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WP5 – "Logistics and Environmental Analysis"
D5.1 – "Preliminary screening of the environmental impacts of the FC genset"

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Executive Summary

This report summarises the screening life cycle assessment (LCA) of Proton-Exchange Membrane Fuel Cell (PEMFC) based power system developed in the EVERYWH2ERE-project. Actually, the scope of the project is to develop cost-effective, energy-efficient and durable "plug and play" FC gensets for temporal power supply at urban level to replace traditional diesel generators. The developed system uses hydrogen as its power source, and can be used for off grid electricity production for example in outdoor events and construction sites. The Fuel cell genset system consists of five units: the fuel cell subsystem, electronic components, gas management devices, H_2 tank and mechanical enclosure. Six environmental impacts were studied: global warming potential, acidification potential, eutrophication potential, photochemical oxidation potential, and abiotic depletion potential of elementary resources and fossil fuel resources. The results were compared to traditional diesel generator.

The 25 kW FC genset has been studied assuming a lifetime of 20 000, resulting to 500 MWh produced during the entire lifetime. The assessment results were calculated per MWh produced with three hydrogen production options, firstly with steam reforming from methane (SMR), secondly with hydrogen produced by electrolysis using European average energy (E-PEM) and thirdly with electrolysis using German wind energy (E-PEM-R).

The impacts from the FC genset in cases with SMR and E-PEM-R are significantly smaller in the acidification, eutrophication, and in the photochemical oxidation category than of the diesel generator. The global warming potential is also a bit lower than that of diesel generator in the SMR case and significantly lower in the E-PEM-R case. However, in the E-PEM scenario, the diesel generator has lower impact in all studied categories except eutrophication. The use stage of the fuel cell is nearly emission-free, which can be important especially when using the system in urban areas.

Since this was a screening LCA, the results are only preliminary and intended primarily to project internal usage: the results provide information for project partners to support decision-making and to see where the environmentally potential risks may be in the FC system. Thus,

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these results should not be considered final but only indicative. The calculation will be updated with more accurate data and with filled data gaps in a later stage of EVERYWH2ERE project, so the final comprehensive LCA results are available later.

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Abbreviations and acronyms

ADP	Abiotic depletion potential
AP	Acidification potential
BOM	Bill of materials
BoP	Balance of plant
CFP	Carbon footprint of a product
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EP	Eutrophication potential
E-PEM	Electrolysis with a proton exchange membrane
E-PEM-R	Electrolysis with a proton exchange membrane using renewable energy
FC	Fuel cell
FC1	Fuel cell case with hydrogen produced with steam reforming from methane (SMR)
FC2	Fuel cell case with hydrogen produced with electrolysis using European average energy (E-PEM)
FC3	Fuel cell case with hydrogen produced with electrolysis using German wind energy (E-PEM-R)
FCHJU	Fuel Cells and Hydrogen Joint Undertaking
GHG	Greenhouse gas
GWP	Global warming potential
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International standardization organization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
N_2O	Dinitrogen monoxide

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NO_x	Nitrogen oxides
POCP	Photochemical oxidation potential
SO_2	Sulphur dioxide

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1. Introduction

This public report is part of H2020-FCH-JU project "EVERYWH2ERE - Making Hydrogen affordable to sustainably operate Everywhere in European cities" and it was prepared within the framework of Work Package 5.

EVERYWH2ERE aims to demonstrate the reliability of using FC technologies in temporary power gensets replacing current state-of-the-art solutions mostly based on diesel engines, thus opening a niche but relevant market for FC technologies. During the whole project 8 PEMFC (4x25 kw and 4x100 kW) equipped containered "plug and play" gensets will be realized and tested through a pan-European demonstration campaign in a demonstration to market approach. The prototypes will be tested in construction sites, music festivals and urban public events all around Europe, demonstrating their flexibility and their.enlarged lifetime. Demonstration results will be widely promoted and they will be helpful for the promotion of replicability studies (for the use of gensets in further end-user contexts) and for the definition of a commercial roadmap and suitable business model for the complete marketability of the gensets within 2025

As starting report of WP5, the environmental impact of FC generators was assessed and then compared to that of diesel generators. The work was done by VTT's sustainability assessment experts. The assessment methodology was based on appropriate parts of HyGuide guidance document for performing LCA on Fuel Cells and Hydrogen Technologies assessing the environmental impacts throughout the value chain (according to the ISO 14040 and 14044 standards). Data collection for the different life cycle stages of the fuel cell system was made in cooperation with project partners.

Since this was a screening LCA, the results are only preliminary and intended primarily to project internal usage: the results provide information for project partners to support decision-making and to see where the environmentally potential risks may be in the FC system. Thus, these results should not be considered final but only indicative. The calculation will be updated with more accurate data and with filled data gaps in a later stage of EVERYWH2ERE project, so the final comprehensive LCA results are available later.

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2. Methodology and framework for Life Cycle Assessment (LCA)

2.1 Life Cycle Assessment as a method

Life cycle assessment (LCA) means assessing the potential environmental impacts of a product or a service. It 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".

Modelling of a products or services life cycle is based on interlinked unit processes that are connected to each other with material or energy flows. Each process consists of inputs and outputs, which connect the process to previous and following processes. 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.

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

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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.

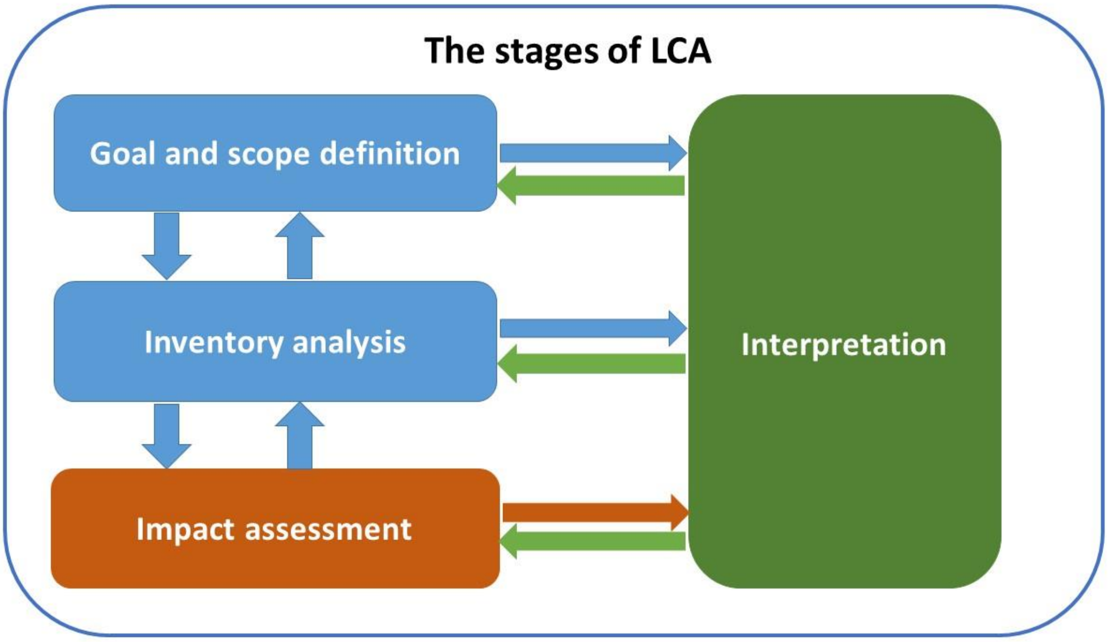

Figure 1. The four stages of life cycle assessment according to ISO 14040 (2006).

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. Some methods include only characterization factors but not normalization or weighting factors. These methods are called midpoint methods. The endpoint methods include also the normalization and weighting phase. E.g. CML 2001 impact assessment method can be mentioned as a midpoint method, and ReCiPe method includes both midpoint and endpoint –indicators.

According to Goedkoop et al. (2009) the midpoint indicators can be seen as more robust and less subjective than the endpoint indicators, but they might be difficult to compare or interpret due to their abstract meaning. The selection between midpoint and endpoint indicators has to be based on the goal of the study, and on which level of detail the impacts need to be studied.

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2.2 Environmental impact categories

For this project, six environmental impact categories were selected to be studied. The selection was based on the relevance of the impacts for the studied technologies. The selected categories include impacts on climate, air quality, water systems and resource availability. Other impacts (such as impacts on human health from particulate formation) may be considered in a later stage of the project.

2.2.1 Global warming potential (GWP)

Climate change caused by human actions has created a need to measure and mitigate greenhouse gas emissions. Carbon footprint is a concept that describes the greenhouse gas emissions and removals over the life cycle of a product expressed as CO_2 equivalents (CO_2e) (PAS2050, 2011). Benefits of carbon footprint as an indicator are that it is easily understandable, globally interesting, broadly applicable and easy to implement for different strategies (Alvarez et al., 2016).

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).

Life cycle assessment using climate change as the single impact category creates a method for carbon footprint assessment, facilitates performance tracking in GHG emissions reduction and supports reporting and communication of carbon footprint information. Double counting of emissions and removals is avoided within both the studied product system and other product systems (in the context of allocation). Public communication of carbon footprints supports the providing of information to consumers and other interested parties as well as shows company

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commitment to address climate change challenges. The options for carbon footprint communication are external communication report, performance tracking report, CFP label and CFP declaration (ISO 14067, 2018).

Carbon footprint study calculates the contribution of the studied product to global warming potential. The most important greenhouse gases are fossil carbon dioxide (CO_2), methane (CH_4) and dinitrogen monoxide (N_2O). The impacts from different greenhouse gases are converted into carbon dioxide equivalents (CO_2e) by multiplying the inventory results of each greenhouse gas with conversion factors given by Intergovernmental Panel on Climate Change (IPCC 2013). The factors describe the global warming potential of emissions within the next 100 years, which is the most typical time frame used. The CO_2 equivalents are then summed together and reported as carbon footprint. The factors for the most important greenhouse gases are reported in Table 1. It shows that the impacts of different greenhouse gases on climate change vary so notably per physical unit, that they cannot be directly compared and summed together at the inventory result level, but need to be converted into the impact assessment level instead (Fang and Heijungs, 2015).

Table 1. Conversion factors of the most important greenhouse gases to carbon dioxide equivalents for 100 year perspective (IPCC, 2013).

	Conversion factor by IPCC
Carbon dioxide, CO_2	1
Methane, CH_4	28 / 30
Dinitrogen monoxide, N_2O	265

The most important source of GHG emissions in carbon footprint calculations is often found in energy solutions. Energy production and consumption in forms of electricity, heat or fuels should be studied in high level of detail. In addition, transportation and selection of raw materials play an important role in the calculations. Like in the LCA calculations, also the results of footprint calculations can be divided into life cycle steps, and thus the most important emission sources can be easily found.

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2.2.2 Acidification potential (AP)

Acidification is caused by sulphur dioxide and nitrogen oxide emissions (Acero, Rodríguez and Ciroth, 2016.). These oxides react with the existing steam in the atmosphere and form acids which fall back to the earth in the form of rain or snow, or as dry deposits. Acidification damages environment e.g. by reducing forest development and in aquifer ecosystems, such as lakes, acidification is apparent in the disappearance of some living organisms. In addition, constructions and buildings may be damaged as a result of the effects of acid rain. Acidification potential is expressed in sulphur dioxide equivalents (SO_2).

2.2.3 Abiotic depletion of resources potential (ADP)

Abiotic depletion of elements and fossil fuels (potential) measure the consumption of non-biological resources (Acero, Rodríguez and Ciroth, 2016). These resources include e.g. minerals, metals and fossil fuels. The scarcity of the substance depends on the amount of resources available and the extraction rate. The consumption of elements (ADP Elements) is reported as antimony equivalents while the fossil fuel depletion (ADP fossil fuels) is reported as MJ.

2.2.4 Eutrophication potential (EP)

Eutrophication happens when organic compounds and nutrients are enriched in water ecosystems (Acero, Rodríguez and Ciroth, 2016). This increases production of plankton, algae and other water plants with the resulting reduction in water quality. In this case the main sources related to this phenomenon are nitrogen and phosphorous. A secondary effect is the decomposition of dead organic material, a process which consumes oxygen and may result in anaerobic environments. The eutrophication potential is expressed as nitrous oxide (NO_x) equivalent in CML (2016).

2.2.5 Photochemical ozone creation potential (POCP)

Photochemical oxidation potential or photochemical ozone creation potential (POCP) is also known as summer smog (Acero, Rodríguez and Ciroth, 2016). While ozone is protective in the stratosphere, it is toxic to humans in ground level in high concentration. Photochemical ozone,

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also called “ground level ozone”, is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. The main reasons for this impact are the emissions of carbon monoxide, sulphur dioxide, nitrogen oxide, ammonium and non-methane volatile organic compounds (NMVOC). The impact is reported as equivalent kg of ethene (ethylene).

2.3 FC-HY guides

FC-Hy Guides are public guidance documents for performing LCA on fuel cells (Masoni and Zamagni, 2011) and hydrogen production technologies (Lozanovski, Schuller and Faltenbacher, 2011). They are two parts of the public deliverable D3.3 from an EU-project called “FC Hy Guide”. These documents are based on ISO standards on life cycle assessment (See also Chapter 2.1) and build on the International Reference Life Cycle Data System (ILCD) through the European Platform of LCA. These two documents are especially aimed for projects funded by the Fuel Cells and Hydrogen Joint Undertaking (FCHJU), by giving technical guidance on functional units, system boundaries, allocation rules, and other relevant issues.

The FC-HY guide for fuel cells requires the LCA studies to be considered as a cradle-to-gate assessment, with an optional inclusion of the end-of-life stage. This means that the manufacturing of the fuel cell stack and balance of plant (BoP) needs to be considered, as well as the operation stage of the fuel cell. The system boundaries are presented in Figure 2.

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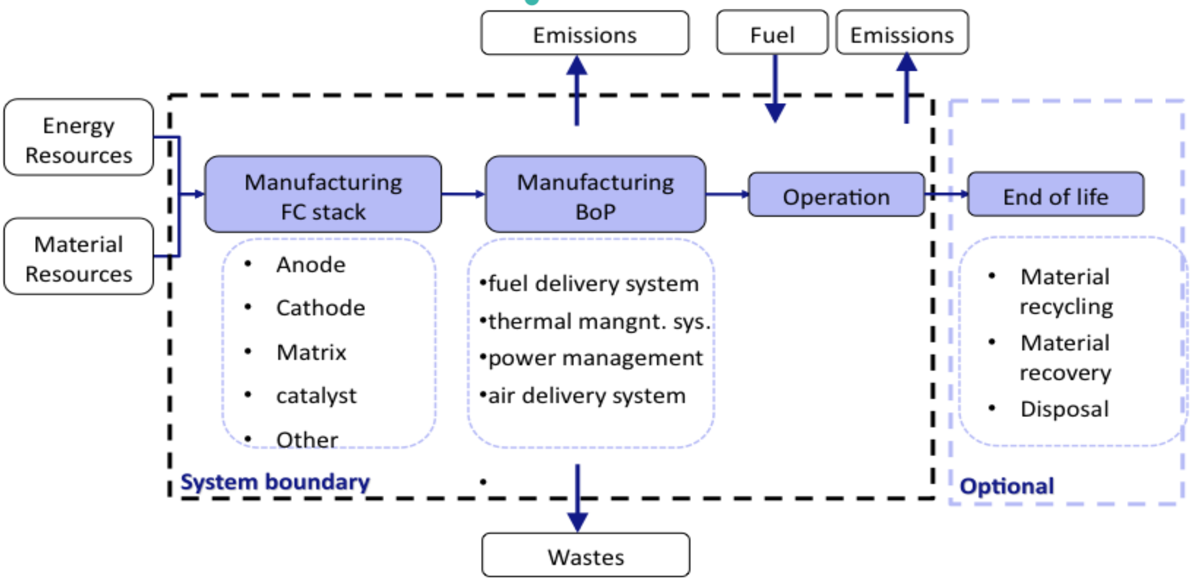

Figure 2. System boundaries and processes for fuel cell systems suggested in the FC-HY guide for fuel cells (Masoni and Zamagni, 2011).

The system boundaries of the hydrogen delivery chain are presented in the FC-Hy guide for hydrogen production systems (Lozanovski, Schuller and Faltenbacher, 2011). Again, the cradle-to-gate boundary is mandatory, while the distribution to the usage location is optional. The boundaries are presented in Figure 3.

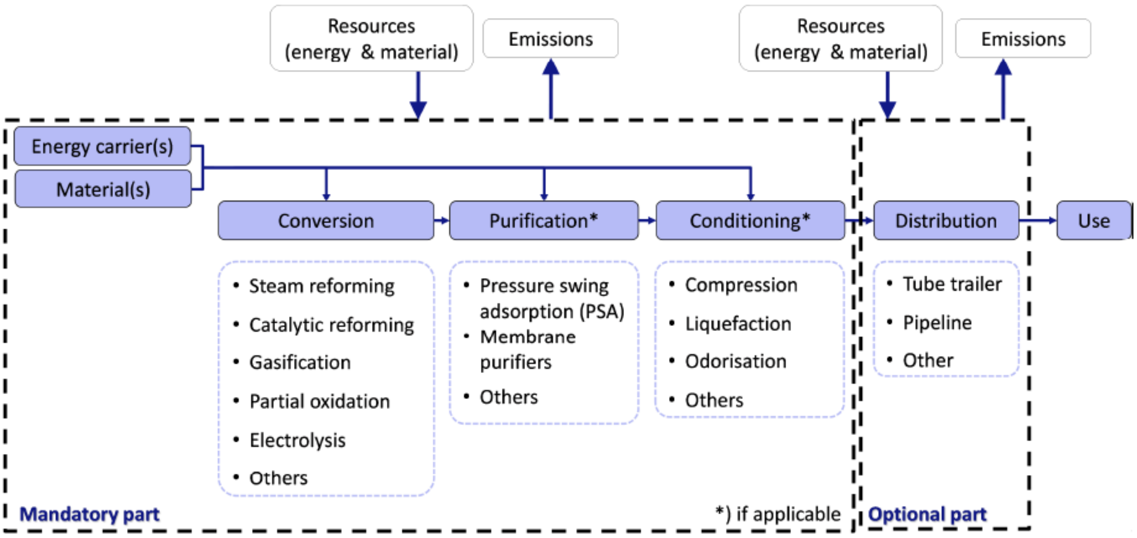

Figure 3. System boundaries and processes for the hydrogen delivery chain suggested in the FC-Hy guide for hydrogen production systems (Lozanovski, Schuller and Faltenbacher, 2011).

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Both of the guidance documents have requirements considering the data collection, which is often one of the most difficult tasks in LCA calculations. The documents state that the data collected must be site specific primary data, which is valid for the reference time of the study, and which reflects the technology actually used. All data gaps and their filling must be clearly documented and explained.

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3. Description of the study

3.1 Fuel Cell system

3.1.1 Fuel cell genset

The Proton-Exchange Membrane Fuel Cell (PEMFC) genset system developed in the EVERYWH2ERE project consisted of five units: the fuel cell subsystem, gas management devices, H_2-tank, electronic components and mechanical enclosure. The data about components and materials used in the different units were collected from all project partners to a single excel file. *Powercell Sweden Ab* provided data for the fuel cell subsystem, *Linde Ag* collected data for the gas management devices, *MAHYTEC* was responsible for the H_2 tank, *Genport* and *FRIEM* delivered data for the electronic components and *THT Control Oy* was responsible for the mechanical enclosure to complete the genset. Data collection was done during autumn 2018 and spring 2019.

The bill of materials (BOM) of the FC genset was produced based on the collected data and WP1 output and it is presented in Table 2. There were some plastics that while listed in the BOM, there was no production data available for them. These are grouped as unspecified and are marked in red text in the table below. Ruthenium is presented on its own but in the calculations, it is treated as platinum. Carbon felt is treated as graphite, as there was no production data available for carbon felt as such. Aluminum is assumed to be 100% primary aluminum. The total amount of missing materials was c. 1 kg, which is approximately 0,04 % of all the materials used in the FC genset and thus the impact of the missing materials can be considered negligible.

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Table 2. Bill of materials for the FC genset. The numbers may not match due roundings.

Materials	Fuel Cell Subsystem	Gas Management Devices	Electronic Components, I	Electronic Components, II	H2 tanks (3 pcs)	Mechanical Enclosure	Total amount
Metals	**[g]**	**[g]**	**[g]**	**[g]**	**[g]**	**[g]**	**[kg]**
steel, stainless	55270	81730	0	0	8950	0	146
aluminium	110050	25	200	13390	5530	0	129
steel, low-alloyed	604	425000	0	548600	0	1500000	2474
copper	0	252	2420	53300	0	0	56
platinum	37	0	0	0	0	0	0,039
ruthenium	13	0	0	0	0	0	0,013
Plastics							
polyvinylchloride	0	0	900	0	0	0	0,9
polyethylene, high density	0	4160	0	0	21280	0	25
epoxy resin insulator, Al2O3	1050	0	0	0	137120	0	138
polycarbonate	450	0	0	0	0	0	0,45
polyurethane	0	3288	0	0	0	25000	28
nylon 6	74	1565	5550	0	0	0	7
unspecified	0	0	0	1040	0	0	1,04
Electrical components							
printed wiring board, through-hole mounted, Pb free	0	0	1040	0	0	0	1,04
battery				162900			163
capacitor, for surface mounting	0	0	0,0	14450	0	0	14
Others							
silicone product	0	0	0	0	11	0	0,011
carbon felt	1880	0	0	0	0	0	2
ethylene glycol	17						0,017
water	17						0,017
tetrafluoroethylene	822	3	0	0	0	0	0,82
glass fibre	32	0	0	6300	0	0	6
synthetic rubber	0	0	0	0	0	20000	20
carbon fiber	0	0	0	0	390260	0	390
carbon black	145	0	0	0	0	0	0,15
alkyd paint, without solvent	0	0	0	0	0	10000	10
TOTAL WEIGHT [kg]	**171**	**516**	**10**	**800**	**563**	**1555**	**3615**

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3.1.2 Hydrogen production and consumption

In addition to the materials presented above, the use stage of the system uses hydrogen to produce electricity. The 25 kW genset system studied in this analysis has a lifetime of 20 000 h thus enabling the production of 500 000 kWh of energy during that time. The hydrogen used in the system can be produced in several different ways. Since it was expected that the hydrogen production would have a big impact on the results, tree different cases for hydrogen production were considered in this study. In the first case, hydrogen is produced from natural gas by steam methane reforming (SMR, later in the results describes as FC1). In the second case, hydrogen is produced with electrolysis with a proton exchange membrane (E-PEM) using average European market electricity (later in the results described as FC2). In the third case (FC3), hydrogen is produced similarly to FC2 but with renewable energy (E-PEM-R). In this case, German wind power is used as the source of electricity. The hydrogen production was modeled by VTT based on information from an article by Mehmeti et al (2018), and the main assumptions for hydrogen production are presented in Table 3. The resources consumed in each hydrogen production method were modeled in the life cycle calculation with SULCA along with the rest of the fuel cell value chain.

Table 3. Resources required to produce 1 kg of hydrogen with different production methods (Mehmeti et al. 2018)

Hydrogen production method	SMR (FC1)	E-PEM (FC2)	E-PEM- R (FC3)
Natural gas [MJ]	165	-	-
Electricity [kWh]	1,11	54,6	54,6
Water [kg]	21,87	18,04	18,04

It is assumed that the genset then transforms hydrogen into electricity with a 45 % efficiency. There is an additional loss of 0,5 % of the hydrogen during purging. Hydrogen has a lower heating value of 33,3 kWh/kg H_2. Therefore, an amount of 33 534 kg hydrogen is needed in order to produce 500 MWh energy during the systems lifecycle. The system runs with three hydrogen tanks that can deliver 4,6 kg H_2 each. The tanks are replaced and/or refilled multiple times during the genset's lifetime. Each tank has a lifetime of 5 000 cycles and a total of 7252 tanks of hydrogen is needed to produce the 500 000 kWh of electricity. In order to model the use of hydrogen tanks, it was decided to take into account the manufacturing of three tanks and

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assume that they are constantly refilled and therefore no new tanks enter the system during its lifetime.

The end of life stage where the equipment is disassembled and the materials are recycled or disposed of in some other way was left out of the study due to lack of data and due to the "optional" status of that life cycle stage defined in the FC-Hy documents. Therefore, the system boundaries of the performed LCA can be considered as a cradle-to-end of utilization study.

3.1.3 Life cycle modeling of the Fuel Cell genset

The life cycle of the FC genset was modelled with an LCA calculation tool called SULCA[1]. The functional unit for the calculations was chosen to be 1 MWh electricity produced. The flowsheet of the genset system is shown in Figure 4. The life cycle model is divided into ten parts with distinct colors:

- electronic components I (forest green) meaning control electronics
- electronic components II (light blue) meaning power electronics
- FC subsystem (yellow) is the fuel cell itself plus a stack
- gas management devices (red)
- H_2 tank (orange)
- mechanical enclosure (mustard)
- use stage (purple)
- maintenance (pink)
- hydrogen manufacturing (turquoise)
- hydrogen transport (brown)

[1] https://www.simulationstore.com/sulca

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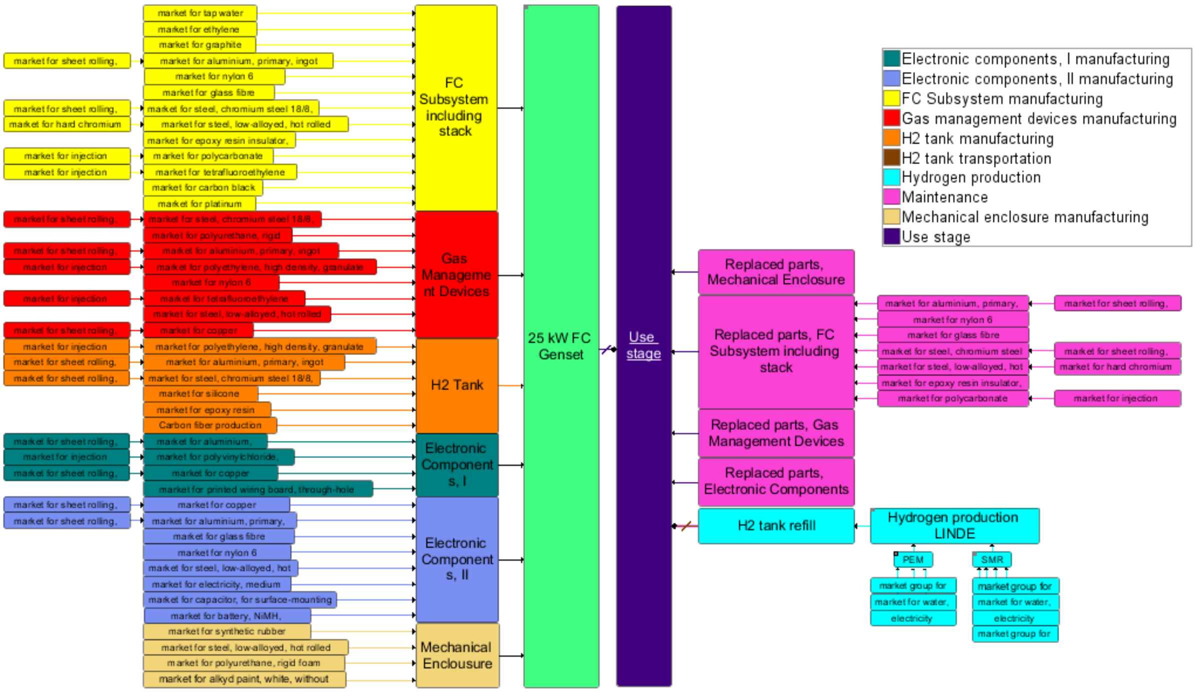

Figure 4. Flow sheet of the FC genset system

The material production data was collected from the commercial database Ecoinvent 3.5. The allocation method used was “Allocation, cut-off by classification”. The list of used datasets is presented in Annex I. Transportation of the materials and/or components during the manufacturing stage were not considered in the study due to the expected small importance. However, transportation of the genset to its place of utilization and refill times was taken into account, assuming 100 km transportation in one direction with 16-32 metric ton EURO 6 lorry.

The main assumptions and constant values used in fuel cell genset modeling are presented in Table 4.

Table 4. Assumptions and constant values used in fuel cell modelling.

Topic of assumption	Value assumed
Power of the FC system	25 kW
Life time of the FC system	20 000 h = 500 MWh
Functional unit	1 MWh electricity
Efficiency of the FC system	45 %

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Hydrogen heating value	142 MJ/kg = 39,4 kWh/kg
Hydrogen from one tank	4,6 kg (350 bar)
Life time of hydrogen tank (3 pcs)	5 000 cycles (or 20 years)
Life time of FC stack	10 000 h
Life time of electronic components	100 000 h (N.A.)
Life time of gas management devices	5 years (N.A.)
Life time of storage frame	15 years (N.A.)
End of life	Not considered
Hydrogen tank transportation	EURO 6 lorry 16-32 mton 200 km (100 km one direction)
Hydrogen production methods	• Steam methane reforming • Electrolysis with proton exchange membrane with European market electricity (E-PEM) • Electrolysis with proton exchange membrane with wind electricity (E-PEM-R)
Carbon fiber GWP	31 kg CO_2e/kg
Ruthenium	Production assumed to be the same as of platinum
Nafion	Production assumed to be the same as of PTFE

3.2 Diesel generator as comparison

In this study, the FC genset was compared to diesel generator. The data for diesel generator was collected from Ecoinvent 3.5 database. No data was available for generators with 25 kW electrical power output, so instead a generator with 18,5 kW power output was scaled up to represent a 25 kW generator. The original dataset of diesel genset was described in Ecoinvent as "a rough estimation of the production of diesel-electric generating set which can be attached to a reefer". Thus, it is not originally for the same purpose as the fuel cell genset, but this was the best available data to be used as a reference case at this point. The scaling was done by VTT by multiplying the manufacturing inputs, fuel consumption and emissions by a scaling factor based on the power and operating time of the genset.

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The life cycle of the diesel generator includes production of the generator, production of diesel used during the lifetime and the use stage, where the diesel was burned in the generator. The amount of diesel needed per kWh was 0,24 kg in the Ecoinvent dataset, which means that 120000 kg diesel was needed in order to produce 500 MWh with the diesel genset. The transportations of the materials/components and of the diesel generator are taken into account in the Ecoinvent datasets used. The transportation of diesel was assumed to be 100 km both ways with a 16-32 metric ton EURO 6 lorry. Similarly to the FC genset life cycle, the end-of-life-stage was not included in this study. The flowsheet of the diesel generator can be seen in Figure 5.

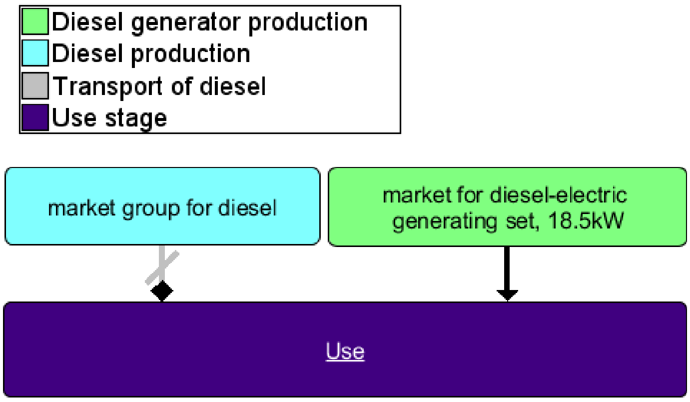

Figure 5. Flow sheet of diesel generator.

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4. Results of the screening LCA

4.1 Results as tables

The results of the impact assessment for the 25 kW FC genset system and the diesel generator per 1MWh electricity produced are presented in the tables below. The CML impact assessment method updated in August 2016 (CML 2016) was used in this study. The results include acidification potential (AP), global warming potential (GWP), eutrophication potential (EP), photochemical oxidation (summer smog) potential (POCP), and abiotic depletion potential (ADP) of elementary and fossil fuel resources. Table 5 shows the impact assessment results for genset manufacturing and maintenance which are the same for all cases, FC 1, FC 2 and FC 3. The results of the full life cycle with hydrogen production and use stage are shown in the following tables: Table 6 shows the impact assessment results for the FC genset with hydrogen from SMR, Table 7 with hydrogen from E-PEM and Table 8 with hydrogen from E-PEM-R. Diesel generator impact assessment results are presented in Table 9.

Table 5. Impact assessment results for genset manufacturing and maintenance in all cases per MWh electricity produced. The results may not match due to roundings.

	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]	AP [kg SO_2 eq.]	EP [NO_x eq]	GWP [kg CO_2e]	POCP [kg ethylene eq.]
Electronic components, I manufacturing	0,000041	3	0,0029	0,0011	0,19	0,00021
Electronic components, II manufacturing	0,00104	154	0,59	0,054	11	0,027
FC Subsystem manufacturing	0,00026	95	0,28	0,026	6	0,012
Gas management devices manufacturing	0,000042	45	0,014	0,01	3	0,0013
H_2 tank manufacturing	0,000010	22	0,0068	0,0041	25	0,00054
H_2 tank transportation	0,00024	1169	0,18	0,13	76	0,0116

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Mechanical enclosure manufacturing	0,000073	94	0,029	0,022	6	0,0034
Maintenance	0,000008	12	0,0042	0,0027	0,83	0,00022
Total	**0,0017**	**1593**	**1,11**	**0,25**	**129**	**0,056**

Table 6. Impact assessment results per MWh electricity produced for full life cycle of FC genset with hydrogen from steam methane reforming (FC 1, SMR, case 1). The results may not match due to roundings.

SMR	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]	AP [kg SO_2 eq.]	EP [NO_x eq]	GWP [kg CO_2e]	POCP [kg ethylene eq.]
Genset manufacturing and maintenance	0,0017	1593	1	0,25	129	0,056
Hydrogen production	0,000057	13430	0,54	0,44	517	0,034
Use stage	0,000001	3	0,00046	0,00034	0,19	0,000029
Total life cycle	**0,0018**	**15026**	**2**	**0,69**	**646**	**0,09**

Table 7. Impact assessment results per MWh electricity produced for full life cycle of FC genset with hydrogen from electrolysis using European market electricity (FC 2, E-PEM, case 2). The results may not match due to roundings.

E-PEM	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]	AP [kg SO_2 eq.]	EP [NO_x eq]	GWP [kg CO_2e]	POCP [kg ethylene eq.]
Genset manufacturing and maintenance	0,0017	1593	1	0,25	129	0,056
Hydrogen production	0,00043	24500	9	8	1589	0,31
Use stage	0,000001	3	0,00046	0,00034	0,19	0,000029
Total life cycle	**0,0021**	**26096**	**10**	**8**	**1718**	**0,36**

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Table 8. Impact assessment results per MWh electricity produced for full life cycle of FC genset with hydrogen from electrolysis using German wind electricity (FC 3, E-PEM-R, case3). The results may not match due to roundings.

E-PEM-R	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]	AP [kg SO_2 eq.]	EP [NO_x eq]	GWP [kg CO_2e]	POCP [kg ethylene eq.]
Genset manufacturing and maintenance	0,0017	1593	1	0,25	129	0,056
Hydrogen production	0,0053	1438	1	0,47	104	0,060
Use stage	0,000001	3	0,00046	0,00034	0,19	0,000029
Total life cycle	**0,0070**	**3034**	**2**	**0,72**	**233**	**0,12**

Table 9. Impact assessment results per MWh electricity produced for the diesel generator (DG). The results may not match due to roundings.

	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]	AP [kg SO_2 eq.]	EP [NO_x eq]	GWP [kg CO_2e]	POCP [kg ethylene eq.]
Diesel generator manufacturing	0,00017	62	0,03	0,02	5	0,002
Diesel production	0,00011	12540	1	0,52	124	0,080
Transport of diesel	0,000024	119	0,02	0,01	8	0,001
Use stage	0,000009	224	8	17	787	0,225
Total life cycle	**0,00032**	**12944**	**9**	**17,6**	**923**	**0,31**

As the tables 6-8 show, the manufacturing of hydrogen plays an important role and affects the results remarkably.

4.2 Results as figures by life cycle stages

The results are also shown in the following figures where the lifecycle has been divided into four stages only: manufacturing of the FC genset or diesel generator including maintenance; fuel production; fuel transportation; and use stage. It can be seen from Figure 6 that the global

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warming potential is mainly caused by hydrogen production process in FC cases, i.e. natural gas production in FC1 and electricity production in FC 2 and FC 3. The carbon footprint of diesel generator based electricity comes mainly from the use stage, i.e. burning of diesel. The impact from the use stage of the fuel cell systems is only caused by the transportation of the genset to the usage location.

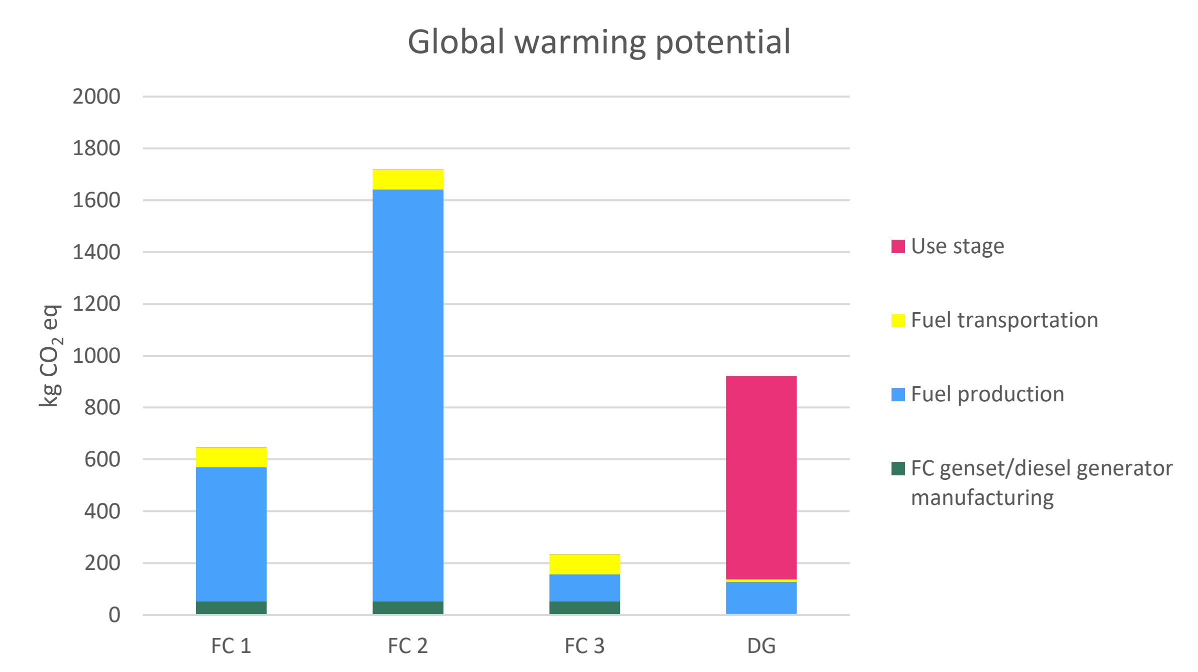

Figure 6. Global warming potential results per MWh electricity produced with FC system with three different hydrogen production options and with the reference diesel generator.

Figure 7 shows the abiotic depletion potential of elements. Abiotic depletion of elements in FC gensets is mainly caused by the rare metals and minerals used in the value chains of electronic components like capacitors. FC 3 main contributor is the production of the wind power plant used for electricity production for hydrogen production. Diesel generator manufacturing is the main cause for its ADPe impacts. Since the diesel generator is lighter than the FC genset (diesel generator weighs 817 kg and FC genset 3600 kg) and does not need as much rare metals as the FC genset, the total impact in this category is lower than all the FC cases.

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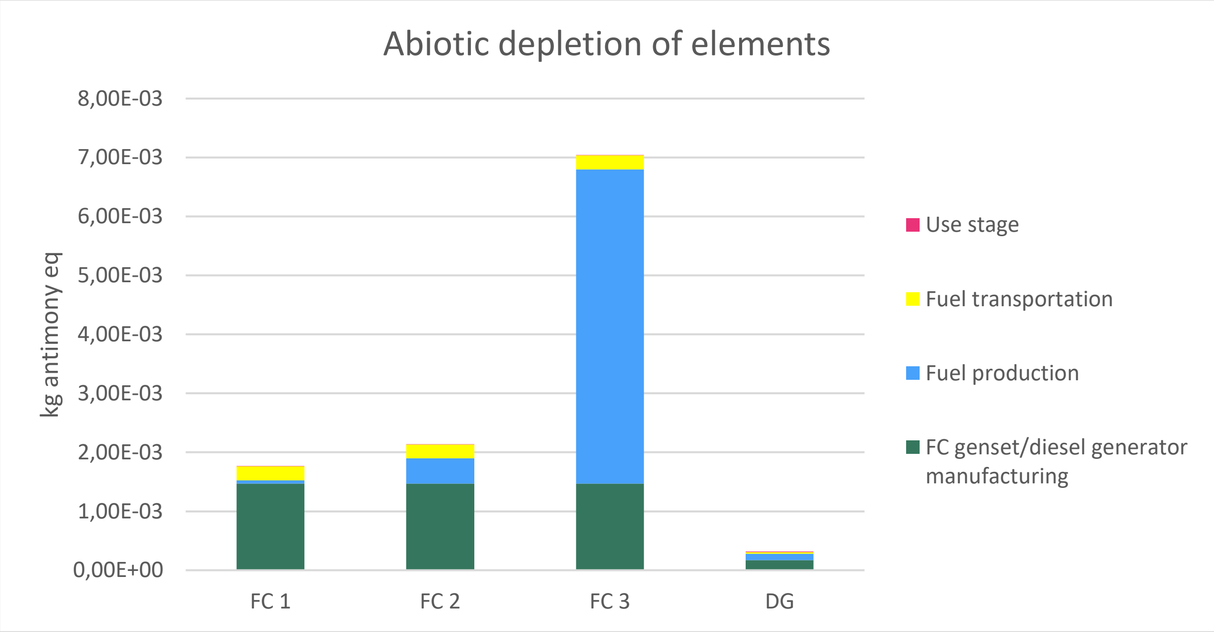

Figure 7. Abiotic depletion of elements results per MWh electricity produced with FC system with three different hydrogen production options and with the reference diesel generator.

From Figure 8, it can be seen that fossil fuel depletion is caused by fuel manufacturing/consumption. This means that the production of natural gas for hydrogen production in FC 1 and similarly the production of the average European electricity used in hydrogen production in FC 2 are the main contributors to this impact category. Fuel cell case 3 produces H_2 with wind power, which requires fossil fuels only in the production and maintenance operations of the wind power plant, and thus the overall impact remains much lower than in the other cases. The production of diesel causes most of the ADPff impacts for the diesel generator case.

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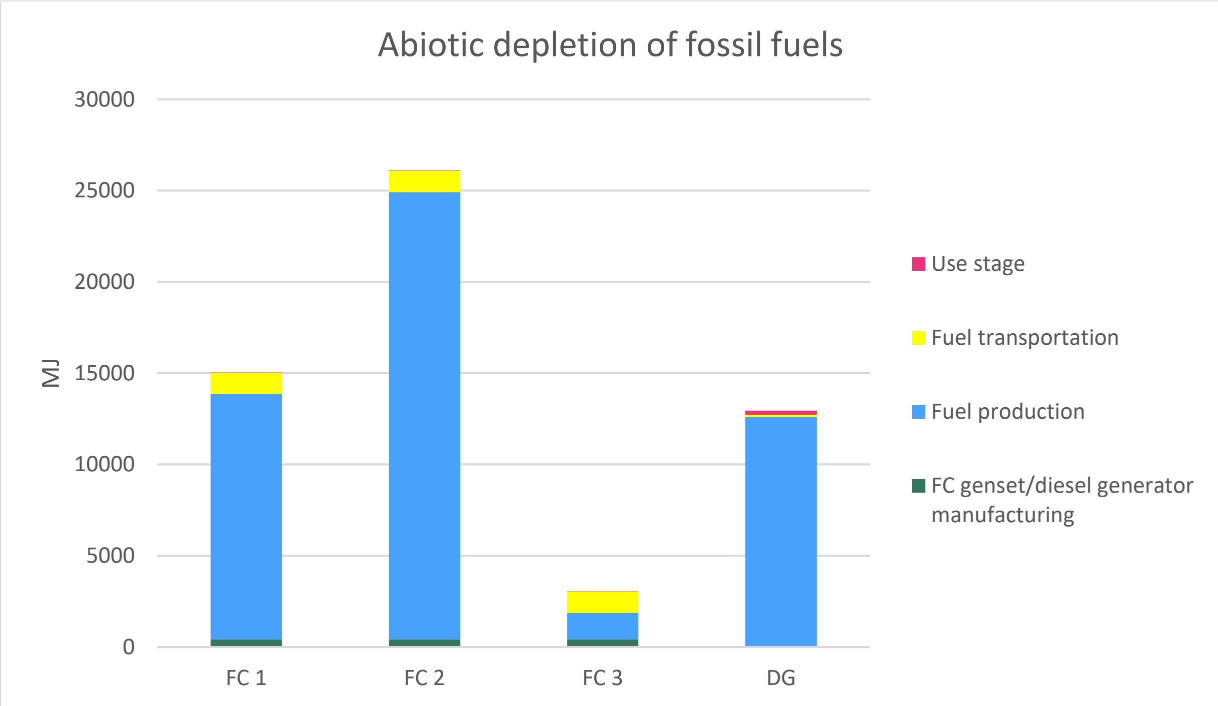

Figure 8. Abiotic depletion of fossil fuels results per MWh electricity produced with FC system with three different hydrogen production options and with the reference diesel generator.

Acidification potential, presented in Figure 9, in FC 1 is mainly caused by the production of natural gas for hydrogen production and the production of platinum for the genset. In FC 2 and FC 3, acidification is caused by the production of electricity and the power plant (in FC3) for hydrogen production. Burning of diesel is the main contributor in the diesel generator. Again, the local emissions at the use stage are practically non-existent in FC cases, which is a good thing if local air quality would be considered.

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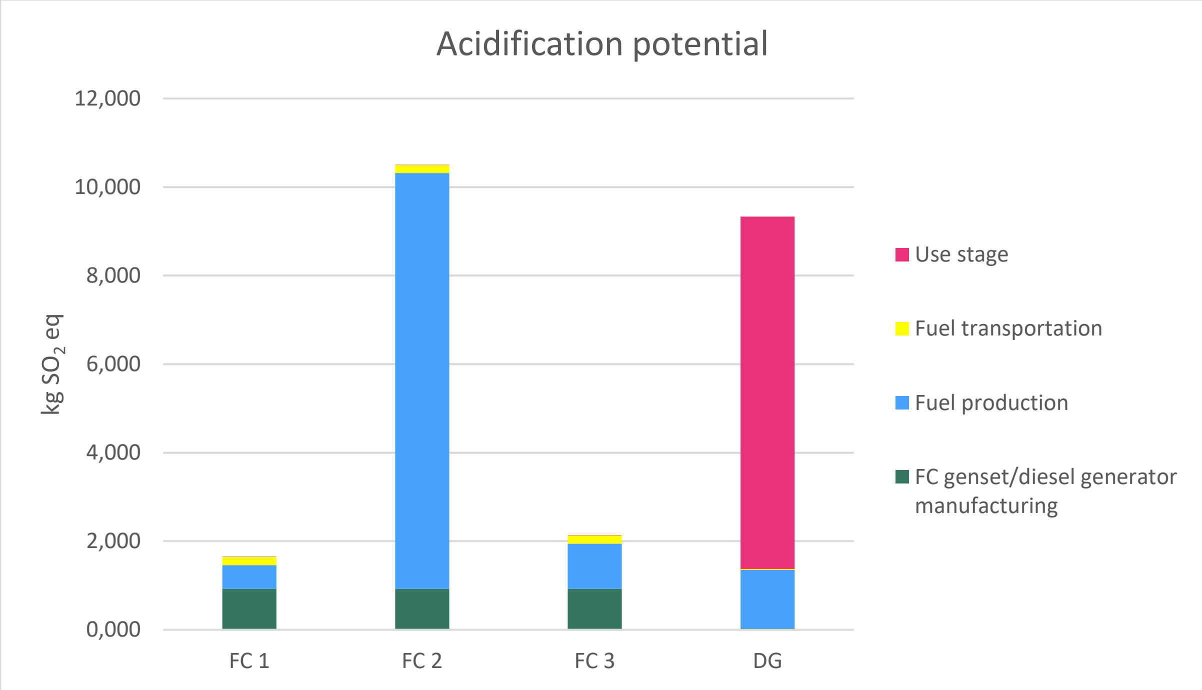

Figure 9. Acidification potential results per MWh electricity produced with FC system with three different hydrogen production options and with the reference diesel generator.

Eutrophication potential as shown in Figure 10 is the biggest for the diesel generator genset, since burning of diesel creates NO_x emissions while the fuel cell operation does not. The impacts of fuel cell cases FC1 and FC3 are rather small but the FC2 is higher due to the average

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European electricity used in H_2 production stage. Once more, the local emissions in FC cases are negligible.

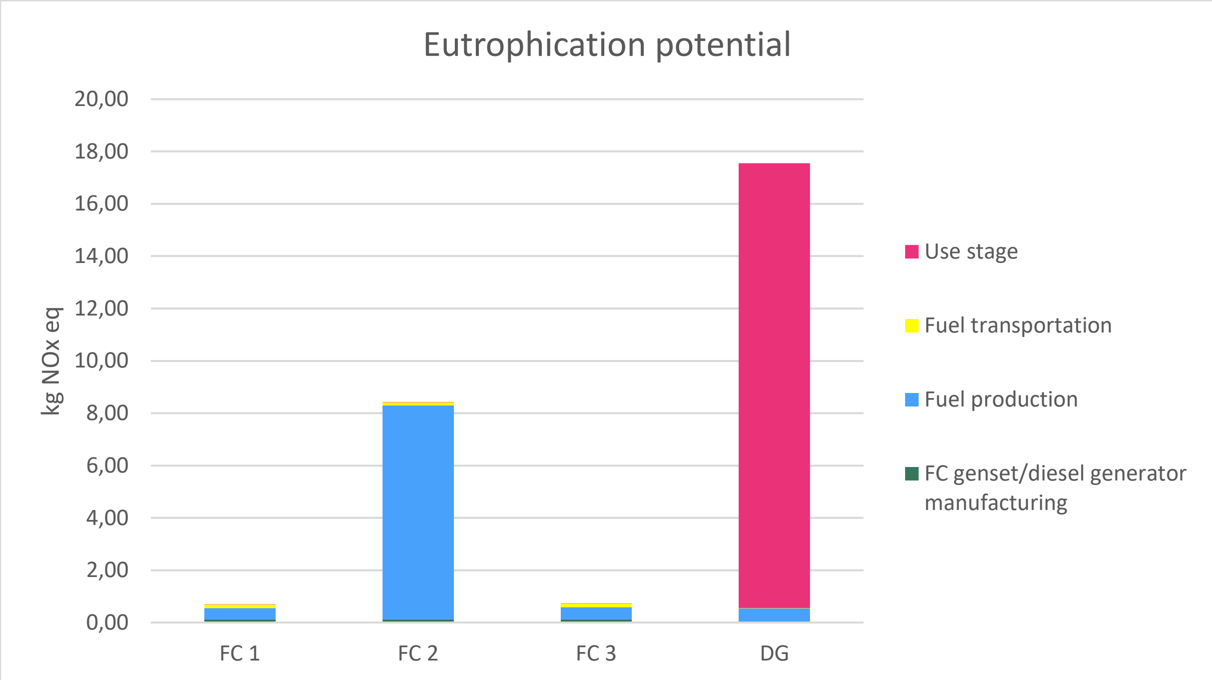

Figure 10. Eutrophication potential results per MWh electricity produced with FC system with three different hydrogen production options and with the reference diesel generator.

Figure 11 shows that photochemical oxidation potential for FC 1 comprises mostly of emissions from natural gas manufacturing and from the manufacturing of gensets electronic components like capacitors and battery. For FC 2 and FC 3 the POCP impacts come from the production of electricity used in hydrogen production and for the diesel generator from burning diesel. Again, the local emissions at the use stage are minimal in the FC cases.

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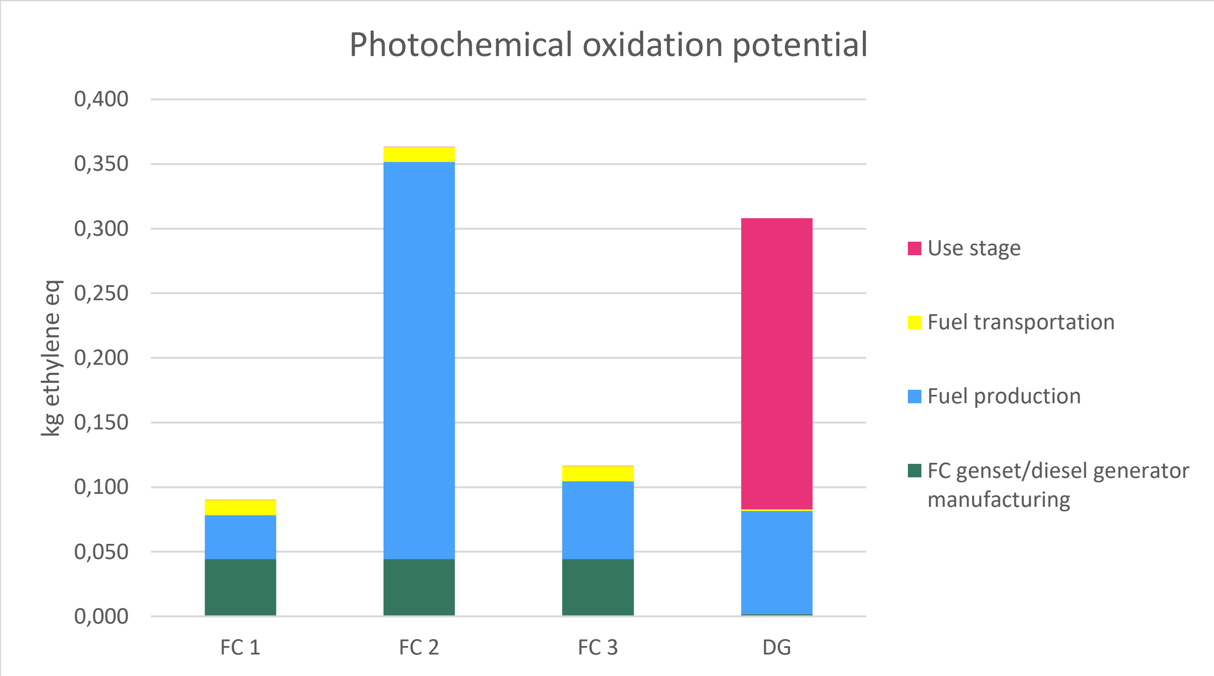

Figure 11. Photochemical oxidation potential results per MWh electricity produced with FC system with three different hydrogen production options and with the reference diesel generator.

4.3 The shares of impacts as figures by life cycle stages and FC genset units

The shares of impacts from more detailed life cycle stages in each impact category are presented below in Figure 12 for the FC1 with SMR, Figure 13 for FC2 with E-PEM and Figure 14 for FC3 with E-PEM-R. It is seen that the Electronic components II manufacturing stands out in abiotic depletion of elements, acidification and photochemical oxidation potential for case 1. This is due to the platinum and capacitors used in the power electronics. Although capacitors themselves do not contain precious metals in high volumes, their production process uses them in such amounts that it shows in the depletion of abiotic elements. Hydrogen production has the biggest impact on abiotic depletion of fossil fuels, eutrophication and global warming potential due to natural gas consumption.

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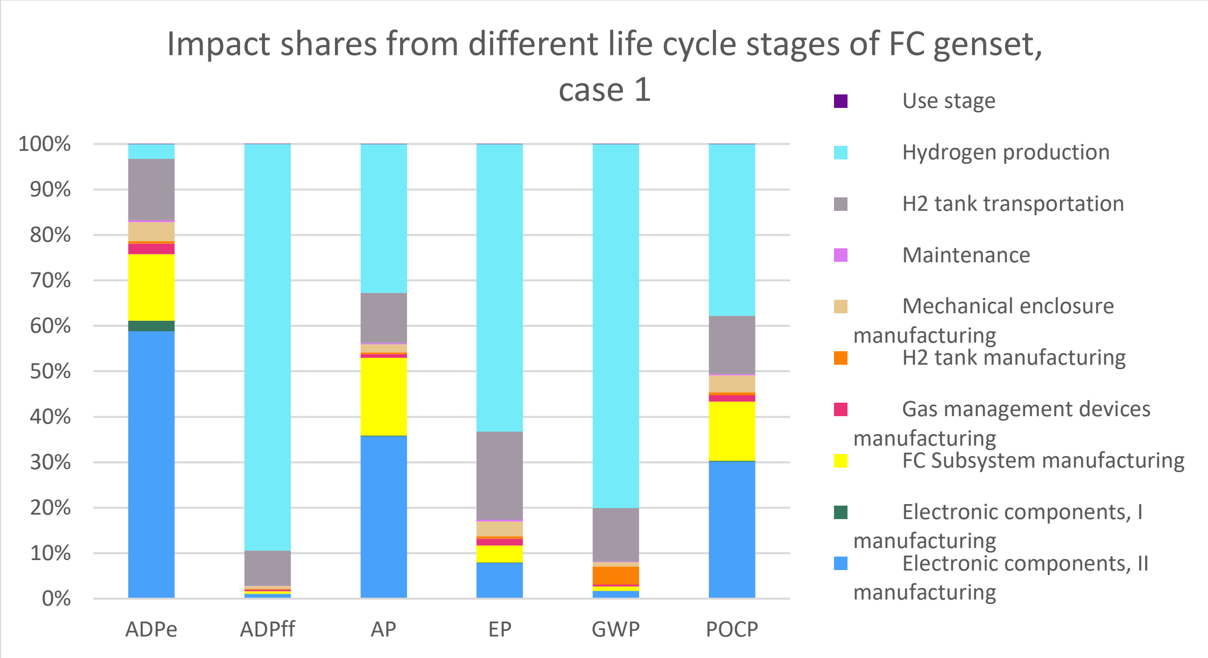

Figure 12. The shares of impacts from different life cycle stages of FC genset with hydrogen from steam methane reforming (FC1).

Impact shares for case 2 are presented in Figure 13. In case 2, where hydrogen is produced via electrolysis using European market electricity, the main impacts come from hydrogen production (other impact categories than ADPe) and electronic components II manufacturing (in ADPe). The ADPe impact is mainly created by the platinum and capacitors used in power electronics. Although capacitors themselves do not contain precious metals, their production process uses them in such amounts that it shows in the depletion of abiotic elements.

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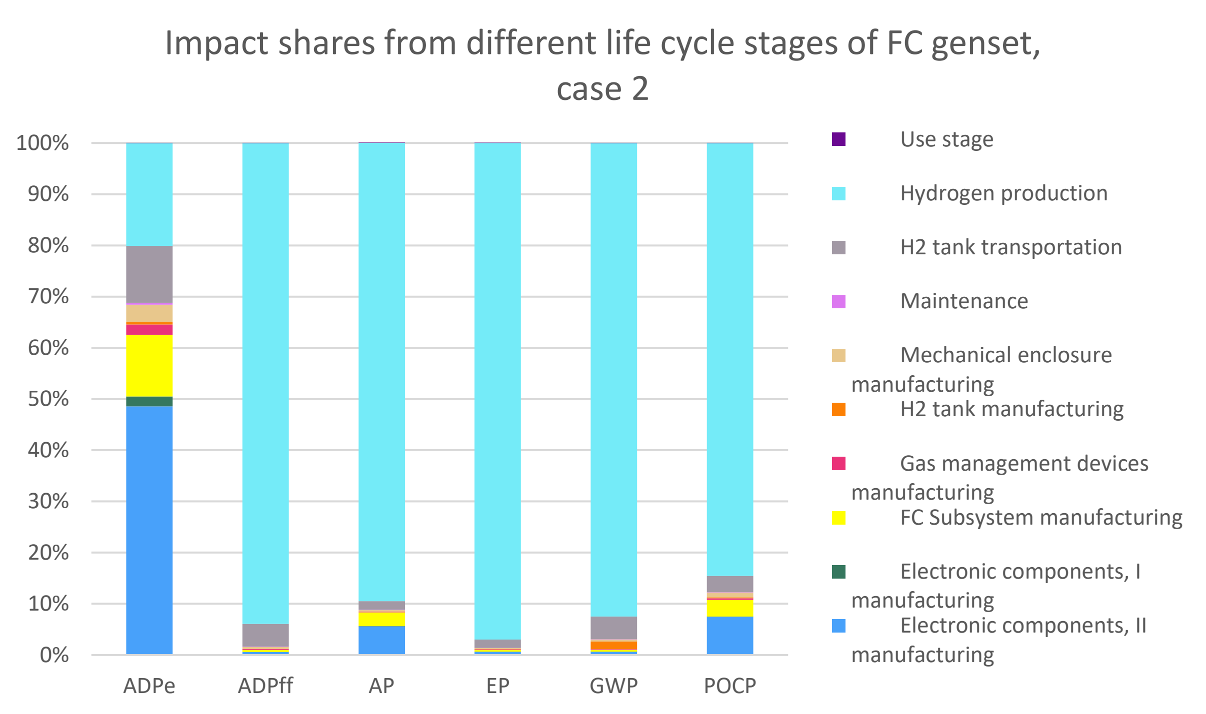

Figure 13. The shares of impacts from different life cycle stages of FC genset with hydrogen from electrolysis using European market electricity (FC 2).

Case 3 impact shares from different life cycle stages are shown in Figure 14. Case 3 uses German wind electricity to produce the hydrogen and therefore the share of hydrogen production related impacts is lower than in FC2. It is still the most significant factor in all impact categories nonetheless. The impacts from wind electricity come mainly from the infrastructure needed to operate a windfarm. Platinum and capacitors cause the Electronic components II manufacturing to be prominent in the comparison. Although capacitors themselves do not contain precious metals, their production process uses them in such amounts that it shows in the depletion of abiotic elements. Transporting the H_2 tank when it is refilled has a relatively bigger impact in case 3 than in the other cases. This is simply due to the smaller relative impact of hydrogen manufacturing.

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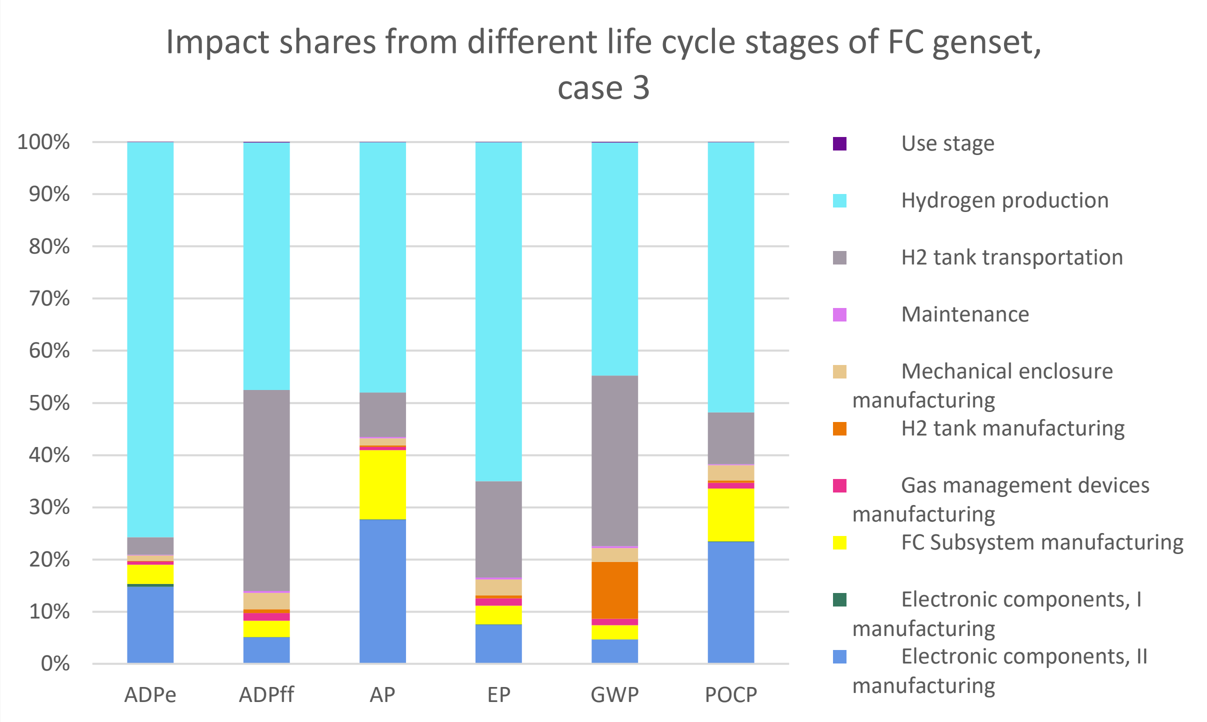

Figure 14. The shares of impacts from different life cycle stages of FC genset with hydrogen from electrolysis using German wind electricity (FC 3).

4.4 Results compared to diesel generator

Figure 15 shows the relative results of the three cases when compared to the diesel generator. From abiotic depletion of elements point of view, diesel generator is the best option as it uses less materials that the FC genset. This is because the modern diesel generator is a product of years of designing and upgrading and therefore is less material intensive. When depletion of fossil fuels is considered, case 3 with wind electricity has the lowest impact and case 2 with market electricity the highest. In global warming potential and abiotic depletion of fossil fuel resources, case 3 has the lowest impacts. This is because of the actual hydrogen production process has smaller emissions that the others. Compared to a diesel generator both cases 1 and 3 have smaller impacts in categories with use stage emissions (AP, EP, GWP, POCP). Case 2 in comparison to a diesel generator is not so good due to the energy profile of the market electricity in Europe being highly fossil fuel based. Table 10 compares the best and worst performing cases and diesel generator. Red blocs display the worst value and green the best.

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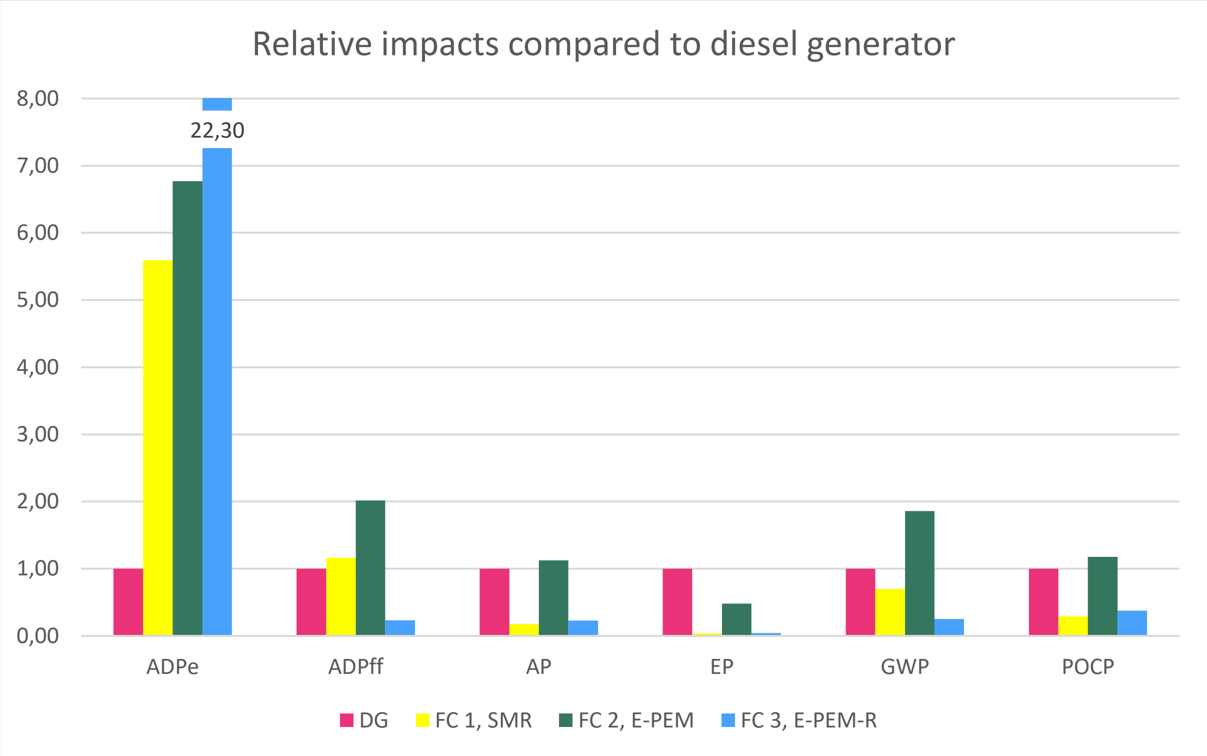

Figure 15. The relative impacts of all three cases studied compared to diesel generator.

Table 10. Comparison between all three cases and diesel generator in all impact categories studied. Red blocs display the worst value and green blocs the best.

	Diesel generator, DG	**Steam methane reforming, SMR FC 1**	**PEM with European electricity, FC 2**	**PEM with wind electricity, FC 3**
ADPe [kg antimony eq.]	0,00032	0,0018	0,0021	0,007
ADPff [MJ]	12940	15026	26096	3034
AP [kg SO_2 eq.]	9,33	2	10	2,27
EP [kg NO_x eq.]	17,55	0,69	8	0,72
GWP [kg CO_2e]	923	646	1718	233
POCP [kg ethylene eq.]	0,31	0,09	0,36	0,12

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To understand why the E-PEM case FC2 is the least favorable and FC3 the best option when considering the global warming potential, we need to look at the electricity used in H_2 production. FC2 used European average electricity with c. 0,44kg CO_2e/kWh for H_2 production, while FC3 used German wind power with c. 0,028 kg CO_2e/kWh (both values were based on Ecoinvent database). The break-even point for carbon footprint, i.e. when the climate impact of the fuel cell with hydrogen produced with electrolysis is similar to diesel generator, is somewhere in between. The break-even point has been be defined in the following Figure 16. The production of the fuel cell system, transportation of hydrogen tanks and the amount of hydrogen needed during the lifetime of the FC, have been kept constant. The GHG emissions of electricity used in hydrogen production have been varied from 0 kg CO_2e/kWh to 0,5 kg CO_2e/kWh in the X-axis, and the total amount of emissions per MWh produced (y-axis) with the FC system are shown as the green line drawn to the figure. The red line describes the carbon footprint of MWh electricity produced with the diesel generator, and the crossing point of green and red line show the emission limit for electricity used for hydrogen production in the FC system in the X-axis, i.e. 0,22 kg CO_2e/kWh used in hydrogen production. The FC2 and FC3 cases have also been marked to the figure.

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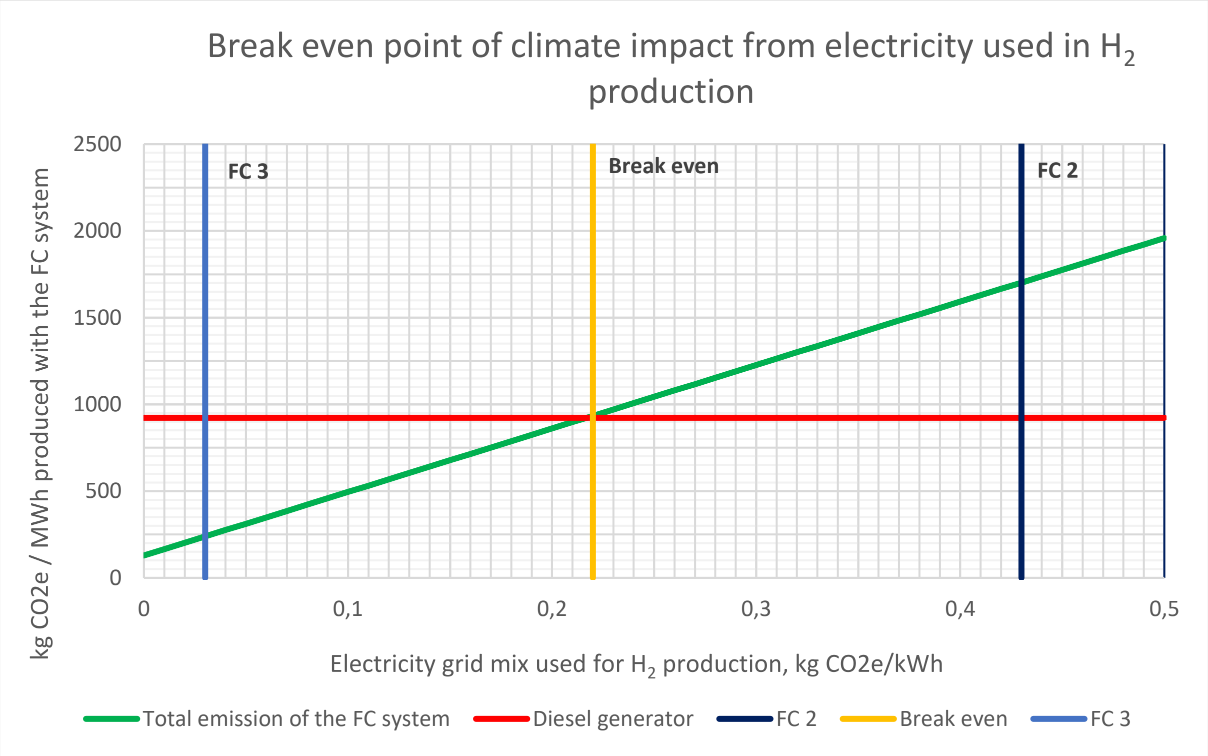

Figure 16. The impact of emission factor of electricity used for hydrogen production to the total carbon footprint of electricity produced in the FC systems. The break-even point for the fuel cell using electrolysis-based hydrogen (i.e. the maximum emission factor of electricity which creates the same amount of emissions than the diesel generator) is 0,22 kg CO2e/kWh electricity used in hydrogen production.

Figure 17 shows how electricity is produced in the European union. Based on the figure, it is easy to see that European energy profile is heavily dependent on fossil fuels. The break-even limit of 0,22kg CO_2e/kWh electricity used for H_2 production is achievable in all countries with specific fuel choices, but average fuel mixes in different countries may not fulfil this limit. Thus, it is important to remember, that the emissions of the fuel cell systems are strongly dependent on the method of hydrogen production and of electricity profile used in hydrogen production.

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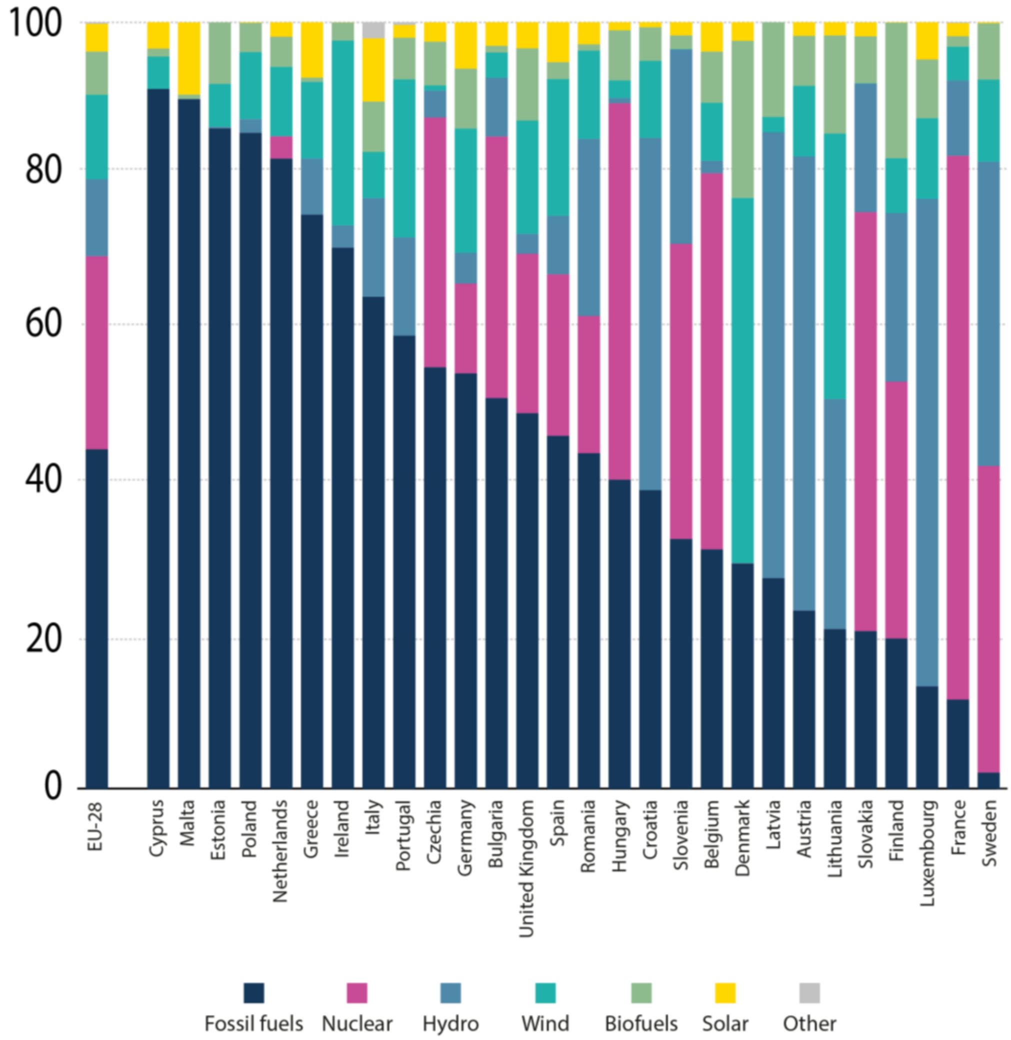

Figure 17. EU production of electricity by source in 2017 (Eurostat, 2019)

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5. Conclusions and Next steps

This screening LCA report compared a 25 kW fuel cell genset system with three different hydrogen production methods to a traditional diesel generator. When studying the global warming potential, acidification potential, eutrophication potential, photochemical oxidation potential and abiotic depletion potential of fossil resources of MWh electricity produced with fuel cell system or diesel generator, at least one of the three fuel cell cases had a smaller impact on the environment than the diesel generator. The diesel generator was the best option only when the abiotic depletion potential of elements was considered.

Hydrogen production method has by far the biggest impact on how environmentally friendly the fuel cell genset system is. In this study where the life cycle of fuel cells was considered without the end-of life stage, the biggest environmental impact vs. the smallest impact between the different fuel cell cases varied from 1,2 to 12,3 fold depending on the impact category. Also Mehmeti et al. (2018) studied the life cycle impacts of different hydrogen production methods with ReCiPe impact assessment method, and found that the results vary remarkably, as shown in Annex II. Therefore, there is a huge difference between the "best" and the "worst" hydrogen manufacturing technology. It is important to choose a hydrogen production method that affects the environment the least. If chosen wrongly, it can very well be that the FC genset is no better than a diesel generator when the full value chain is considered, even though the local emissions at the use stage are minimal when compared to diesel generators.

In this study, the FC1 case with steam methane reforming technology had the smallest impact in three categories: acidification potential, eutrophication potential, and ozone creation potential (POCP). The wind-powered hydrogen production (FC3) had the smallest environmental impacts in two impact categories: the global warming potential and abiotic depletion potential of fossil fuels. Also the eutrophication potential and ozone creation potential (POCP) was among the lowest results (very similar to the smallest impact of FC1). However, the results in the abiotic depletion potential of elements was the highest for the FC3. At the same time, the E-PEM case FC2 where hydrogen is produced with European average

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energy was found the least favorable option in all other impact categories than in the abiotic depletion potential of elements.

The FC genset has a higher impact on the use of natural abiotic resources than the manufacturing of the diesel generator because the FC genset equipment is being developed in this project and is only at a prototype stage. It is very likely that once the FC genset is ready to be commercialized, the amount of materials used will decrease. This is due to optimizing the size of needed components. Therefore, the impact on elemental depletion from the FC genset production would likely be smaller in the future. Still, the life cycle of the genset should be prolonged and at the end of life stage (not considered in this study) the materials should be recycled as efficiently as possible. However, the FC genset uses rare materials in for example capacitor manufacturing and it is possible that the impact on elemental depletion from the system manufacturing will never be lower than that of the diesel generator. Thus, to reduce the overall impact, the benefits come mainly through higher efficiency and low impact of the fuel itself.

The efficiency with which the FC genset transforms hydrogen into electricity is another thing that needs to be taken into consideration in the development of the technology. With poor efficiency, the need to refill the hydrogen tanks during operation increases as does the need to produce and transport more hydrogen to the use site. This is linked to the increase of hydrogen production related impacts.

This study analysed only the 25 kW EVERYWH2ERE genset and it was a screening LCA, which means that it was done at a stage when the fuel cell genset developed in the EVERYWH2ERE project is not yet completed in practice but is still being developed (design is fixed as WP1 outcome, realization is on going). Later in the project, the study will be re-assessed and completed with an LCA of 100kW fuel cell genset. The results of the final LCA will be reported in D5.6 “Life cycle assessment (LCA) of the FC gensets in construction sites and temporary venues”.

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Annexes

Annex I. Ecoinvent processes used in the life cycle assessments.

Ecoinvent 3.5 processes (with Allocation, cut-off by classification system model)
electricity production, wind, >3MW turbine, onshore
market for alkyd paint, white, without solvent, in 60% solution state
market for aluminium, primary, ingot
market for battery, NiMH, rechargeable, prismatic
market for capacitor, for surface-mounting
market for carbon black
market for copper
market for electricity, medium voltage
market for epoxy resin insulator, Al2O3
market for ethylene glycol
market for glass fibre
market for graphite
market for hard chromium coat, electroplating, steel substrate, 0.14 mm thickness
market for injection moulding
market for nylon 6
market for platinum
market for polycarbonate
market for polyethylene, high density, granulate
market for polyurethane, rigid foam
market for polyvinylchloride, bulk polymerised
market for printed wiring board, through-hole mounted, unspecified, Pb free
market for sheet rolling, aluminium
market for sheet rolling, chromium steel
market for sheet rolling, copper
market for silicone product
market for steel, chromium steel 18/8, hot rolled
market for steel, low-alloyed, hot rolled
market for synthetic rubber
market for tap water
market for tetrafluoroethylene
market for water, deionised, from tap water, at user
market group for electricity, high voltage
market group for natural gas, high pressure

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Annex II. Environmental impacts of hydrogen production methods by Mehmeti et al (2018).

Impact Category [2]	Unit	H_2 Production Pathways [1]											
		SMR	CG	BMG	BDL-E-Corn	BDL-E-Wheat	E-PEM	E-PEM-R	E-SOEC	E-SOEC-R	DF-MEC w/out ER	DF-MEC w/ER	DF-MEC w/H_2 Recovery
GWP	kg CO_2-eq	12.13	24.2	2.67	9.193	14.02	29.54	2.21	23.32	5.10	16.29	6.60	14.57
ODP	kg CFC-11-eq	2.99×10^{-6}	3.35×10^{-6}	2.18×10^{-5}	1.70×10^{-4}	1.23×10^{-4}	1.22×10^{-5}	1.40×10^{-6}	9.36×10^{-6}	2.16×10^{-6}	4.16×10^{-5}	3.79×10^{-5}	4.11×10^{-5}
IRP	kBq Co-60-eq	0.501	1.188	0.406	0.835	0.87	19.33	0.52	12.8505	0.3142	7.53	2.11	7.50
EOFP	kg NO_x-eq	0.0085	0.055	0.00375	0.037	0.0424	0.0487	0.0039	0.0349	0.0050	0.0247	0.01055	0.024
PMFP	kg $PM_{2.5}$-eq	0.002	0.039	0.00284	0.007	0.021	0.0337	0.0041	0.0222	0.0025	0.0172	0.008266	0.016989
HOFP	kg NO_x-eq	0.0089	0.055	0.00382	0.037	0.043	0.0492	0.0041	0.0353	0.0052	0.025	0.010696	0.023983
TAP	kg SO_2-eq	0.0087	0.139	0.03706	0.124	0.112	0.1087	0.0118	0.0724	0.0078	0.104	0.074636	0.103
FEP	kg P-eq	0.0007	0.008	0.00081	0.003	0.00568	0.0242	0.0014	0.0162	0.0009	0.0098	0.00312	0.009749
TETP	kg 1,4-DCB-eq	0.0005	0.003	0.0003	0.007	0.142	0.012	0.0048	0.0078	0.0030	0.0041	0.001442	0.003977
FETP	kg 1,4-DCB-eq	0.0208	0.268	0.01875	0.162	0.646	0.7519	0.15	0.4974	0.097	0.268	0.080308	0.27
METP	kg 1,4-DCB-eq	0.0423	0.377	0.02706	0.227	0.483	1.07	0.22	0.7111	0.145	0.384	0.12	0.38
HTPc	kg 1,4-DCB-eq	0.0803	0.64	0.0433	0.128	0.357	1.58	0.43	1.1213	0.356	0.565	0.16	0.55
HTPnc	kg 1,4-DCB-eq	21.36	277.6	19.69	284.129	268.94	764.98	157.25	507.42	102.26	272.6	82.10	269.3
LOP	m^2a crop-eq	0.008272	0.235	0.02062	23.518	20.2	0.22	0.05	0.1525	0.04	0.104	0.043	0.102467
SOP	kg Cu-eq	0.00389	0.004	0.00186	0.028	0.04	0.12	0.16	0.0632	0.09	0.0153	0.006	0.014159
FFP	kg oil-eq	4.45	4.914	0.655	1.524	3.042	7.81	0.62	6.5058	1.72	4.38	1.68	3.78
WCP	m^3 consumed	5.77	13.1	4.94	2.246	3.875	223.39	16.40	146.82	8.82	84.9	23.98	84.50
WSF	m^3	247.5	570.2	212.4	94.61	149.4	9604.3	629.8	6312.3	379.3	3650.2	1030.8	3632.9

[1] SMR: Steam methane reforming; CG: Coal gasification; BMG: Biomass Gasification; BDL: Biomass Reformation; E-PEM: Electrolysis with Proton exchange membrane (PEM): E-PEM-R: Electrolysis with Proton exchange membrane with wind energy; E-SOEC: Electrolysis with Solid oxide electrolysis cells (SOEC); E-SOEC-R: Electrolysis with Solid oxide electrolysis cells with wind energy; DF-MEC: Dark fermentation + microbial electrolysis cell (MEC) without energy recovery, with energy recovery and H_2 recovery. [2] Global warming potential (GWP); Stratospheric ozone depletion (ODP); Ionizing radiation (IRP); Photochemical oxidant formation: human health (HOFP); Photochemical oxidant formation: ecosystem quality (EOFP); Human toxicity potential: cancer (HTP_c); Human toxicity potential: non-cancer (HTP_{nc}); Terrestrial ecotoxicity freshwater ecotoxicity (TETP); Freshwater ecotoxicity (FETP); Marine ecotoxicity (MAETP); Freshwater eutrophication potential (FEP); Fine particulate matter formation (PMFP); Terrestrial acidification (TAP); Land use (LOP); Water consumption potential (WCP); Mineral resource scarcity (SOP); Fossil resource scarcity (FFP); Water Scarcity Footprint (WSF).

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