Deliverable 6.11

Report on environmental analysis – carbon footprint screening

Authors: Essi Paronen (VTT) and Katri Behm (VTT)

Deliverable due date: 30.11.2022

Deliverable submission date: 7.12.2022

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	
CON	Confidential, only for members of the Consortium	

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 875081. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research

Co-funded by the European Union

Clean Hydrogen Partnership

Table of Contents

1. Introduction

Fuel cell technologies are clean and efficient manner to produce electricity. They can be utilized in many different applications. They are reported to have less emissions compared with conventional combustion engines. (US Department of Energy, n.d.).

However, to verify the fuel cell sustainability advantages as new technologies arise, sustainability assessments such as Life Cycle Assessment (LCA) are needed. LCA as a method makes sure that no life cycle stage is excluded and that environmental burdens don’t shift along the value chain or environmental impact categories.

This document contains the preliminary estimation of the carbon footprint of the EMPOWER system. The study is a screening in which preliminary data is used to evaluate the carbon footprint in order to identify already in the technology development stage the main contributors of the carbon footprint of the EMPOWER system. To evaluate the potential of the EMPOWER system, the carbon footprint is compared with carbon footprint of system combined by diesel generator and air pump.

2. Life Cycle Assessment (LCA) as methodology

Life Cycle Assessment (LCA) means evaluating the potential environmental impacts of a product or a service. The assessment is an ISO standardized method. The standards of LCA are ISO 14040 “Environmental management – Life cycle assessment – Principles and framework” and ISO 14044 “Environmental management – Life cycle assessment – Requirements and guidelines”.

Carbon footprint of products (ISO 14067, 2018) standard provides principles, requirements and guidelines for the quantification and communication of the carbon footprint of products and services. Partial product footprints are also addressed. It is also possible to do calculations on organizational level. Carbon footprint calculation is based on life cycle assessment using the single impact category of climate change. The quantification and reporting of a carbon footprint of a product (CFP) in accordance with this technical specification is based on the principles of the LCA (ISO 14040, 2006; ISO 14044, 2006).

The LCA modelling is based on linking unit processes which are connected to each other with material or energy flows. For each process, inputs and outputs are defined which are then interconnected.

Life cycle assessment has several approaches. “Cradle to grave” approach starts from the very beginning or raw material acquisition and ends in final disposal and end-of-life treatment. It includes the production of raw materials and energy, manufacturing of the product, all transportations, use phase, and final disposal of the product or other end-of-life treatment. “Cradle to gate” and “cradle to customer” approaches are a little less thorough. They consider the life cycle until the production of the product (cradle to gate) or until the product has been transported to the customer (cradle to customer) but exclude the use phase and end-of-life treatments. In this project, the EMPOWER system includes the methanol manufacturing, distribution and use stage, but the fuel cell equipment manufacturing and disposal are excluded from the study. In the section 3.3 the system boundary of the EMPOWER project is presented.

Life cycle assessment has four stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results. Goal and scope stage defines the goal of the study, sets the system boundaries and lists the assumptions needed in the calculation. The life cycle inventory includes data collection and a balance calculation to all unit processes in the life cycle. The results of LCI are presented as inputs and outputs of the entire system. The LCIA stage converts the LCI results into impacts. One example of this is the carbon footprint calculation; the emitted greenhouse gases (GHG) from the inventory calculation are converted into global warming potentials (GWP) in the impact assessment stage. The final stage of LCA is interpretation of the results based on all three previous stages of the assessment. The results are represented per functional unit, which describes the need that is fulfilled with the product or service. Typical functional units are numbers of product (e.g. one car or a book) or amounts of product (e.g. 1000 MWh or 1 litre of diesel). The stages of the life cycle assessment are presented in Figure 1.

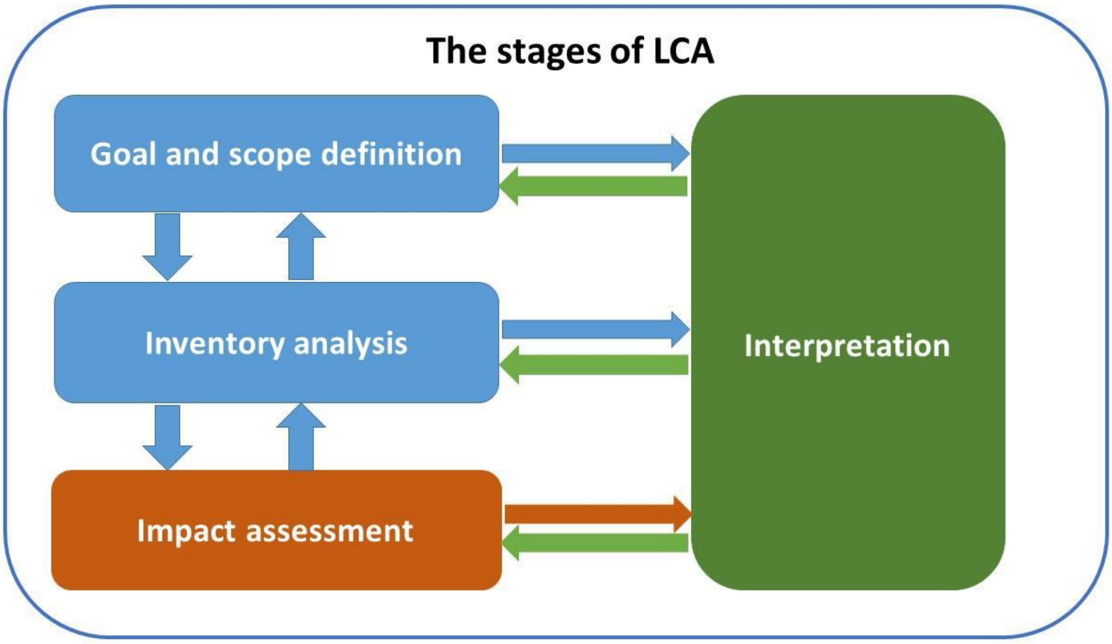

Figure 1. The four stages of life cycle assessment according to ISO 14040 (2006).

There are several impact assessment methods with different characterization, normalization and weighting factors. The LCA standards do not determine which impact assessment methods should be used in a study. The selection of the method should be done in the goal and scope definition phase (stage 1), considering the spatial and temporal aspects of the study. In this study, The Environmental footprint EF 3.0 method by the European Commission (European Commission, 2013) is applied.

3. Goal and scope

In this chapter the framework and definitions of the calculation is presented.

This study is a screening LCA where the carbon footprint of EMPOWER system is evaluated. The screening means that the most relevant processes are evaluated based on preliminary available data to have the first view on the sustainability of the technology. The results of the screening enable the technology developer to focus first on the most relevant sustainability aspects of the technology.

The infrastructure of the EMPOWER system is excluded because it is expected to have a minimum impact on the carbon footprint due to long expected lifetime of the equipment.

3.1 Goal

This study has two main goals:

1. Estimate the preliminary carbon footprint of the EMPOWER system for screening purposes
2. Compare the estimated carbon footprint with a conventional system of diesel generator and air pump in order to be able to evaluate the carbon footprint performance of the EMPOWER system

The comparison system of diesel generator and air pump is created to be able to compare the two functionalities, electricity and heat production, of the EMPOWER system with a conventional fossil-based technology.

The main audience of the study is the project consortium and specially the technology developers. This screening LCA's purpose is to provide important preliminary information about the carbon footprint of the EMPOWER system for technology development purposes.

3.2 Functional unit

The functional unit in a LCA study defines the qualitative and quantitative aspects of the function(s) and/or service(s) provided by the product being evaluated. In this study the functional unit is 1 MJ of produced electricity and 0,1 MJ of produced utilizable heat. The heat value is scaled based on the electricity production. The heat is included as well because it is a significant element that the EMPOWER system generates.

3.3 System boundary

In this section, the studied systems which are included in the LCA calculation are presented. More detailed case presentations are described in chapter 4.

The studied EMPOWER system is presented in the Figure 2. The included processes are:

- Methanol raw material extraction, production and distribution to user
- Deionised water production
- Use stage of the HT-PEMFC (High Temperature Proton Exchange Membrane Fuel Cells) system producing electricity and heat.

The methanol in this study is focusing on renewable alternatives and thus it is assumed to be produced from various biomass- and power-based sources. The methanol is the only input considered in the use stage since the EMPOWER system generates the electricity which it needs to run the operations.

The excluded elements are the physical devices and their construction materials, coolant used in the system, air flows within the EMPOWER system and possible waste in EMPOWER system, such as methanol or coolant containers. The coolant is excluded because it is re-used in the system and air flows because they do not generate emissions.

The EMPOWER system is simplified for this LCA and for instance, the device components such as burner, evaporator, compressor etc. are not presented in the Figure 2.

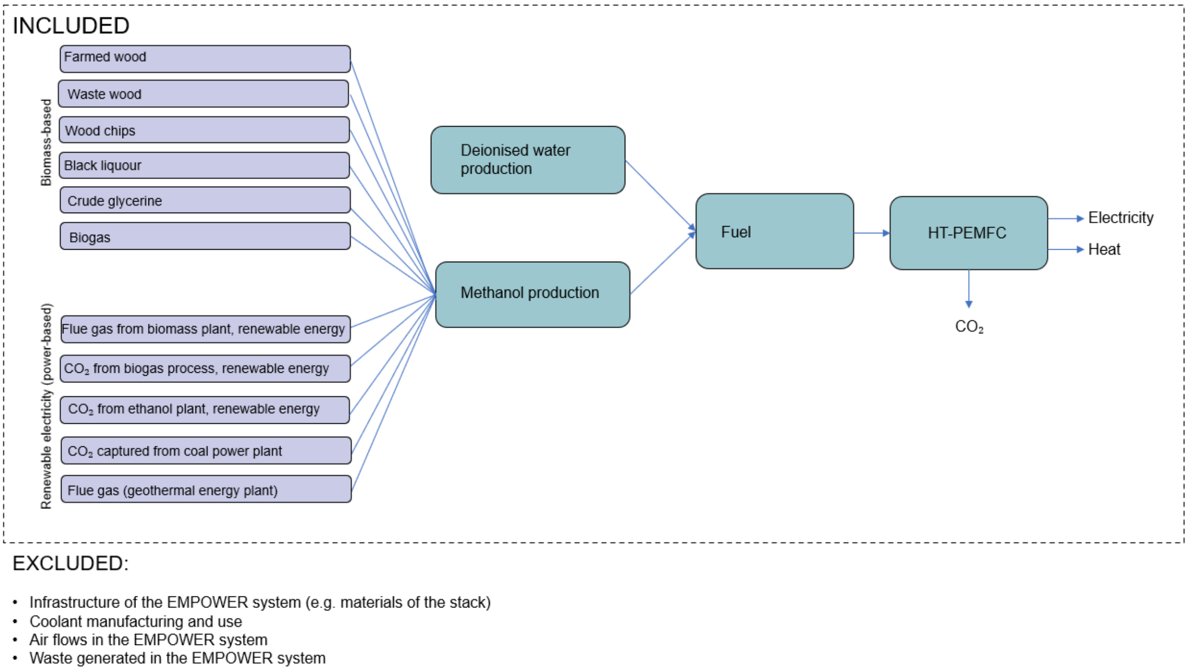

Figure 2. Included and excluded EMPOWER processes of the LCA screening.

Similarly, the system boundary of the comparison system, diesel generator and air pump, is presented in the Figure 3. Diesel generator represents the electricity production and air pump the heat generation. These both forms of energy are required to be included to be able to compare them with the EMPOWER system. The included processes are:

- Diesel raw material extraction, manufacturing and distribution to user
- Lubricant raw material extraction, manufacturing and distribution to user
- Refrigerant raw material extraction, manufacturing and distribution to user
- Use stage of the diesel generator and air pump.

In this system, also the infrastructure of the devices and generated waste (e.g. lubricant containers) is excluded.

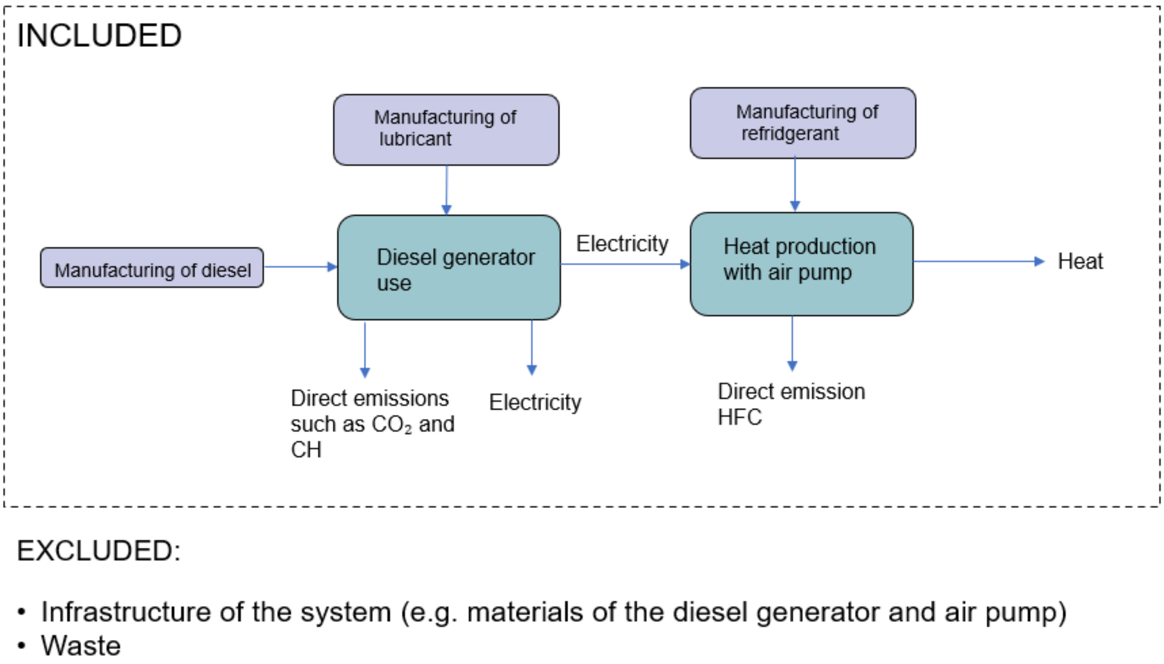

Figure 3. Included and excluded processes of the comparison system diesel generator and air pump.

3.4 Impact assessment method

The carbon footprint is calculated using the characterisation factors of EF 3.0 impact assessment method. The unit of carbon footprint is carbon dioxide equivalent (CO_2eq). According to Eurostat: “the carbon dioxide equivalent is used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential”. The characterisation factors for the most important greenhouse gas emissions are listed in the Table 1 below.

Table 1. Characterisation factors to carbon dioxide equivalent (CO_2eq) for the most important greenhouses gases in EF 3.0 impact assessment method.

Greenhouse gas	**Characterisation factor to CO_2eq**
Carbon dioxide, fossil	1
Carbon dioxide, biogenic	0
Methane CH_4, fossil	36,8
Methane CH_4, biogenic	34
Dinitrous oxide, N_2O	298

From the Table 1 it can be seen that the biogenic (also called non-fossil) carbon dioxide does not contribute to the carbon footprint. For this reason, it is relevant to differentiate the fossil and biogenic carbon dioxide emissions from the methanol carbon that is released in the EMPOWER system.

4. Studied systems

In this chapter the two studied systems, EMPOWER and diesel generator with air pump, are presented in more detail together with life cycle inventory (LCI) data. Additionally, the data sources are discussed and used assumptions presented.

4.1 EMPOWER system

As shown in Figure 2, the main components of the EMPOWER system are the biomass- and power-based methanol and the methanol-fuelled fuel cell system.

The utilized fuel in EMPOWER system consists of methanol and deionised water. To put if briefly, the fuel is inserted to the system and electricity and heat are generated with the hydrogen fuel cell stack. When the fuel cell system is in use, it releases carbon dioxide. Other released emissions are water and nitrogen (N_2), but these are excluded because they don't contribute to the carbon footprint.

The used inventory data for the EMPOWER system life cycle assessment can be seen in Table 2.

Table 2. Inventory data for the EMPOWER system LCA. The values are calculated for 1 MJ of produced electricity and 0,1 MJ of produced heat.

Input	Amount	Unit	Source
methanol	0,1134	kg	EMPOWER consortium
deionised water	0,0957	kg	EMPOWER consortium
Output	**Amount**	**Unit**	**Source**
electricity	1	MJ	EMPOWER consortium
heat	0,10	MJ	EMPOWER consortium
carbon dioxide, non-fossil	155,8	g	EMPOWER consortium

The carbon footprint of methanol raw material extraction, production, transport and distribution is retrieved from a report by IRENA and Methanol Institute (2021). The values used in this study are shown in Table 3. The IRENA and Methanol Institute (2021) source was chosen because it is recent, and it includes values from different feedstocks. In in the table 11 of the IRENA and Methanol Institute (2021) publication, carbon footprint values are collected from various literature sources. The values for biomass-based and power-based methanol are included. Fossil-based methanol was excluded because the focus of the project is in the renewable and power-based methanol. The listed reference articles in table 11 of IRENA and Methanol Institute (2021) which were available in English were browsed only on a high level due to the limited resources of this study.

The values listed in table 11 of IRENA and Methanol Institute (2021) include the life cycle stages from raw materials to final use. From this screening LCA's point of view, the used methanol carbon footprint values should include only the raw material extraction, processing, transport and distribution. The use stage would be the operation of the EMPOWER system where the methanol is inserted and use stage emissions would be generated. However, because the reported methanol carbon footprint reference values by IRENA and Methanol Institute (2021) include also the use stage, assumptions need to be made to match the scopes and to avoid double counting of the carbon footprint use stage emissions. Thus, it is assumed that the use stage carbon dioxide emissions of the EMPOWER system are zero because the use stage emissions of the methanol are already included in the values gathered by IRENA and Methanol Institute (2021). However, since the CO_2 emissions from the bio-based methanol are considered with a characterization factor of 0 (as described in Table 1), this does not affect the results. Only in the case of CO_2 capture from coal power plant, the emissions will impact the carbon footprint and thus occur in the "wrong" life cycle step.

The table 11 of IRENA and Methanol Institute (2021) contains various carbon footprint values for some of the feedstocks. In this screening LCA, only the minimum and maximum reported values of such feedstocks are included. If there is a single value for a certain feedstock, that value is utilized. The methanol carbon footprint values used in this study are listed in Table 3. In the same table, the carbon footprint values are shown in unit gCO_2eq/kg of methanol. These values are calculated from the original unit gCO_2eq/MJ used by IRENA and Methanol Institute (2021) by applying methanol's lower heating value 19,9 MJ/kg reported by IRENA and Methanol Institute (2021) in their table 10.

Table 3. Utilized biomass- and power-based methanol carbon footprint values in this study. This table is modified from table 11 of IRENA and Methanol Institute (2021).

Type	Feedstock	gCO_2eq/kg methanol	Original source in IRENA and Methanol Institute (2021)*
Bio-mass-based	Farmed wood	91,5-328,4	Chaplin, 2013 and RED II, Annex V, 2018
	Waste wood	105,5-449,7	Chaplin, 2013 and BLE, 2017
	Wood chips	416,1	Ecoinvent, 2019
	Black liquor	59,7-238,8	Chaplin, 2013 and Lundgren et al. 2017
	Crude glycerine	608,7	Chaplin, 2013
	Biogas	597-685,4	Majer and Gröngröft, 2010 and Chaplin, 2013
Power-based	Renewable electricity, flue gas from biomass plant	34,6-64,3	Chaplin, 2013 and Bud-denberg et al. 2016
	Renewable electricity, CO_2 from biogas process	10	Hoppe et al., 2018
	Renewable electricity, CO_2 from ethanol plant min	258,7-423,9	Matzen and Demirel, 2016 and Kajaste et al., 2018
	Renewable electricity, CO_2 cap-tured from coal power plant	658,7	Kajaste et al., 2019
	Renewable electricity, flue gas (geothermal energy plant)	240,8	CRI, 2020

* First source is the author(s) of the minimum value and second of the maximum value.

4.2 Diesel generator and air pump

As shown in Figure 3, the comparison diesel generator uses diesel and lubricant as input. The generator produces electricity which the air pump uses for heat generation. Additionally, refrigerant is also inserted to the air pump. Direct emissions arise both from the generator and air pump use. The input and output data for the diesel generator and air pump is from Ecoinvent version 3. The list of used Ecoinvent processes is available in Annex 1.

As seen in Annex 1, the chosen diesel generator is for 18,5 kW output and air pump for 10 kW output. These were chosen to match most the 5 kW output power of the EMPOWER system. Due to lack of data, it is assumed that there are no differences in the efficiencies or other technical characteristics of the generator of 18,5 kW vs. the 5 kW output of the EMPOWER system or air pump of 10 kW vs. 5 kW.

The average transport distances and modalities of the diesel, lubricating oil and refrigerant from producer to consumer is included in their respective Ecoinvent market process data.

In the original Ecoinvent process for diesel generator also waste mineral oil is generated. However, this is excluded from this study due to the limited scope and because the EMPOWER system LCA data does not include the waste generated by the system (such as methanol containers), neither.

5. Results and discussion

The results of both studied systems are presented in this chapter. First, the limitations of the study which should be taken into account when interpreting the results are presented.

5.1 Limitations of this study

In this study the methanol carbon footprint is from the study by IRENA and Methanol Institute (2021) as explained in chapter 4.1. VTT reports the values as they are and is not responsible of the assumptions and calculation decisions of the articles listed in Table 3. As mentioned before, the results are indicative and are highly dependent on the reference carbon footprint values listed in Table 3.

Due to the screening character of this study, the values gathered in Table 3 are not analysed in a thorough manner. However, some observations can be made. In some of the articles of the Table 3, negative carbon footprint values are reported because carbon dioxide capture is applied. The carbon dioxide capture is a rather new technology and many times considered in LCA in a manner that generates a negative carbon footprint. However, Langhorst et al. (2022) proposed LCA guidelines for carbon dioxide utilizations which is considered as the best state of the art guidelines. According to Langhorst et al. (2022), if the carbon footprint value is negative due to carbon dioxide capture (factor -1 is used in the calculations for carbon dioxide emissions), in the use stage, the carbon dioxide emissions should have a calculation factor of +1 and thus, considered as emissions, even if the CO_2 captured is biogenic.

According to VTT’s understanding, IRENA and Methanol Institute’s (2021) table 11 carbon footprint values are not compared with the guidelines of Langhorst et al. (2022). In the future, it should be taken into account that methanol carbon dioxide values are calculated and reported according to commonly agreed guidelines.

Also, the values in Table 3 most likely present the lower values of the carbon footprint where low-carbon renewable energy is used in the methanol production process. Utilization of fossil-based electricity could make the results of this study to look different.

5.2 Results

It should be noted that the results are indicative and contain preliminary data for carbon footprint screening purposes. The technology developers are able to benchmark the current carbon footprint level of the EMPOWER system with a conventional system and identify what is currently the main contributor to the carbon footprint. All the EMPOWER system elements are not included in the study as presented in the Figure 2. For example, the materials (infrastructure) of the devices are not included. In the future, a full LCA can address the limitations of this screening LCA. Recommendations for possible future LCA are presented in chapter 6.

The

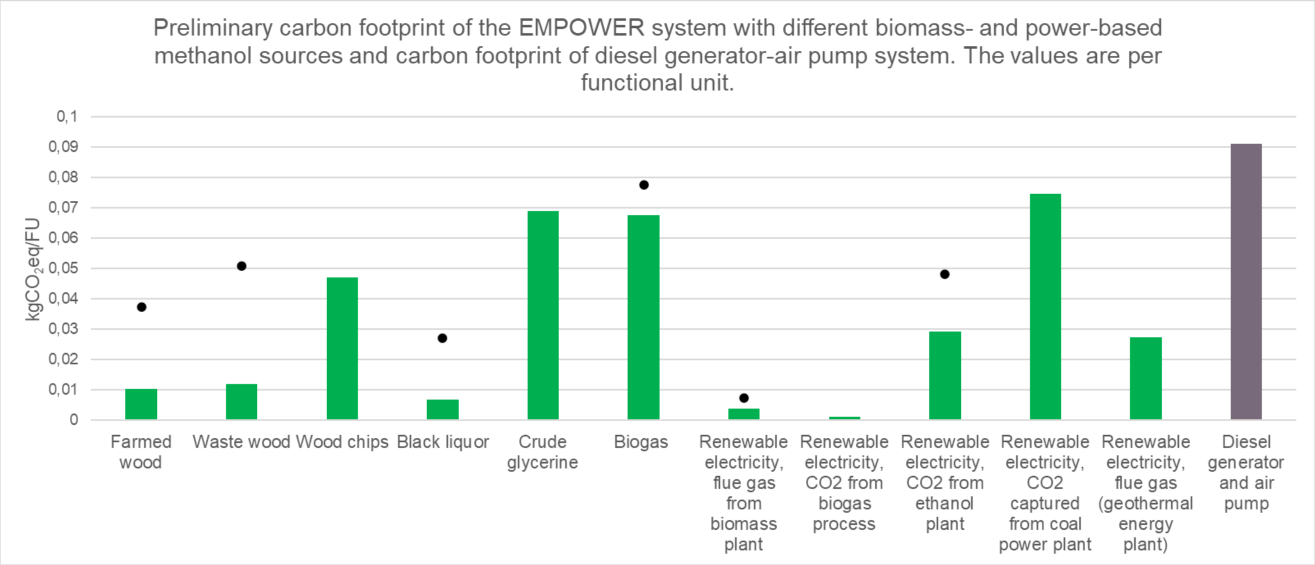

Figure 4 presents the carbon footprint as single value. More detailed breakdown of carbon footprint to different life cycle stages and processes is shown in Figure 5.

From

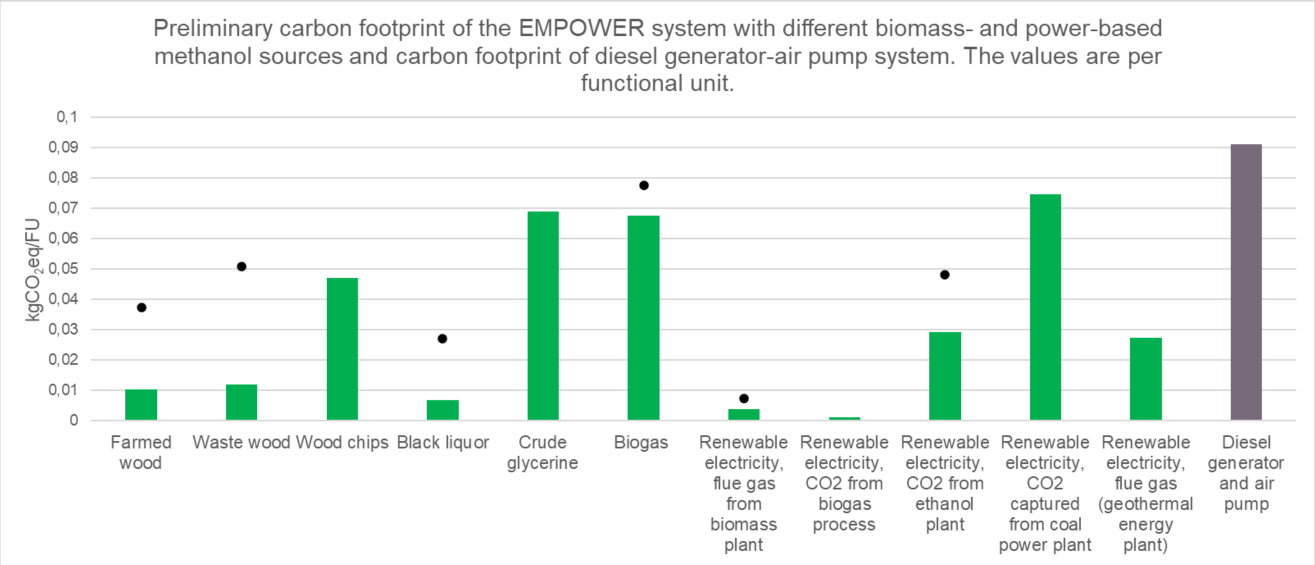

Figure 4 it can be observed that the EMPOWER system has a lower carbon footprint using any of the studied renewable methanol feedstock options than the diesel generator-air pump system. Based on the preliminary results, the lowest carbon footprint of the studied feedstocks is using captured carbon dioxide from biogas process with renewable electricity. Similarly, using methanol from flue gas from biomass plant using renewable electricity has the second lowest carbon footprint.

The highest EMPOWER carbon footprint is generated when crude glycerine, biogas or captured carbon dioxide from coal power plant using renewable electricity is used as methanol feedstock.

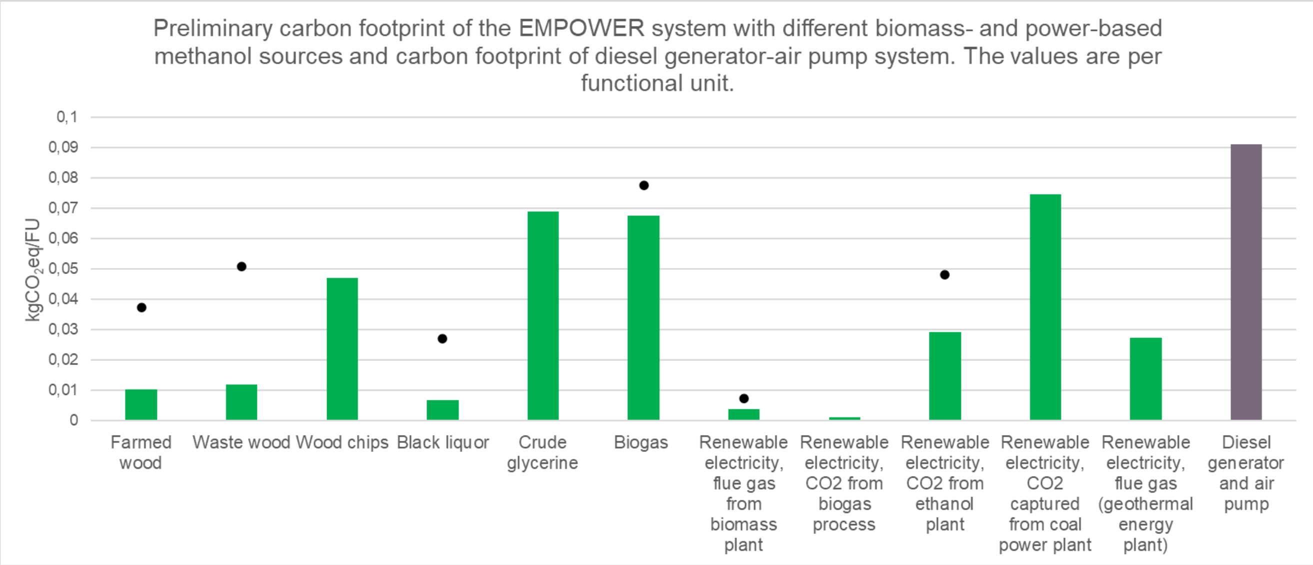

Figure 4. Preliminary carbon footprint of the EMPOWER system and diesel generator-air pump system per functional unit. The functional unit is 1 MJ of produced electricity and 0,1 MJ of produced heat. The black dot describes the maximum carbon footprint value when the maximum value of the methanol carbon footprint is used for the feedstock in question. The green bar in this case describes the minimum carbon footprint value when the minimum value of the methanol carbon footprint is used for the feedstock in question. Table 3 summarizes the applied methanol cradle to gate carbon footprint values of different feedstocks. If a methanol feedstock does not have a minimum and maximum carbon footprint value, only the green bar is visible.

Figure 5 shows the carbon footprint of the EMPOWER system and the comparison diesel generator-air pump system on process or life cycle stage level. From the Figure 5 it can be noted that for the EMPOWER system, the main contributor to the carbon footprint is the methanol production. More detailed information of the composition of the methanol carbon footprint is not available for this study because reference values of the carbon footprint are used in the LCA model as explained in the chapter 4.1.

For the diesel generator-air pump system, the main contributor to the carbon footprint is the use stage of the diesel generator, namely, the direct carbon dioxide emissions arising from using the generator.

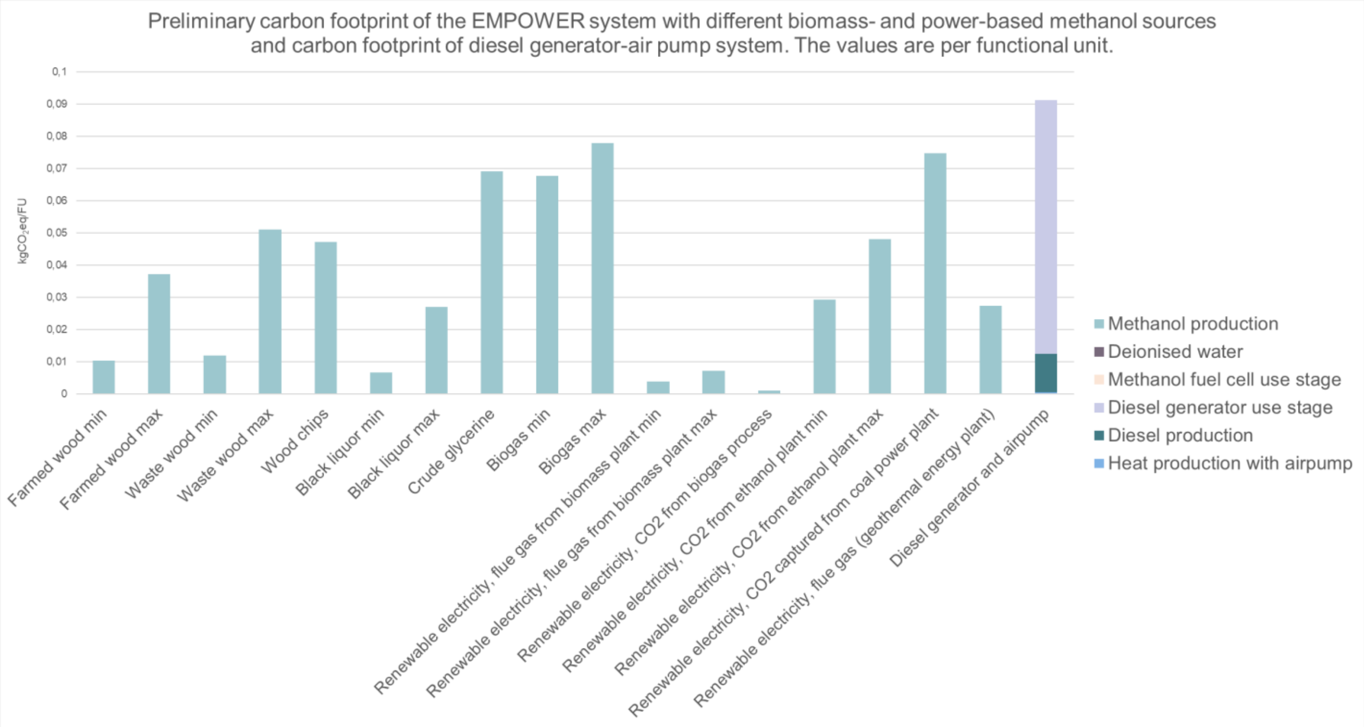

Figure 5. Preliminary carbon footprint of the EMPOWER system and diesel generator-air pump system with breakdown of the main processes and life cycle stages per functional unit. The functional unit is 1 MJ of produced electricity and 0,1 MJ of produced heat. EMPOWER values are for different methanol feedstock's minimum and maximum carbon footprint values. The methanol production includes the transport and distribution of the methanol. For example, the bar for "Farmed wood min" means that the methanol is produced from farmed wood and the lowest carbon footprint of the methanol is used. Table 3 summarizes the methanol production and distribution values of different feedstocks.

6. Conclusions

The conclusions presented in this chapter are preliminary. The used data for the EMPOWER system is an estimation based on the work carried out in this project. The results are highly dependent on the reference methanol carbon footprint values listed in Table 3. The reference values are from the study by IRENA and Methanol Institute (2021) as explained in chapter 4.1. VTT reports the values as they are and is not responsible of the assumptions and calculation decisions of the articles listed in the Table 3 More about the uncertainties related to the reported methanol carbon footprint values is available in chapter 5.1.

According to the screening LCA results of this study, the EMPOWER system using any of the studied biomass- or power-based methanol feedstocks has a lower carbon footprint than the diesel generator and air pump system. The lowest EMPOWER carbon footprint of the studied feedstocks is using captured carbon dioxide from biogas process with renewable electricity. Similarly, using methanol from flue gas from biomass plant using renewable electricity has the second lowest carbon footprint. The highest EMPOWER carbon footprint is generated when crude glycerine, biogas or captured carbon dioxide from coal power plant using renewable electricity is used as methanol feedstock. Still, the impact is 15% lower than for the reference case when methanol feedstock with highest carbon footprint, biogas, is used.

Based on this study, the EMPOWER system developers and other involved parties need to be aware of the cradle-to gate carbon footprint of the selected methanol source and of the selected assumptions behind the calculations, such as use of fossil and renewable electricity. As seen in the results of this study, the variation of the methanol cradle-to gate carbon footprint can be large. This highlights the importance of reporting methanol carbon footprint values in a reliable manner taking into account the carbon dioxide capturing and biogenic carbon calculation rules and transparent reporting.

This study is a preliminary screening study and, in the future, a full LCA its limitations can be improved. The recommended actions for the full LCA are:

- Include other impact categories than carbon footprint in the assessment to capture wider view on the sustainability and make sure that optimizing one impact category does not cause negative impact on other impact category.
- Including the production of both equipment, the fuel cell system and the diesel generator and heat pump reference, to include the use of (potentially rare) materials.
- Using primary data on the selected methanol source(s). This way a reliable value for the methanol's environmental impact can be calculated.
- Following available calculation rules for biogenic carbon and carbon capturing and reporting in a transparent manner
- Using primary diesel generator and air pump data with a similar energy production capacity and efficiency than the EMPOWER system.

7. References

Ecoinvent database. Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: http://link.springer.com/10.1007/s11367-016-1087-8 [Accessed 8.11.2022].

European Commission. (2013) Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations Text with EEA relevance. [online] Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32013H0179 [Accessed 15.11.2022]

Eurostat. Glossary: Carbon dioxide equivalent. [online] Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent#:~:text=A%20carbon%20dioxide%20equivalent%20or,with%20the%20same%20global%20warming [Accessed 15.11.2022]

IRENA and Methanol Institute. (2021) Innovation Outlook: Renewable Methanol. International Renewable Energy Agency, Abu Dhabi.

ISO 14040. (2006) Environmental management, life cycle assessment, principles and framework.

ISO 14044. (2006) Environmental management, life cycle assessment, requirements and guidelines.

ISO 14067. (2018) Greenhouse gases. Carbon footprint of products. Requirements and guidelines for quantification and communication'.

Langhorst, T. et al. (2022) Techno-economic Assessment & Life Cycle Assessment Guidelines for CO2 Utilization (Version 2). [online] Available at: https://dx.doi.org/10.7302/4190 [Accessed 16.11.2022]

US Department of Energy. (n.d.) Fuel Cells - Hydrogen and Fuel Cell Technologies Office. [online] Available at: https://www.energy.gov/eere/fuelcells/fuel-cells [Accessed 10.11.2022]

Annex

Annex 1: Used Ecoinvent processes

Table A1: Used Ecoinvent 3.8 process in the LCA. All processes are for system model "Allocation, cut-off by classification".

Data	Name in Ecoinvent	Geography
Heat production with air pump	heat production, air-water heat pump 10kW	Europe without Switzerland
deionised water	market for water, deionised	Europe without Switzerland
diesel	market group for diesel	RER
electricity generation using diesel generator	diesel, burned in diesel-electric generating set, 18,5 kW	GLO
lubricating oil	market for lubricating oil	RER
refrigerant	market for refrigerant R134a	GLO