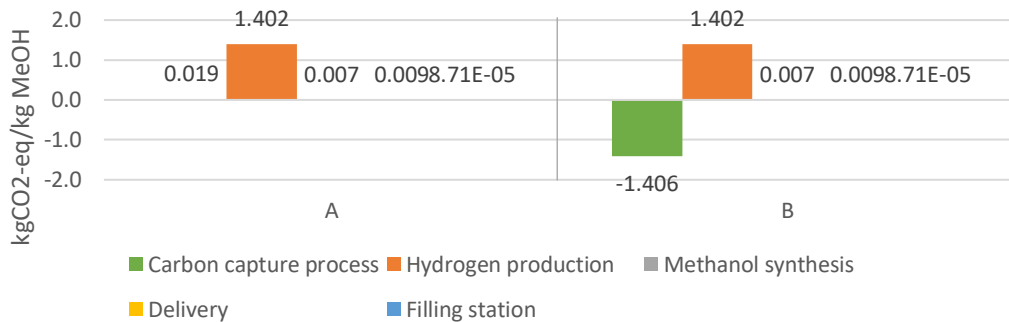


Figure 4.10 The GWP result of methanol fuel production with biogenic and fossil-based carbon source based on grid scenario in well-to-tank approach

4.1.3 LCA result of ammonia as fuel

Accounting for the life cycle assessment of ammonia (+diesel) fuel-mix utilization for heavy-duty vehicle is vital for the current development of the suitable alternative fuel used in conventional diesel engine. Using ammonia as a fuel lower the NO emission than using a pure diesel. This is due to the fact that ammonia entails a low-temperature combustion as a result of the low flame temperature of ammonia. This came from the thermal NO formation is reduced when the combustion temperature is lower. (Zamfirescu & Dincer, 2009). In addition, the GWP saving of using pure ammonia instead of fuel-mix blend will be discussed in the later part of this sub-chapter.

The overall result comparison between the ammonia (+diesel) fuel-mix utilization for both scenarios with a reference in well-to-wheel approach is shown on Figure 4.11. The GHG saving of using electricity from biopower plant records of 55% difference. The GHG emissions are mainly concentrated in the hydrogen production process.

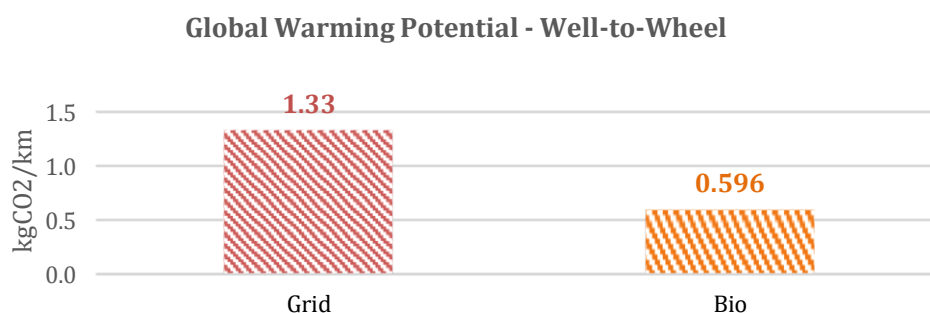


Figure 4.11 GWP result for ammonia fuel-mix blend for well-to-wheel approach

Within the grid scenario, the main contributor of the GWP is hydrogen production (see Figure 4.12). It accounts of 57% of global warming potential impact coming from electricity usage. The GHG emission from the fuel combustion accounts for 20% of the GWP. In the other hand, in biopower plant scenario, the main driver is the tailpipe emission from the fuel combustion which accounts for 44% of the GWP. While in fact the hydrogen production accounts only half of it which is 22% of the GWP.

While we vary the electricity source, we are not able to achieve a slight change in the tailpipe emission GWP due to the combustion process. Hence, it can be argued the tailpipe GHG emission is originated from the diesel fuel used in the engine. From the results, we can outline how electricity source impacts consequently to the emissions drivers of such fuel utilization. When varying the electricity grid source to the biopower plant, it achieves 82% reduction in GHG emission. It is also worth to state on how utilizing renewable energy source on ammonia synthesis process gives considerably impact on halving the global warming impact.

GWP Result Breakdown - Ammonia fuel-mix blend well-to-wheel approach

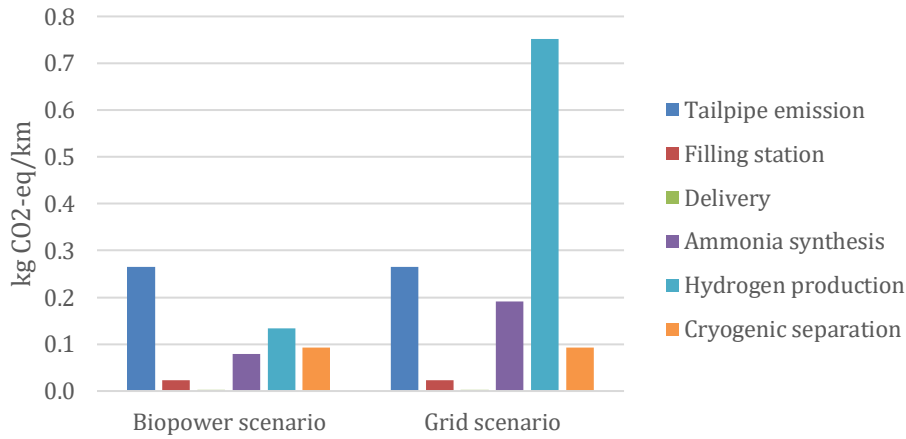


Figure 4.12 GWP result breakdown for well-to-wheel approach in ammonia fuel-mix blend utilization

The well-to-tank approach GWP result (see Figure 4.13) helps to emphasize hydrogen production still dominate the GWP even though it's shared almost equally with ammonia synthesis and cryogenic separation process in biopower plant scenario. From Figure 4.14, we can estimate the hydrogen production accounted 68% of GWP in the fuel production within grid scenario while it accounts 35% in biopower plant scenario. It also shows a consistency where by altering the electricity source from grid into biopower plant, we can achieve a reduction of 82% of CO₂-eq emission from electrolysis process.

Global Warming Potential - Well-to-Tank

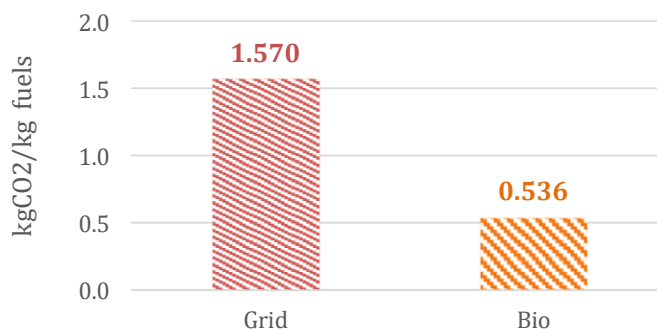


Figure 4.13 GWP result for ammonia fuel-mix blend for well-to-tank approach

GWP Result Breakdown - Ammonia fuel-mix blend production well-to-tank approach

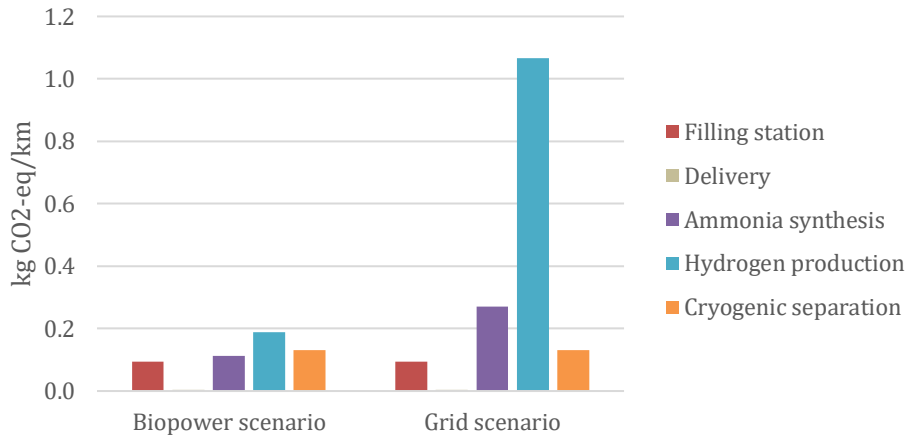


Figure 4.14 GWP result breakdown for well-to-tank approach in ammonia fuel-mix blend production

Even when using pure (100%) ammonia fuel is not feasible to use it in heavy-duty vehicle engines with the current technology. However, analysis of the speculative scenario can be an interesting topic to discuss. Based on Figure 4.15, the utilization of the pure ammonia favours the global warming impact only when the electricity source is from a biopower plant. On the other hand, for the grid scenario, the ammonia (+diesel) fuel-mix blend option would be more beneficial. This is due to the lower GHG emission from hydrogen production and tailpipe emission of the fuel-mix blend compared to the emission generated from producing hydrogen to fulfil the requirement of 100% ammonia fuel option.

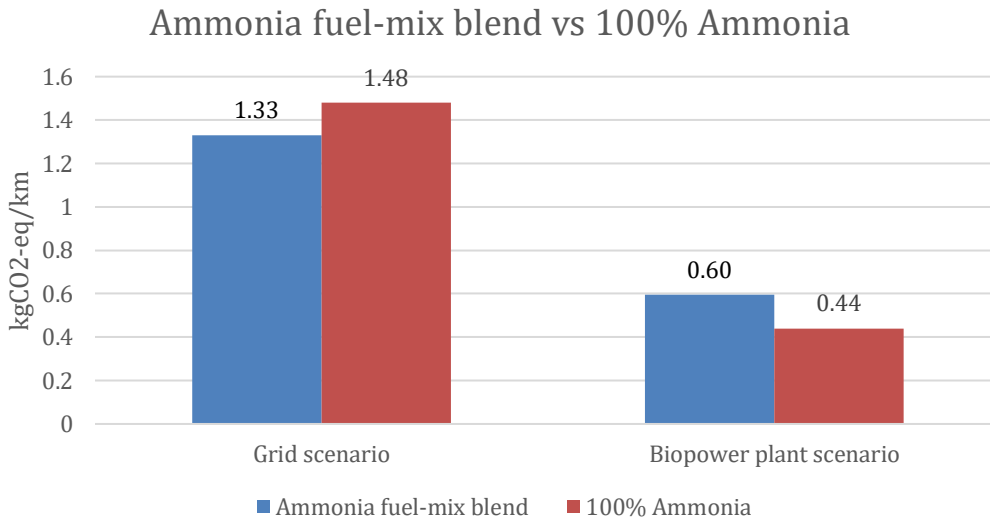


Figure 4.15 The GWP result comparison of utilizing ammonia fuel-mix blend and pure (100%) ammonia for heavy-duty vehicle in well-to-wheel approach

4.1.4 Global warming potential comparison between eFuels

The global warming impact of the fossil-fuel based, diesel, is used for reference to help determine the emission savings achievable from different alternative fuels. Since the GWP100 impact of each eFuels have been specifically explained in the previous sub-chapters, the CO₂-eq emissions savings are going to be presented in this sub-chapter. Figure 4.16 shows the results obtained for all eFuels and diesel fuel for well-to-wheel approach while Table 4.1 summarizes the conceptual emission savings relatively to diesel fuel for each scenario.

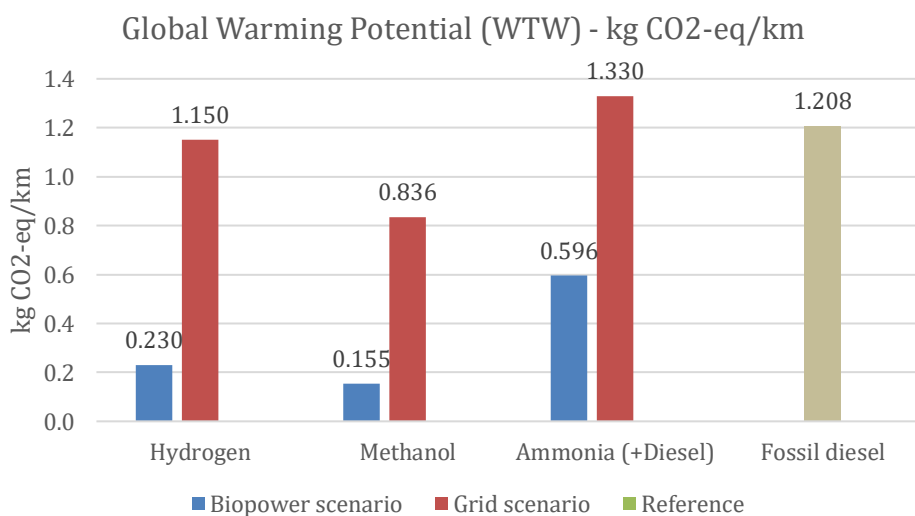


Figure 4.16 GWP result for all eFuels while using diesel as reference for well-to-wheel approach

Table 4.1 CO₂-eq savings for all eFuels relative to diesel fuel

eFuel	Savings (%)	
	Biopower Scenario	Grid Scenario
Hydrogen	81	4
Methanol	87	31
Ammonia (+Diesel)	50	-10

It is worth to emphasize that the use of methanol as an alternative fuel for heavy-duty vehicle attains almost the same emission result as those achieved by hydrogen fuel in biopower plant scenario. The research's conclusions concur with other studies as well, for instance study done by Al-Breiki and Bicer (2021) and Nauman (2023).

The assessment of global warming potential on well-to-tank approach would enhance better understanding of how electricity source influences the potential emission savings. On the other hand, the well-to-tank approach also can assist on whether this pathway (as in mostly utilizing electricity to produce such alternative fuels) is more beneficial or not for further study. Figure 4.17 depicts the result of well-to-tank approach for global warming potential for all eFuels with diesel fuel as reference.

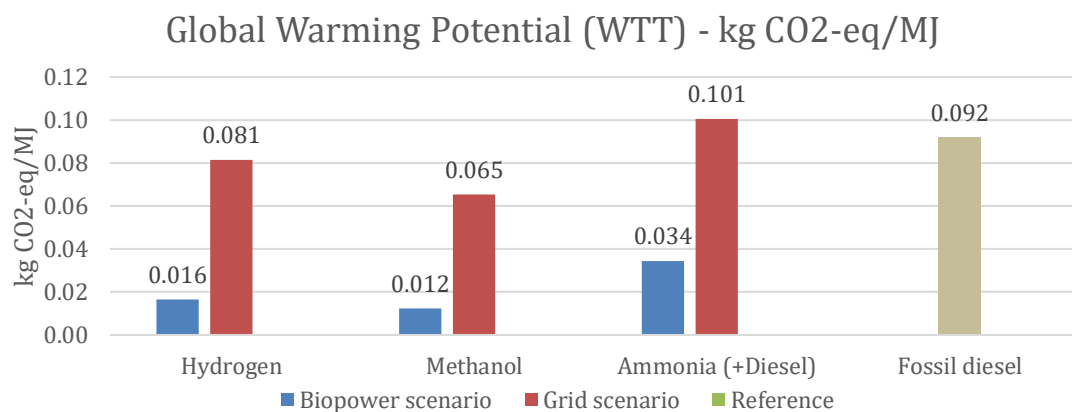


Figure 4.17 GWP result for all eFuels while using diesel as reference for well-to-tank approach

Among the available alternative eFuels, ammonia (+diesel) alternative fuel has the highest global warming potential effect for both scenarios in both

approaches (WTT and WTW approach). As explained earlier, this is due to the relatively high energy utilized to in the ammonia synthesis process as well as the tailpipe emission from the fuel combustion. The share of GWP impact from diesel fuel as a fuel blend also gives some impacts on it. The lowest one comes to methanol fuel due to the low energy applied on producing hydrogen along with the methanol synthesis process.

As expected, the source of the electricity has a significant impact on the fuel life cycle emissions, potentially resulting in up to 87% of global warming potential savings. Figure 4.16, Figure 4.17 and Table 4.1 imply that when compared to the fossil fuel benchmark, there is always opportunity for a net saving in carbon dioxide equivalent emission if the electricity is taken from biopower plant. Meanwhile, from the current Finland's national electricity grid mix, there is chance of to increase the net saving of emissions if the renewable sources share in the grid mix is improving. The detailed environmental impact from the grid and biopower plant electricity production is explained in Appendix.

In addition, by comparing the calculated results from this study with those from the literatures mentioned in the previous sub-chapters, we can outline that the present results generally accord with the data from the literatures, demonstrating the validity of the present method.

4.2 Techno-economic Analysis

Estimating the production cost of the alternative fuels can be done by comparing the operational and capital costs. The results of the cost analysis provide preliminary estimation on the economic feasibility of utilization of the alternative fuels. In this section, the estimation of production cost of each alternative fuels will be demonstrated.

4.2.1 Production cost of Hydrogen fuel

Capital investment of hydrogen production is estimated from the equipment cost from literature review. The equipment cost is assumed to be including the installation and all construction work including piping, civil, and architectural work. The capital cost calculation for hydrogen production is based on equipment needed showed in the respected process flow diagram displayed on Figure 3.3. The main parts are feedwater treatment system, electrolyzer system, storage tank, pipeline for delivery, and land. The total capital cost calculation is written on Table 4.2 and the capital cost breakdown is shown on Figure 4.18.

Table 4.2 Capital cost calculation for hydrogen production

	Cost	Total cost (€)	Source
Feedwater treatment system	0.4371 €/m ³	3 707 304	(Jonsson & Mässgård, 2021)
Electrolyzer system	458 €/kW _{el}	11 453 750	(IRENA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, 2020)
Compressor	2756 €/kW	3 299 257	(Hawkins, 2006)
Storage tank	500 €/kg-H ₂	1 617 317	(Hawkins, 2006)
Pipeline retrofitting	0.5 €/kg-H ₂	1 930 502	(Collins, 2023)

Land	1 €/m ² (per year)	258 388	(RRT Railgate, 2023)
TOTAL		22 266 518	

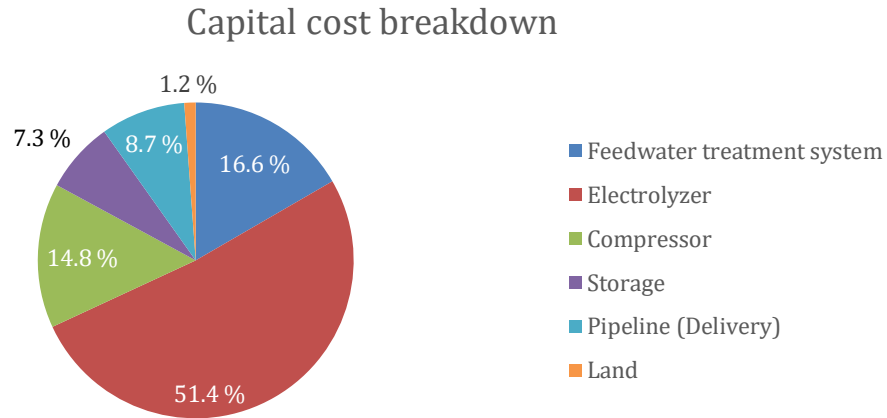


Figure 4.18 Capital cost breakdown of hydrogen plant

The largest share in the capital cost for hydrogen production is electrolyzer where it is dominated by the stack cell. This is due the fact that the stack has limited economy of scale. On the other hand, the balance of plant has a possibility to have an economy of scale (IRENA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, 2020). In addition, feedwater treatment system and compressor also has relatively big share in capital cost due to the high pressure of compression capacity and high amount of water needed. The cost breakdown of the electrolyzer system and feedwater treatment system are depicted on Figure 4.19 and Figure 4.20, respectively.

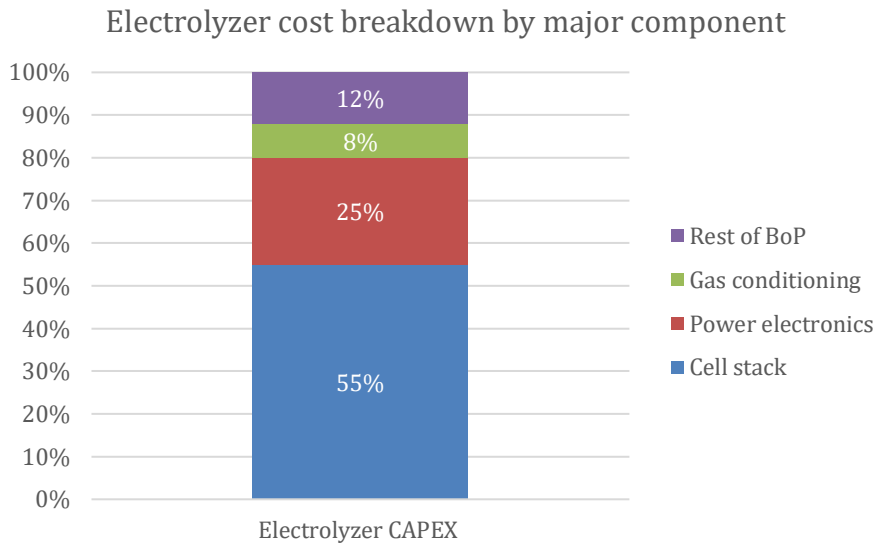


Figure 4.19 Electrolyzer capital cost breakdown by major component (IRENA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, 2020)

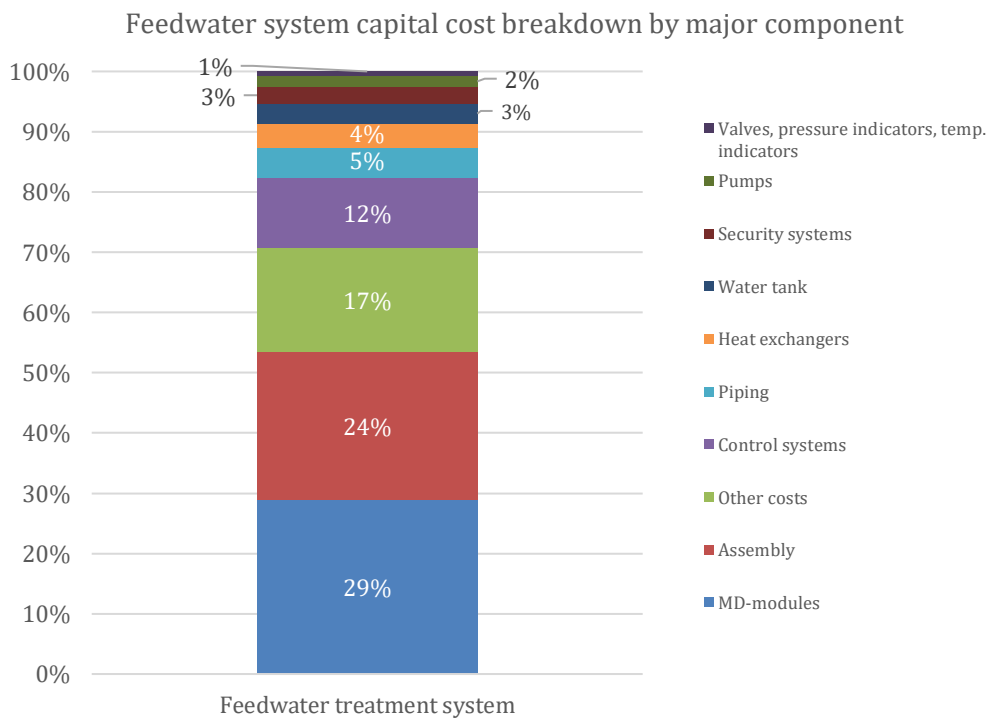


Figure 4.20 Feedwater treatment capital cost breakdown by major component (Jonsson & Mässgård, 2021)

Operational cost of hydrogen production is estimated similarly to the capital investment cost. In this study, variable production cost related to the process is considered. Table 4.3 gives the operational cost calculation for

hydrogen production with biopower plant scenario and Table 4.4 with grid scenario. In addition, Figure 4.21 shows the breakdown cost of each category for each scenario.

Table 4.3 Operational cost calculation for hydrogen production with biopower plant scenario

	Cost	Total cost	Source
		(€/a)	
Electrolyzer			
Electricity	0.05 €/kWh	10 000 000	(Larjava, 2022)
KOH	3.9 €/kg	222 300	(Chem, 2023)
Compressor			
	0.05 €/kWh	768 340	(Larjava, 2022)
	0.1976 €/kWh	74 005	(Jonsson & Mässgård, 2021)
Feed water treatment			
	0.02 * Fixed Capital (FCI)	30 295	(Turton, Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2012)
Operational and Maintenance			
Labor	25 €/person/h	6 000 000	
TOTAL		17 094 939	

Table 4.4 Operational cost calculation for hydrogen production with grid scenario

	Cost	Total cost	Source
		(€/a)	
Electrolyzer			
Electricity	0.1002 €/kWh	20 040 000	(Eurostat, 2022)
KOH	3.9 €/kg	222 300	(Chem, 2023)
Compressor			
	0.1002 €/kWh	1 539 753	(Eurostat, 2022)

Feed water treatment	0.1976 €/kWh	74 005	(Jonsson & Mässgård, 2021)
Operational and Maintenance	0.02 * Fixed Capital (FCI) cost	30 295	(Turton, Bailie, Whiting, & Shaeiwitz, & Bhattacharyya, 2012)
Labor	25 €/person/h	6 000 000	
TOTAL		27 906 352	

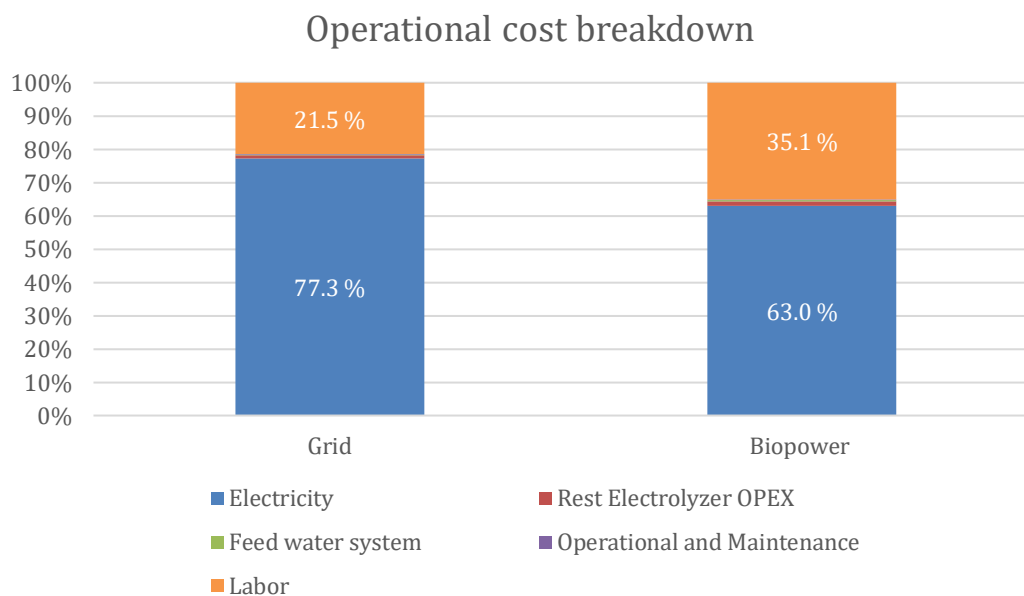


Figure 4.21 Operational cost breakdown of hydrogen plant

The largest share in operational cost of hydrogen production for both scenario is the electricity cost. This is because of the operability of the electrolyzer using electricity as main energy. This aligns with study done by Jeffers et al. (2021), where renewable electricity accounts for 52.3% of the green hydrogen cost. Other than operational and maintenance fee, feedwater treatment system operational cost is the lowest one because of the minimum chemicals needed for the process. The cost breakdown of the feedwater treatment system is shown on Figure 4.22.

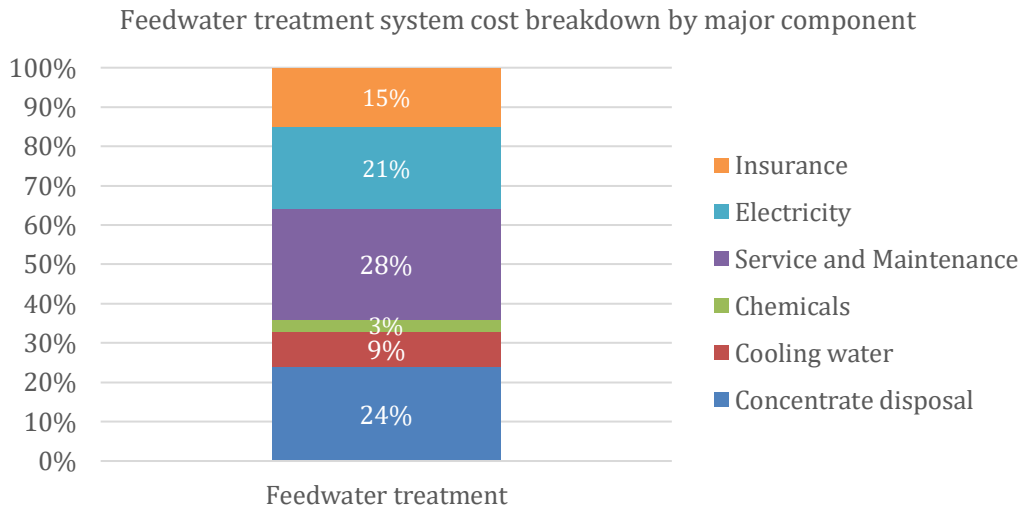


Figure 4.22 Feedwater treatment operational cost breakdown by major component (Jonsson & Mässgård, 2021)

By calculating the capital cost of hydrogen production based on a financial function that returns within the periodic payment, the total capital cost is estimated to be 2 226 652€ per year. The operational cost of the hydrogen production with grid scenario is 27 906 352 € per year while it costs 17 094 939 € per year with biopower plant scenario. Summing up both cost while producing 3 861 004 kg H₂ per year, it can be estimated the production cost of hydrogen fuel to be **7.80 € per kg H₂** for grid scenario and **5.00 € per kg H₂** for biopower plant scenario. Based on Clean Hydrogen Partnership by Roland Berger and INYCOM survey (2023), the current average sales price of hydrogen is ranging from 2 EUR/kg-H₂ into 12 EUR/kg-H₂ with 42.86% of the correspondents have 6.8 EUR/kg-H₂ price. It is also mentioned by H₂ Mobility, a German operator in hydrogen filling station, the price of hydrogen is risen to 12.85 EUR/kg-H₂ (Biogradlija, 2022).

4.2.2 Production cost of Methanol fuel

Methanol plant techno-economic analysis is done similar to the hydrogen plant production. The capital cost calculation for methanol production is based on equipment needed showed in the respected process flow diagram displayed on Figure 3.3. The main parts are carbon capture unit, hydrogen production unit, methanol synthesis unit, delivery unit (trucks), filling station (storage tank), and land. The total capital cost calculation is written on Table 4.5 and the capital cost breakdown is shown on Figure 4.23.

Table 4.5 Capital cost calculation for methanol production

	Cost	Total cost (€)	Source
Carbon capture unit	-0.0008x ² + 0.5835x + 4.0354 M€/kt MeOH per year	26 049 537	(Nyari, 2018)
Hydrogen production unit	458 €/kW _{el}	14 727 781	(IRENA, Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal, 2020)
Methanol synthesis unit			(Nyari, 2018)
Reactor	1.0333*(x ^{0.599})	10 505 727	
Distillation column	-2E-05x ² + 0.0249x + 1.5227 M€/kt MeOH per year	3 351 843	
Heat exchanger network	-2E-05x ² + 0.0517x + 1.0013 M€/kt MeOH per year	3 421 027	
Flash separators	0.0016x + 0.1738 M€/kt MeOH per year	345 403	
Compressors	-0.0002x ² + 0.0786x + 13.891 M€/kt MeOH per year	25 792 084	
Boiler	-2E-05x ² + 0.0152x	675 110	

	+ 0.1027 M€/kt MeOH per year		
Delivery unit (Trucks)	12 000 USD /truck	11 244	(CLW Heavy Industry Co., 2023)
Filling station (Storage tanks)	0.69 €/kg MeOH	17 602	(Dias, Pochet, Contino, & Jeanmart, 2020)
Land	1 €/m ² (per year)	258 388	(RRT Railgate, 2023)
TOTAL		85 155 744	

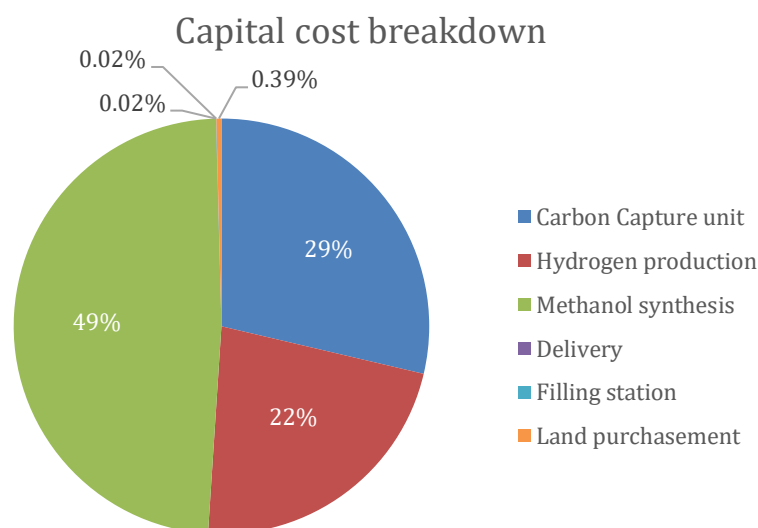


Figure 4.23 Capital cost breakdown of methanol plant

The largest share in the capital cost for methanol production is the methanol synthesis unit. This cost is dominated by compressors equipment mainly for CO₂ compression after being captured in the capture unit. Methanol reactor is the second largest share where it depends on the size. The methanol synthesis unit cost breakdown is shown on Figure 4.24.

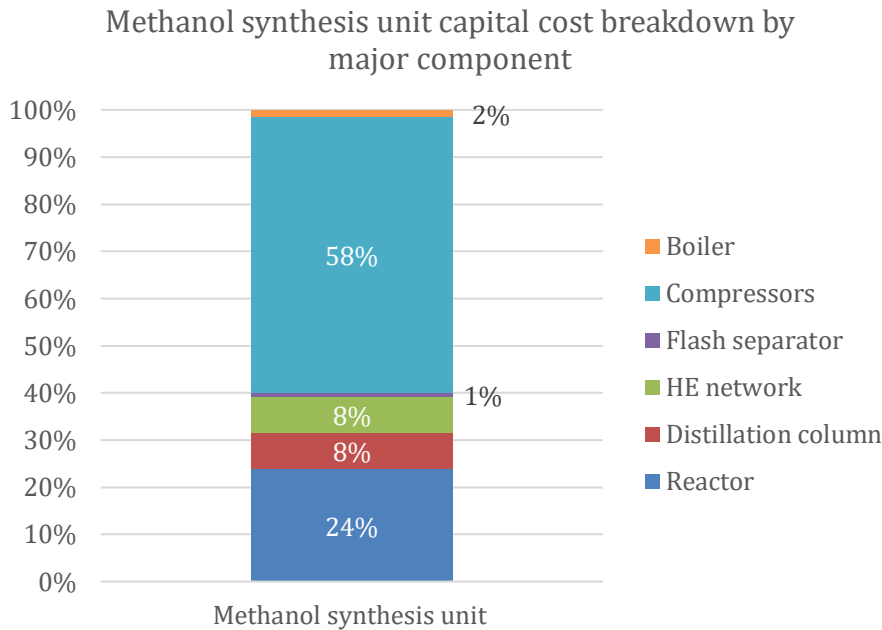


Figure 4.24 Methanol synthesis unit capital cost breakdown by major component

Operational cost of methanol production is estimated similarly to the capital investment cost. In this study, variable production cost related to the process is considered. Table 4.6 gives the operational cost calculation for methanol production with biopower plant scenario and Table 4.7 with grid scenario. In addition, Figure 4.25 shows the breakdown cost of each category for each scenario.

Table 4.6 Operational cost calculation for methanol production with biopower plant scenario

	Cost	Total cost (€/a)	Source
Hydrogen production			
Electricity	0.05 €/kWh	10 000 000	(Larjava, 2022)
Water	1.74 €/m ³	76 303	(HSY, 2023)
KOH	3.9 €/kg	229 204	(Chem, 2023)
Carbon capture unit			
Electricity	0.05 €/kWh	202 690	(Larjava, 2022)
Steam	0.02 €/kg	558 614	(Larjava, 2022)

Water	0.1976 €/m ³	3 748	(Jonsson & Mässgård, 2021)
Activated carbon	0.085 €/kg	146	(Procurement Resource, 2022)
Monoethanolamine (MEA)	2.23 €/kg	71 150	(Index Box, 2023)
Caustic soda (NaOH)	0.63 €/kg	2 858	(Chemanalyst, 2022)
Methanol synthesis			
Catalyst	2e-05*(x ^{1.004})	0.043	(Nyari, 2018)
Electricity	0.05 €/kWh	43 423	(Larjava, 2022)
Operational and Maintenance	0.02 * Fixed Capital cost (FCI)	115 858	(Turton, Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2012)
Labor	25 €/person/h	6 000 000	
TOTAL		17 303 993	

Table 4.7 Operational cost calculation for methanol production with grid scenario

	Cost	Total cost (€/a)	Source
Hydrogen production			
Electricity	0.05 €/kWh	20 040 000	(Larjava, 2022)
Water	0.1976 €/m ³	76 303	(Jonsson & Mässgård, 2021)
KOH (Potassium hydroxide)	3.9 €/kg	229 204	(Chem, 2023)
Carbon capture unit			

Electricity	0.05 €/kWh	406 190	(Larjava, 2022)
Steam	0.02 €/kg	558 614	(Larjava, 2022)
Water	0.1976 €/m ³	3 748	(Jonsson & Mässgård, 2021)
Activated carbon	0.085 €/kg	146	(Procurement Resource, 2022)
Monoethanolamine (MEA)	2.23 €/kg	71 150	(Index Box, 2023)
Caustic soda (NaOH)	0.63 €/kg	2 858	(Chemanalyst, 2022)
Methanol synthesis			
Catalyst	2e-05*(x ^{1.004})	0.043	(Nyari, 2018)
Electricity	0.05 €/kWh	87 020	(Larjava, 2022)
Operational and Maintenance	0.02 * Fixed Capital cost (FCI)	115 858	(Turton, Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2012)
Labor	25 €/person/h	6 000 000	
TOTAL		27 591 090	

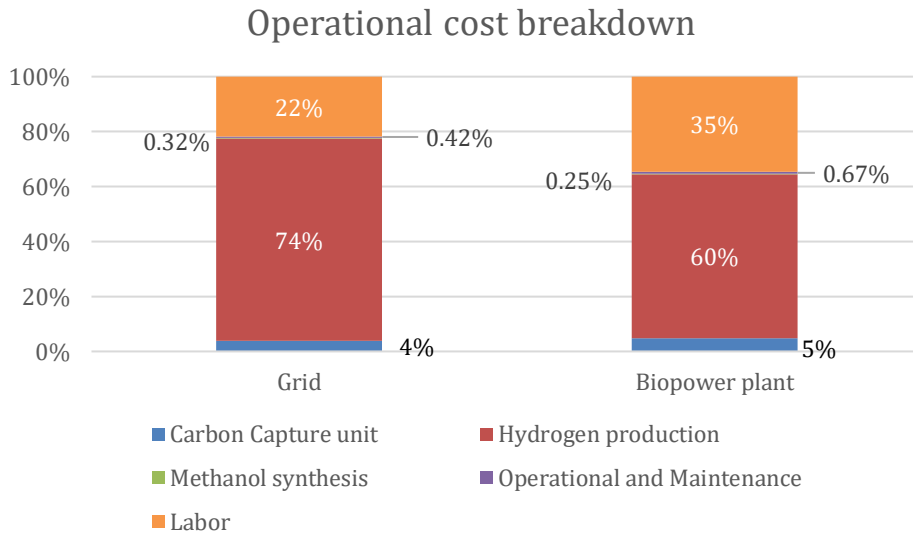


Figure 4.25 Operational cost breakdown of methanol plant

The largest share in operational cost of methanol production for both scenario is the hydrogen production. This is because of the most energy intensive equipment is electrolyzer while the electrolyzer uses electricity as its main energy. Based on study by S. Sollai et al. (2023), the main variable operating cost in e-methanol plant is accustomed by electricity. Methanol synthesis is the lowest one for both scenario due to its exothermic reaction which only requires cooling energy. The catalyst spent per year is also low since it has been long used for the hydrogenation of CO₂ process to methanol.

By calculating the capital cost of methanol production based on a financial function that returns within the periodic payment, the total capital cost is estimated to be 85 155 744 € per year. The operational cost of the methanol production with grid scenario is 27 591 090€ per year while it costs 17 303 993 € per year with biopower plant scenario. Summing up both cost while producing 20 286 645 kg MeOH per year, it can be estimated the production cost of methanol fuel to be **1.78 € per kg MeOH** for grid scenario and **1.27 € per kg MeOH** for biopower plant scenario. According to the Renewable Methanol Outlook made by Methanol Institute and International Renewable Energy Agency (2021), e-methanol cost is estimated to reach 1.07 – 1.43 € per kg MeOH. Worth noting as a consequence of utilizing methanol produced by the plant for delivery process of the fuel from the plant to the filling station, the amount of produced methanol for techno-economic analysis is being subtracted while in the same time curbs the total emission.

4.2.3 Production cost of Ammonia fuel

Ammonia plant consists of three main process plant, namely separation of nitrogen from air, hydrogen production, and the ammonia synthesis itself. The capital cost calculation for ammonia production is based on equipment needed showed in the respected process flow diagram displayed on Figure 3.4. The main parts are cryogenic air separation unit, hydrogen production unit, ammonia synthesis unit, delivery unit (trucks), filling station (storage tank), and land. The total capital cost calculation is written on Table 4.8 and the capital cost breakdown is shown on Figure 4.26.

Table 4.8 Capital cost calculation for ammonia production

	Cost	Total cost (€)	Source
Cryogenic separation	ai 29.5 M\$ (2020) for 432-ton O ₂ /day	3 226 165	(Zhang, Wang, Van herle, Marechal, & Desideri, 2020)
Hydrogen production unit	458 €/kW _{el}	11 782 225	(IRENA, 2020)
Ammonia synthesis unit	52.11 M\$ (2021) for 300-ton NH ₃ /day	14 829 791	(Noshewani & Neto, 2021)
Delivery unit (Trucks)	12 000 USD /truck	11 244	(CLW Heavy Industry Co., 2023)
Filling station (Storage tanks)	8.39 M\$ (2021) for 14,503 m ³ NH ₃	207 486	(Noshewani & Neto, 2021)
Land	1 €/m ² (per year)	258 388	(RRT Railgate, 2023)
TOTAL		30 315 298	

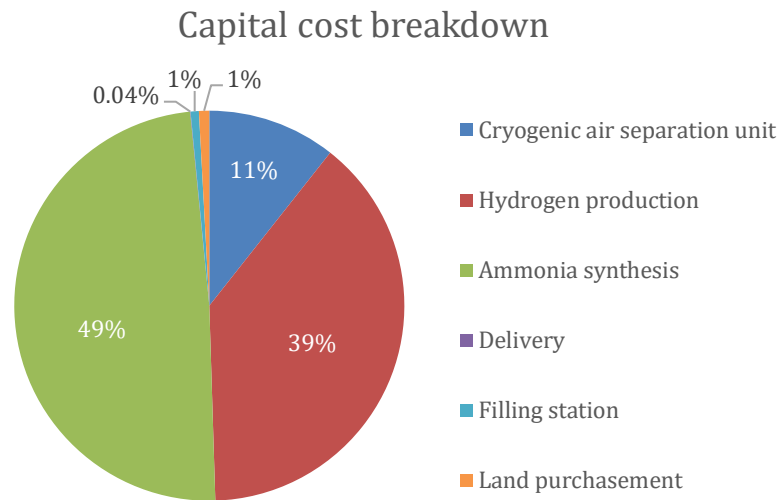


Figure 4.26 Capital cost breakdown of ammonia plant

The largest share in the capital cost for ammonia production is the ammonia synthesis unit. This cost is dominated by compressors equipment mainly for feed compression. Heat exchanger is the second largest share where it aims to maximize the energy recovery within the process. The ammonia synthesis unit cost breakdown is shown on Figure 4.27.

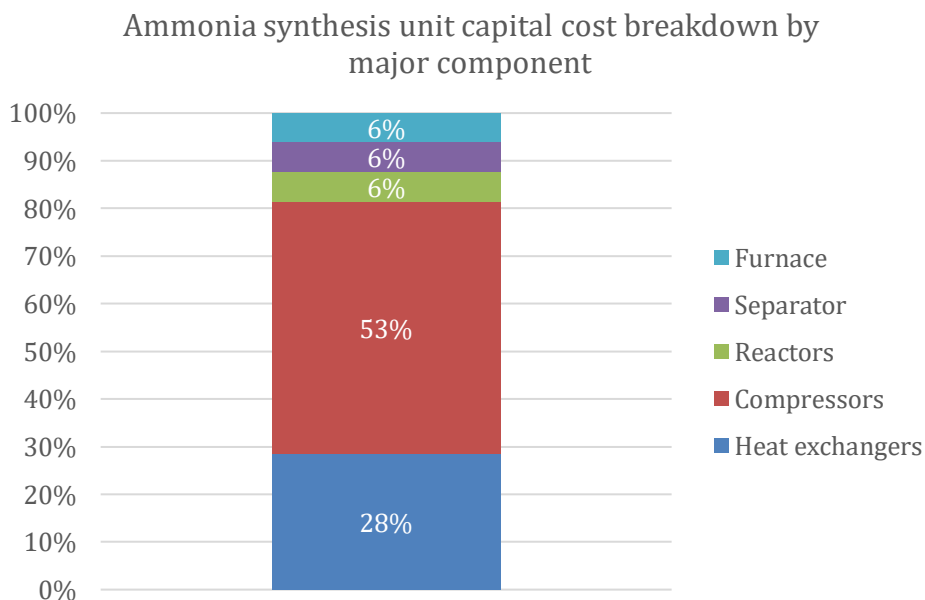


Figure 4.27 Ammonia synthesis unit capital cost breakdown by major component (Nosherwani & Neto, 2021)

Operational cost of methanol production is estimated similarly to the capital investment cost. In this study, variable production cost related to the

process is considered. Table 4.9 gives the operational cost calculation for methanol production with biopower plant scenario and Table 4.10 with grid scenario. In addition, Figure 4.28 shows the breakdown cost of each category for each scenario.

Table 4.9 Operational cost calculation for ammonia production with biopower plant scenario

	Cost	Total cost	Source
		(€/a)	
Hydrogen production			
Electricity	0.05 €/kWh	7 942 024	(Larjava, 2022)
Water	0.1976 €/m ³	58 606	(Jonsson & Mässgård, 2021)
KOH	3.9 €/kg	176 045	(Chem, 2023)
Cryogenic air separation unit			
Electricity	0.05 €/kWh	539 923	(Larjava, 2022)
Ammonia synthesis			
Catalyst	23 €/kg	795	(Zhang;Wang;Van herle;Marechal;& Desideri, 2020)
Electricity	0.05 €/kWh	1 727 478	(Larjava, 2022)
Sodium hydroxide	0.63 €/kg	22	(Chemanalyst, 2022)
KOH (Potassium hydroxide)	3.9 €/kg	135	(Chem, 2023)
Operational and Maintenance	0.02 * Fixed Capital (FCI) cost	41 245	(Turton, Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2012)
Labor	25 €/person/h	6 000 000	
TOTAL		16 486 274	

Table 4.10 Operational cost calculation for methanol production with grid scenario

	Cost	Total cost	Source
		(€/a)	
Hydrogen production			
Electricity	0.1002 €/kWh	15 915 817	(Eurostat, 2022)
Water	0.1976 €/m ³	58 606	(Jonsson & Mässgård, 2021)
KOH	3.9 €/kg	176 045	(Chem, 2023)
Cryogenic air separation unit			
Electricity	0.05 €/kWh	1 082 006	(Larjava, 2022)
Ammonia synthesis			
Catalyst	23 €/kg	795	(Zhang;Wang;Van herle;Marechal;& Desideri, 2020)
Electricity	0.1002 €/kWh	15 915 817	(Eurostat, 2022)
Sodium hydroxide	0.63 €/kg	22	(Chemanalyst, 2022)
KOH (Potassium hydroxide)	3.9 €/kg	135	(Chem, 2023)
Operational and Maintenance	0.02 * Fixed Capital cost (FCI)	41 245	(Turton, Baillie, Whiting, Shaeiwitz, & Bhattacharyya, 2012)
Labor	25 €/person/h	6 000 000	
TOTAL		26 736 537	

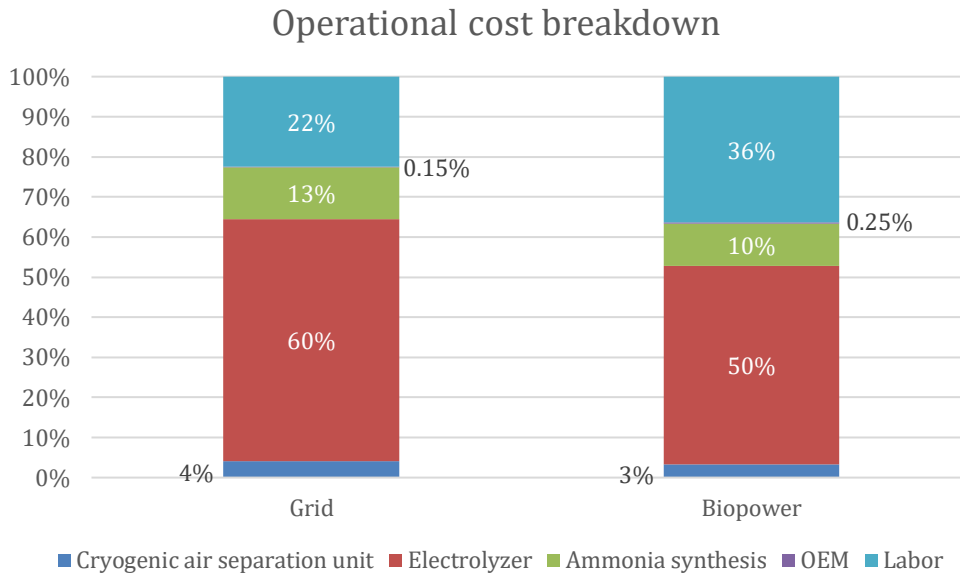


Figure 4.28 Operational cost breakdown of ammonia plant

The largest share in operational cost of methanol production for both scenarios is hydrogen production process. As mentioned before, this is because the electrolyzer is an energy-intensive unit. Even though the ammonia synthesis unit has the highest capital investment, the operational cost of the unit is relatively low because of the low spent of catalyst as well as the other chemicals. The cryogenic air separation unit contributes as the second highest share of the operational cost because of the amount of electricity it needed to compress the air for the separation process (Li;Roba;& Bastid, 2012).

By calculating the capital cost of ammonia production based on a financial function that returns within the periodic payment, the total capital cost is estimated to be 30 315 298 € per year. The operational cost of the ammonia production with grid scenario is 26 736 537 € per year while it costs 16 486 274 € per year with biopower plant scenario.

Since the ammonia is blended with the diesel, the diesel fuel is assumed to cost the same price as the market diesel fuel price. It was listed that the average diesel cost in Finland is 1.87 € per liter in 2023. Estimating the amount of diesel imported and ammonia produced based on the engine specification, it can be estimated the production cost of the mixed fuel to be **1.88 € per kg fuel** for grid scenario and **1.46 € per kg fuel** for biopower plant scenario. In addition, it was also estimated the production cost of the ammonia fuel -if it was a 100% (pure) ammonia applied for the engine-, it costs 1.73 € per kg NH₃ for grid scenario and 1.13 € per kg NH₃ for bio

powerplant scenario. Innovation Outlook of Renewable Ammonia published by IRENA (International Renewable Energy Agency) and AEA (Ammonia Energy Association) (2022) mentioned that green ammonia is estimated to cost 1.25 € per kg NH₃.

4.2.4 Overall cost comparison between eFuels

In this section, the estimated eFuels production cost will be summarized and compared with the fossil-fuel based, Diesel, for a better outlook the cost competitiveness of eFuel. In addition, the cost of each eFuel is also compared with the current market price and/or previous studies of their respected fuel to understand the variations and market probability. In Figure 4.29, the estimated costs are presented with their references which is explained on Table 4.11. Worth to mention that the ammonia production cost presented on the Figure 4.30 is the 100% Ammonia scenario without considering the fuel-mix blend with diesel - in other words diesel does not contribute in the resulted cost. The diesel price used in this study is based on European Commission Data in 2023.

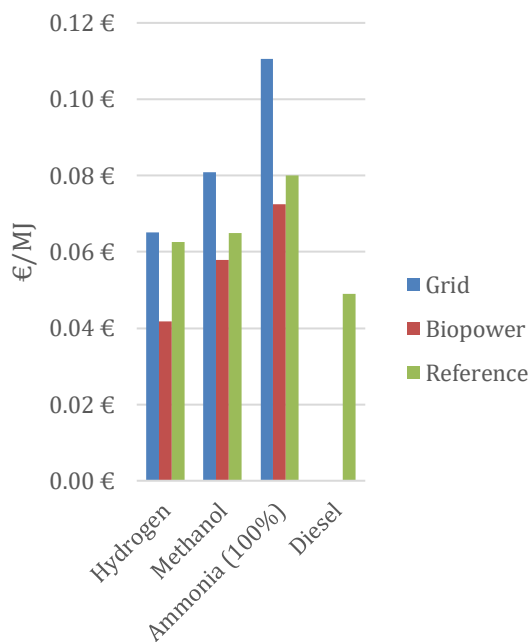


Figure 4.29 Production cost summary for all eFuels per kg of respected fuel

Table 4.11 References for each eFuel market price

eFuels (/MJ)	Price	Source	Notes
Hydrogen	7.5 €	(European Energy	Green hydrogen price

		Exchange, 2023)	
Methanol	1.43 €	(IRENA, 2021)	E-methanol price
Ammonia	1.25 €	(IRENA & Green AEA, 2022)	ammonia (without transportation and distribution cost, still estimation)

From Figure 4.29, we can conclude that the trend for all of the eFuels shows the same pattern, particularly the biopower plant scenario (orange bars) always have lower production cost than the grid scenario (blue bars). In terms of electricity, the use electricity from biopower plant has lower cost than purchasing it from the national grid source. This pattern as a result of the electricity allocates most of the cost in the production cost. By considering CAPEX annuity, OPEX and electricity cost for analysing the overall cost breakdown, it is shown on Figure 4.30 that the electricity always gave the highest share.

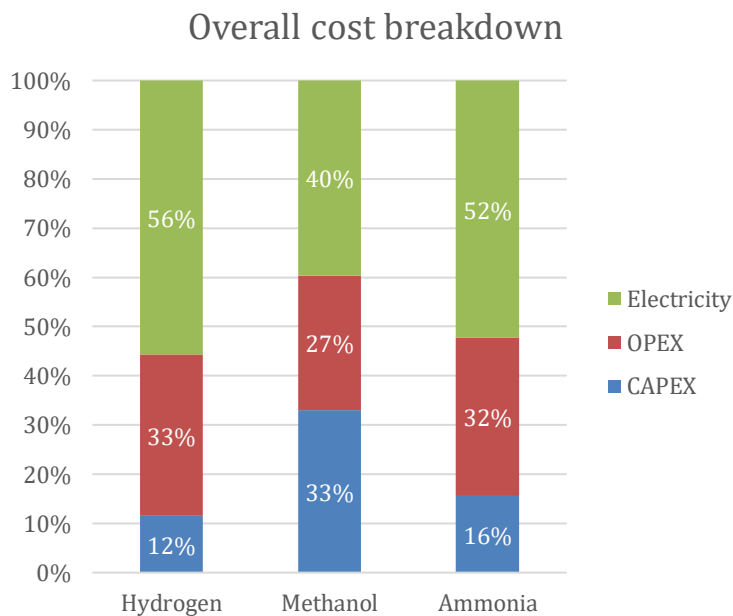


Figure 4.30 Overall cost breakdown of all eFuels for Biopower scenario

Comparing the cost of eFuels with conventional heavy-duty vehicle fuel could assist in the better understanding of the possible potential of eFuels by policymakers and the stakeholder in the industry. Figure 4.31 depicts a better outlook for their comparison. In this case, the ammonia cost is the mixed cost

with diesel. This is due to the limitation of current technology of using 100% ammonia for the engine explained earlier. Results from this study indicate that all eFuels have lower price per km driven than diesel with taxes while hydrogen is the most cost competitive fuel. The diesel price is relatively low without taxes, it even shows that the eFuels cost are higher than diesel price without the taxes. But, due to the current policies, Finland has to apply quite high taxes so the price for diesel is higher than eFuels.

For the eFuels, the price is still a production cost so no taxes applied. This results can help stakeholder to consider the opportunity of the implementation of the eFuels, especially regarding the eFuel policy appraisal. It is also interesting to note that as the price of renewable electricity continues to fall, it is anticipated that production costs will also fall significantly.

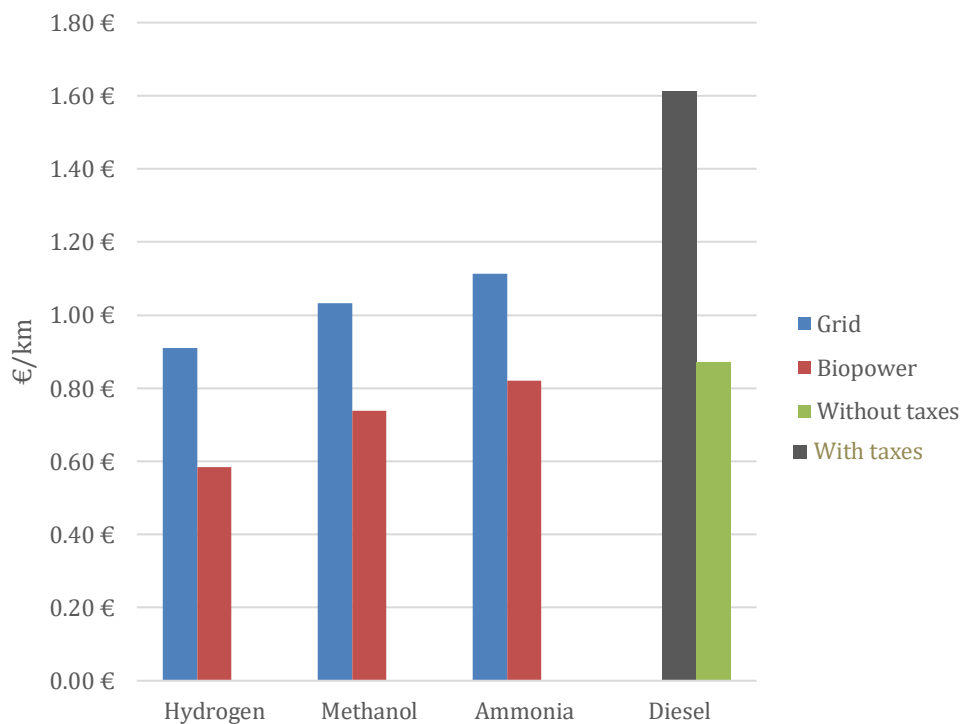


Figure 4.31 Production cost summary for all eFuels per km

5 Conclusions

The purpose of the project is to evaluate how does decarbonization of heavy duty sector by using alternatives fuel impact the environment. The alternative fuels being assessed are hydrogen, methanol, and ammonia-based fuel. In addition, the techno economic analysis for the eFuels would be also analyzed. Integration of life cycle assessment (LCA) and techno-economic analysis (TEA) enables systematic analysis of the relationships between technical, economic, and environmental performance. Two scenarios are applied where two electricity sources, grid and biopower plant, are the electricity supplier for each eFuel production process. GaBi software with Ecoinvent and literature database were used to carry out the LCA while Microsoft Excel is used to demonstrate the TEA.

Our modelling of the different eFuel choices indicates that utilizing hydrogen, methanol, and ammonia (+diesel) alternative fuel on heavy-duty vehicle can all result in GHG savings (>50%), specifically on biopower plant scenario. It is obvious that e-fuels are particularly intriguing choices when electricity with low carbon intensity is used. It shows that the application of methanol fuel on heavy-duty vehicle, as the lowest result, gives global warming impact of 0.155 kg CO₂-eq for one kilometre driven by the vehicle. Fossil fuel (diesel) conventional vehicle will give impact of 1.208 kg CO₂-eq/km, while on the other hand the ammonia (+diesel) fuel with grid scenario demonstrates higher number, precisely 1.33 kg CO₂-eq for one kilometre driven. In addition, hydrogen fuel impacts the lowest on 0.23 kg CO₂-eq per km driven in the biopower scenario.

All of the eFuel LCA results also show the same trend where biopower plant scenario always gives lower global warming impact than grid scenario. Since eFuels production main idea is utilizing electricity as the energy source, we can conclude that the potential benefits of using electricity as an alternative to the present standard vehicle's powertrain are lower when the grid's carbon intensity is high. When compared to the present fossil-based powertrains, all of the fuel-powertrain solutions under consideration offer meaningful GHG savings; this makes it evident that all of these options can be deployed on the market.

The production cost for all eFuels is another important matter to discuss. Every estimated eFuels production cost remains within the range of the current market price. The costs for all eFuels are always lower if its electricity is supplied by biopower plant. Hydrogen fuel has the lowest production cost of 0.04 € per MJ (megajoule) while ammonia (+diesel) fuel is the highest among other options (0.09 € per MJ). Producing methanol alone costs 0.06

€ per MJ. All estimated eFuels cost are still less expensive when compared to the cost of fossil fuels (diesel) with taxes, even though the alternative fuels are used as grid sources. Furthermore, every estimated eFuels price is still within the range of the current market pricing.

Regarding the overall production cost breakdown, the cost of the e-fuels technologies is dominated by electricity cost. In the grid scenario, it accounts >60% of the total cost for producing the alternative fuels. This means that the eFuel cost will depend on the electricity price in the market. Increasing eFuel production and utilization is anticipated to draw significant development in renewable electricity sources and this would be a key lever for the governmental support for these technological advancements. On the other hand, if there isn't any investment backed by a sound policy framework, such costs will continue to be high and output levels may be minimal.

The freight industry will continue to be a key component of this modern economy, but there is a need to address the rising GHG impact of heavy-duty vehicles. In particular, eFuel production is at a very low level right now, despite the transportation industry's tremendous interest in the technology. Due to the poor availability, pilot projects cannot be conducted at an appropriate scale. If there is a sufficient push for decarbonization, other technological solutions may be able to meet the demand. Even if e-fuels are prepared for use in mixtures with conventional fuels, the necessity for novel and intricate infrastructures is frequently a problem that is not fully addressed and looked into in the developed electrification scenarios.

It's also important to note that e-fuels can serve as chemical storage, allowing the storage of variable renewable electricity from production peaks that the grid cannot handle. This serves as a balancing service and eliminates the need to upgrade the distribution grid by eliminating the requirement for balancing services.

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Appendix

A. Global warming impact of the electricity source

The life cycle assessment of the electricity source act as a tool to evaluate and determine the environmental impact of each scenario electricity generation activities. This approach assists in setting priorities by identifying where environmental consequences occur and where life cycle-based mitigation strategies should be used. The environmental impact assessed in this study is expressed in kilograms per kWh of generated electricity based on the modelling of 1MWh electricity generation. The database used for the modelling is from the Ecoinvent database.

The finding of the global warming impact of Finland's national electricity grid is shown on Figure A.1. The total GHG emission of the grid is 0.134 kg CO₂ per kWh. It shows that hard coal is the most carbon intensive source which accounts 56% share of the grid's carbon emission. It is also important to note that coal only cover 7.4% of the grid mix (see Figure 3.7). On the other hand, nuclear energy, the highest contributor in the grid mix, is accountable for 2% of the grid's carbon intensity. Nuclear is a reliable baseload power to support the decarbonisation of power supply role. According to the International Energy Agency (IEA), the second-largest source of low carbon energy in electricity generation, behind hydro power, is nuclear power.

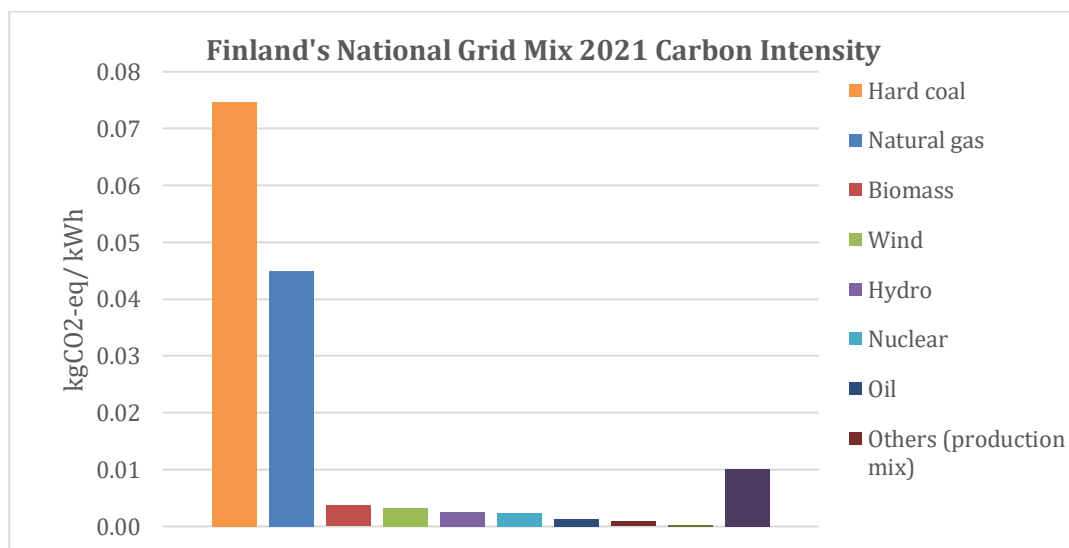


Figure A.1 Finland's national grid mix LCIA result

The biopower plant is modelled similar to the current common existing plant in Finland. Based on the database, it is expected that log boilers burn

hardwood, softwood, and mixed wood that is harvested directly from forests while the sources from residues of wood industry are assumed to be burned at chip furnaces. The carbon intensity of the following biopower plant is 20.2 gCO₂-eq per kWh.

B. Process flow diagram model in GaBi software



Figure A.2 Finland electricity grid mix model



Figure A.3 Hydrogen fuel filling station (+tank-to-wheel) and storage tank material model

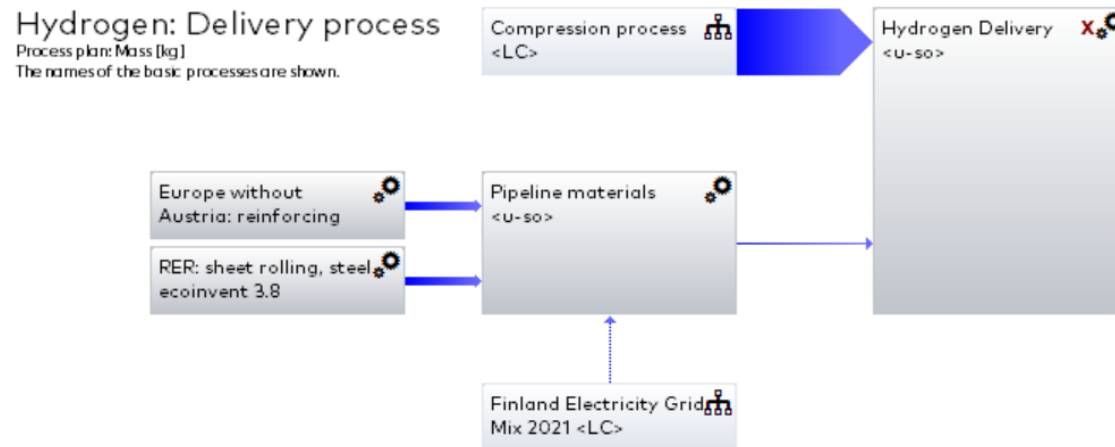


Figure A.4 Hydrogen fuel delivery process model

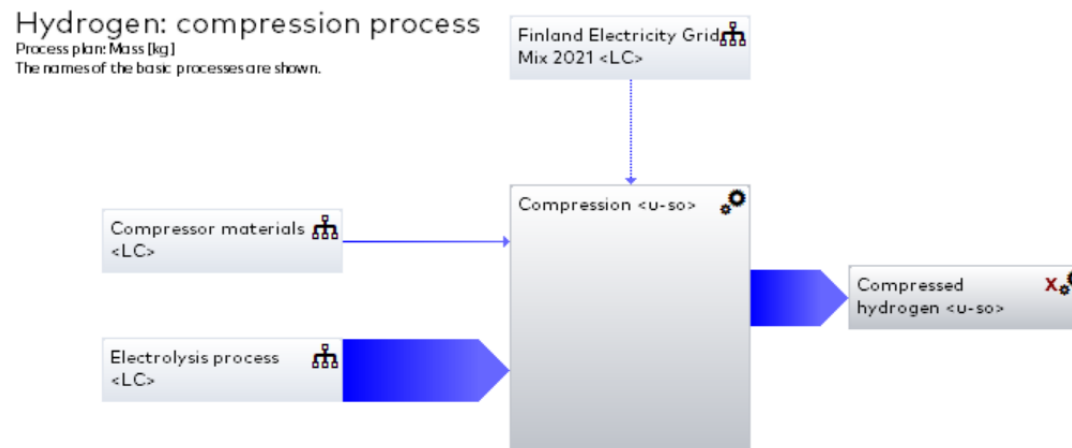


Figure A.5 Hydrogen fuel compression process model

Hydrogen: compressor materials

Process plan: Mass [kg]
The names of the basic processes are shown.

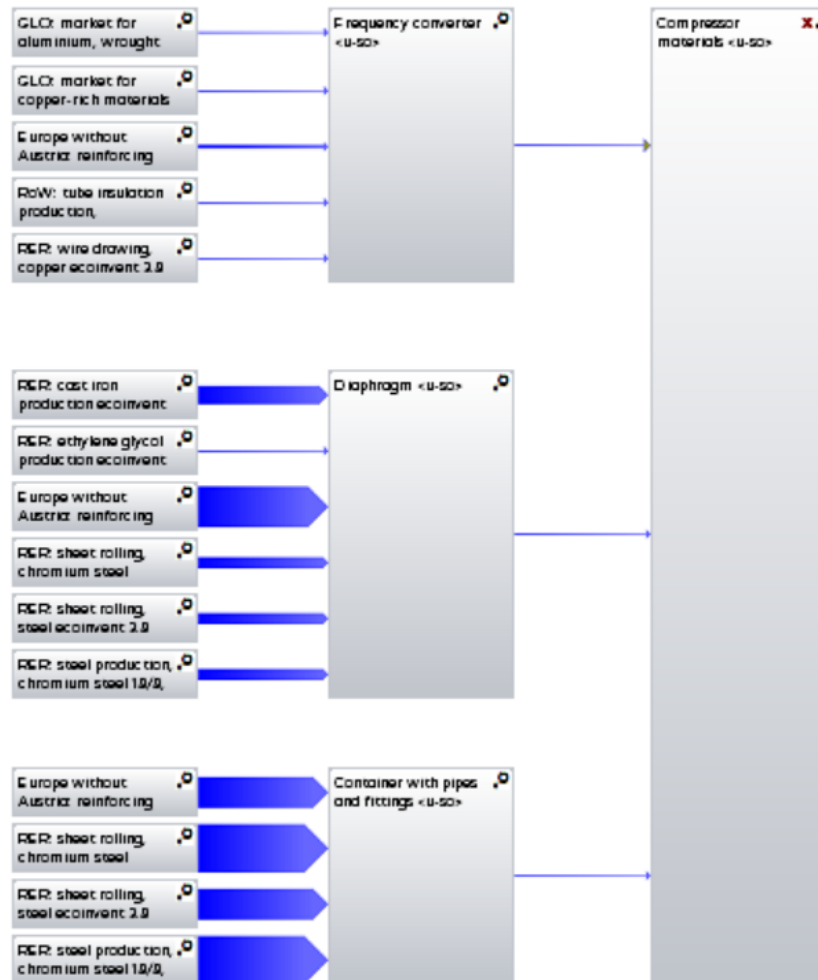


Figure A.5 Hydrogen fuel compressor material model

Electrolysis process

Process plan: Mass [kg]
The names of the basic processes are shown.

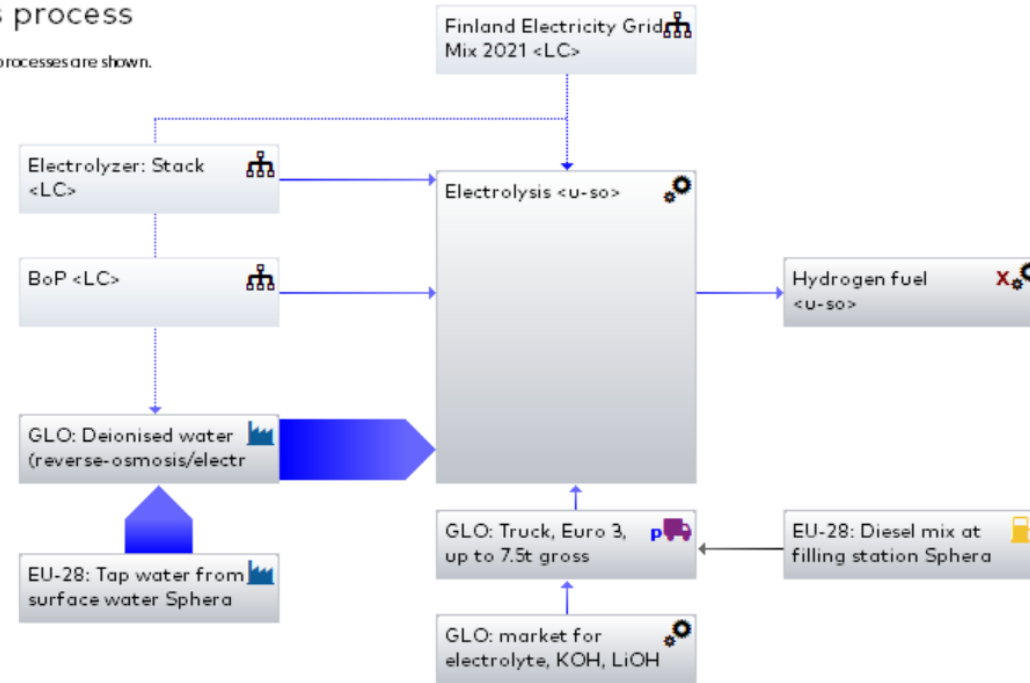


Figure A.5 Hydrogen production by electrolysis process model

Electrolyzer: Stack

Process plan: Mass [kg]
The names of the basic processes are shown.

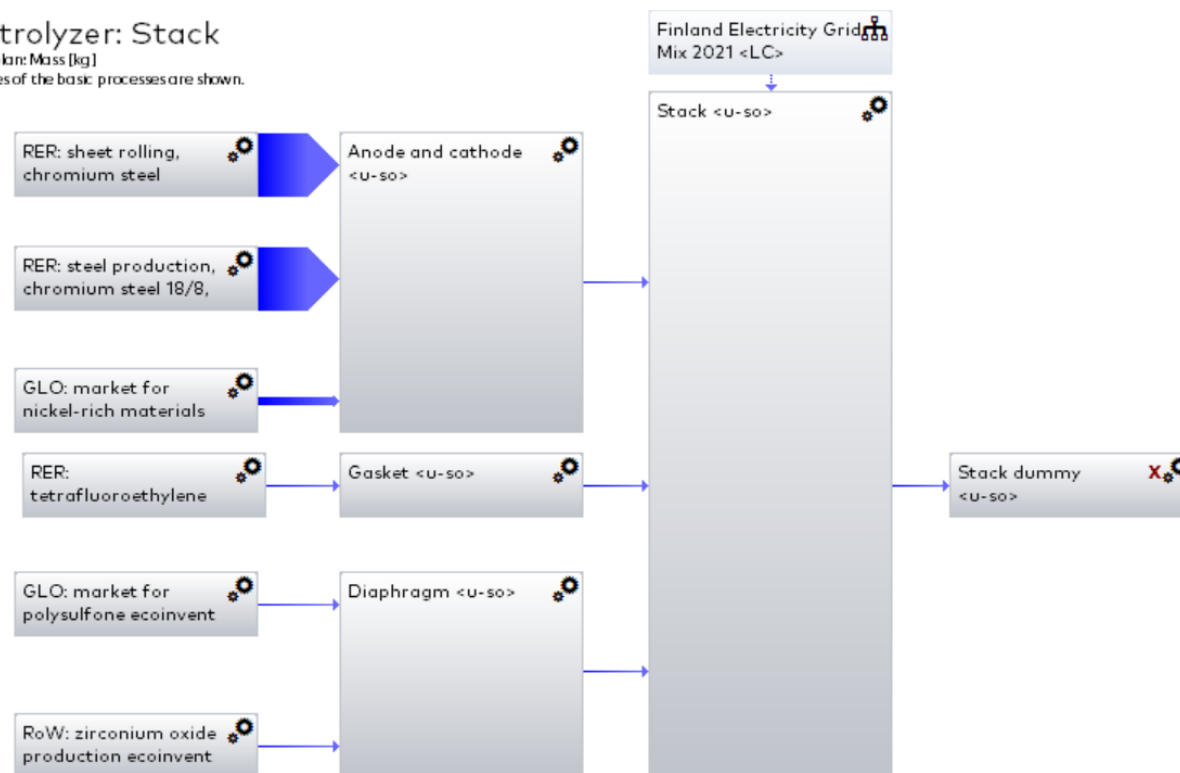


Figure A.6 Stack material for electrolyzer model

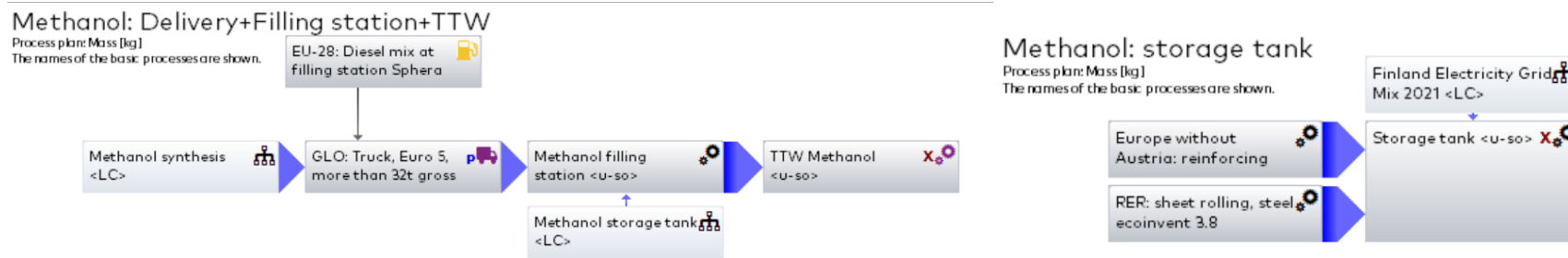


Figure A.8 Methanol fuel delivery process, filling station (+tank-to-wheel), and storage tank material model

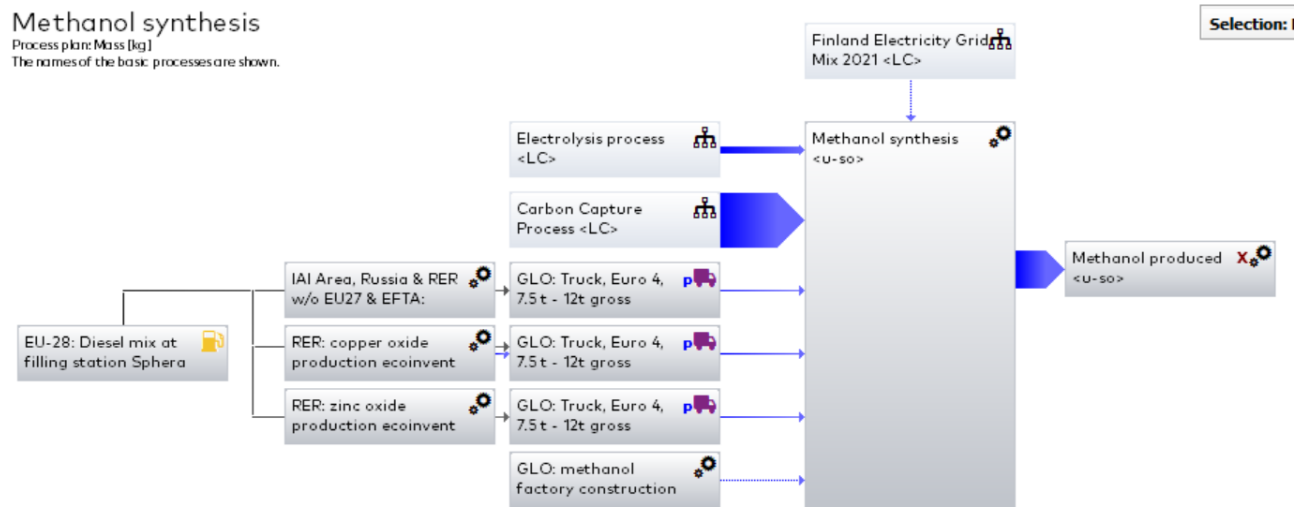
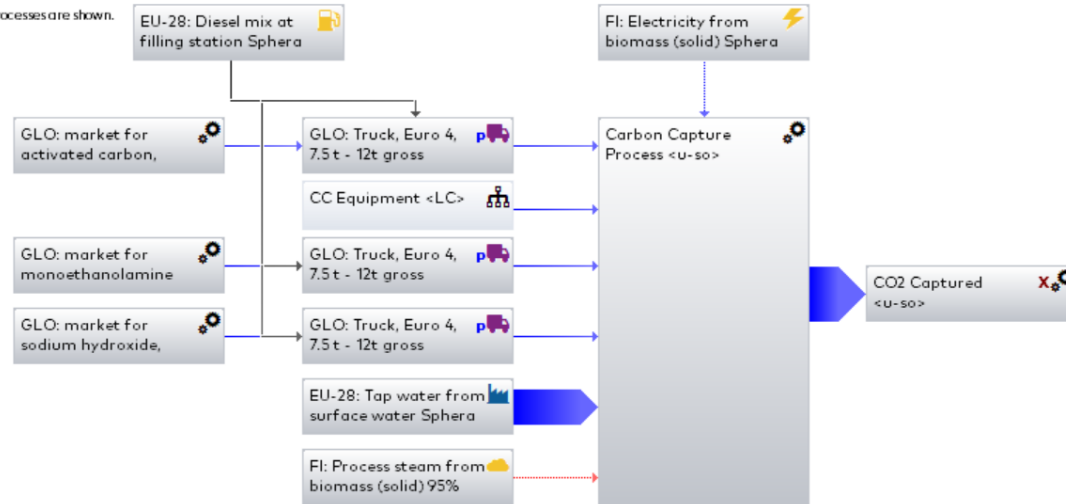


Figure A.9 Methanol synthesis process model

Methanol: Carbon Capture Process

Process plan: Mass [kg]

The names of the basic processes are shown.



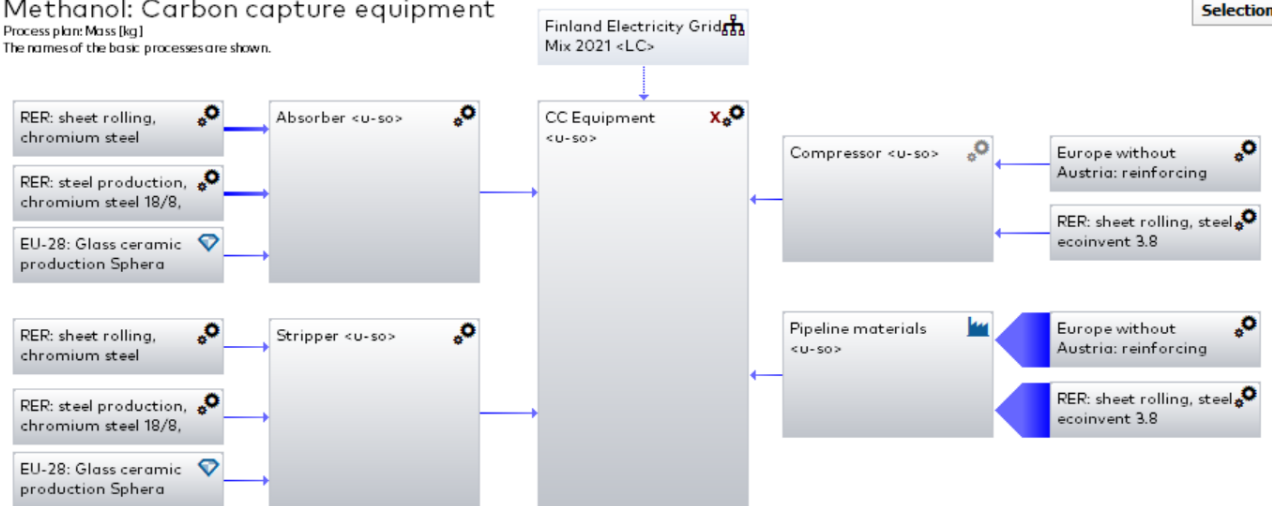
Selection:

Figure A.10 Carbon capture process model

Methanol: Carbon capture equipment

Process plan: Mass [kg]

The names of the basic processes are shown.



Selection: C

Figure A.11 Carbon capture equipment material model

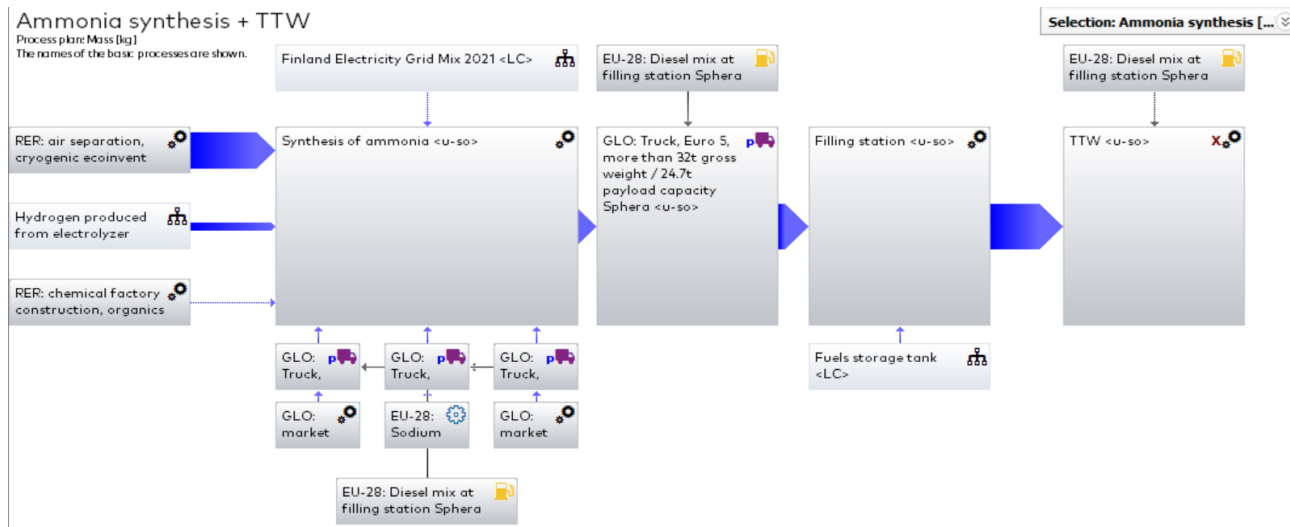


Figure A.12 Ammonia synthesis, delivery, and filling station (+tank-to-wheel) model



Figure A.13 Ammonia fuel storage tank material model

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