PEMBeyond

PEMFC system and low-grade bioethanol processor unit development for back-up and off-grid power applications

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Authors:	Katri Behm, Catharina Hohenthal, Pauli Koski
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FCH JU project officer, e-mail address Nikolaos Lymperopoulos, FCH JU nikolaos.lymperopoulos@fch.europa.eu	**Grant agreement no** 621218
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Author(s) Katri Behm, Catharina Hohenthal, Pauli Koski	**Pages** 29

Summary

This report summarises the life cycle assessment (LCA) of PEMFC based power system developed in the PEMBeyond-project. The system operates on low-grade (crude) bioethanol, and could be used for wireless communication systems, also in developing countries. The Reformed Ethanol Fuel Cell System (REFCS) consisted of four units: the fuel cell system, Pressure Swing Absorption -unit (PSA unit), fuel processor (reformer) and complete system integration. 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 a traditional diesel generator.

Two scenarios were studied: 1) an off-grid scenario with 20 000h usage time at 2 kW power, resulting to 40 MWh produced during the entire lifetime, and 2) a back-up scenario with 100 h / year usage for 20 years at 2 kW power, resulting to 4 MWh produced. Both scenarios were calculated with two ethanol production options, firstly with market ethanol available globally and secondly with ethanol produced as a by-product from cane sugar production.

In the off-grid scenario, the impacts from the REFCS case are approximately 50 % smaller in the acidification category, in the global warming category and in the depletion of the fossil fuel resources category than of the diesel generator. The photochemical oxidation potential is also a bit lower in the REFCS cases. However, in the back-up scenario, the diesel generator has lower impact in all studied categories.

Overall, REFCS has many benefits compared to the diesel generator in off-grid application, e.g. c. 50 % smaller carbon footprint than the diesel based solution. The benefits would be even higher if the equipment would be used for longer period i.e. more electricity would be produced, since there are no direct emissions from the use stage, or if the end of life stage with material recycling would be considered. Due to higher use of resources in the manufacturing stage, using the REFCS for a pure back-up application is not a good option even though the impacts from the REFCS production are probably exaggerated in the scenarios due to some assumptions used in the study.

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Abbreviations

ADP	Abiotic depletion potential
AP	Acidification potential
BOM	Bill of Materials
CFP	Carbon footprint of a product
CH_4	Methane
CO_2	Carbon dioxide
CO_2 eq	Carbon dioxide equivalent
EP	Eutrophication potential
FCS	Fuel cell system
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
N_2O	Dinitrogen monoxide
PEMFC	Proton exchange membrane fuel cell
POCP	Photochemical oxidation potential
PO_4--- eq.	Phosphate ion equivalent
PSA	Pressure Swing Absorption
R-E	Resources - elements
REFCS	Reformed ethanol fuel cell system
R-FF	Resources - fossil fuels
SO_2	Sulphur dioxide

1. Introduction

This report is a public deliverable of an EU-project “PEMBeyond, PEMFC system and low-grade bioethanol processor unit development for back-up and off-grid power applications”. The project aims at developing a cost-competitive, energy-efficient and durable integrated PEMFC based power system operating on low-grade (crude) bioethanol, which could be used for wireless communication systems, also in developing countries, instead of traditional diesel generators.

The environmental impacts and benefits of using crude bioethanol driven fuel cell systems in back-up and off-grid power generation were assessed and are reported in this deliverable. This work was done by VTT’s sustainability assessment experts. Diesel driven generators/existing back-up generators were compared to using bioethanol in proposed system concept. The calculation included analysis of back-up and continuous energy generation. Methodology was based on 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 reformed ethanol fuel cell system was made in cooperation with project partners.

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

2.1 Life Cycle Assessment as a method

Life cycle assessment (LCA) is an ISO standardized method that can be used for assessing the potential environmental impacts of a product or a service. 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”.

The life cycle is modelled from unit processes that are connected to each other with material or energy flows. Each process has inputs and outputs, which are connected to preceding and following processes from the beginning until the end of the life cycle. “Cradle to grave” approach includes the production of raw materials and energy, manufacturing of the product, all transportations, use phase, and finally disposal of the product or other end-of-life treatment. “Cradle to gate” and “cradle to customer” approaches consider the life cycle until the manufacturing of the product is complete (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 is the first stage. It 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 are presented as inputs and outputs of the entire system. The results from the inventory can be converted into impacts in the third stage, the impact assessment. One example of this is the carbon footprint calculation; the emitted greenhouse gases from the inventory calculation are converted into global warming potentials in the impact assessment stage. The final stage of LCA is interpretation of the results, which is based on all three previous stages of the assessment. The stages of the life cycle assessment are presented in Figure 1.

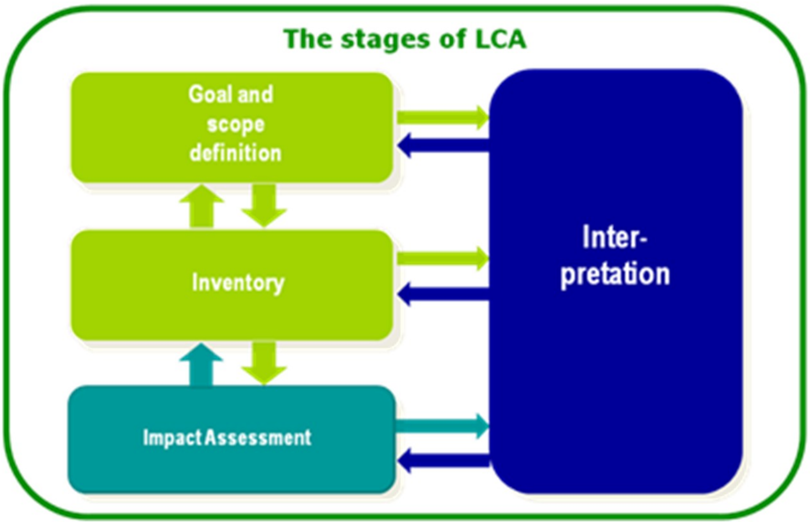

Figure 1. The four stages of life cycle assessment.

The results of LCA are represented per functional unit, which describe 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 liter of diesel).

There are several impact assessment methods with different characterisation, normalisation 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 of the definition phase (stage 1), considering the spatial and temporal aspects of the study. Some methods include only characterisation factors but not normalisation or weighting factors, and these methods are called "the midpoint methods". "The endpoint methods" include also the normalisation 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 the Goedkoop et al. (2008), 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.

2.2 Carbon footprint

Anthropogenic climate change 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 (BSI 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/TS 14067:2013) standard provides principles, requirements and guidelines for the quantification and communication of the carbon footprint of products, including both goods and services. Partial product footprints are also addressed. Calculations on organisational level can also be made. The 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 removal is avoided within both the studied product system and other product systems (in the context of allocation). Public communication of carbon footprints can support providing of information to consumers and other interested parties as well as show company commitment to address climate change challenges. The carbon footprint communication options are external communication report, performance tracking report, CFP label and CFP declaration (ISO/TS 14067 2013).

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 dinitrogenmonoxide (N_2O). The impacts from different greenhouse gases are converted into carbon dioxide equivalents (CO_2 eq.) by multiplying the inventory results of each greenhouse gas with factors given by Intergovernmental Panel on Climate Change (IPCC). The factors describe the global warming potential of emissions within the next 100 years, which is the most common 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 (by IPCC 2013).

	Conversion factor by IPCC
Carbon dioxide, CO_2	1
Methane, CH_4	28 / 30
Dinitrogenmonoxide, 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 fuel 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 identified.

2.3 FC-Hy guides

FC-Hy guides are public guidance documents for performing LCAs on fuel cells (Masoni and Zamagni, 2011) and hydrogen production technologies (Lozanovski et al. 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 (FCH JU), 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-grave 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) need to be considered (cradle-to-gate), as well as the operation stage of the fuel cell. The system boundaries are presented in Figure 2.

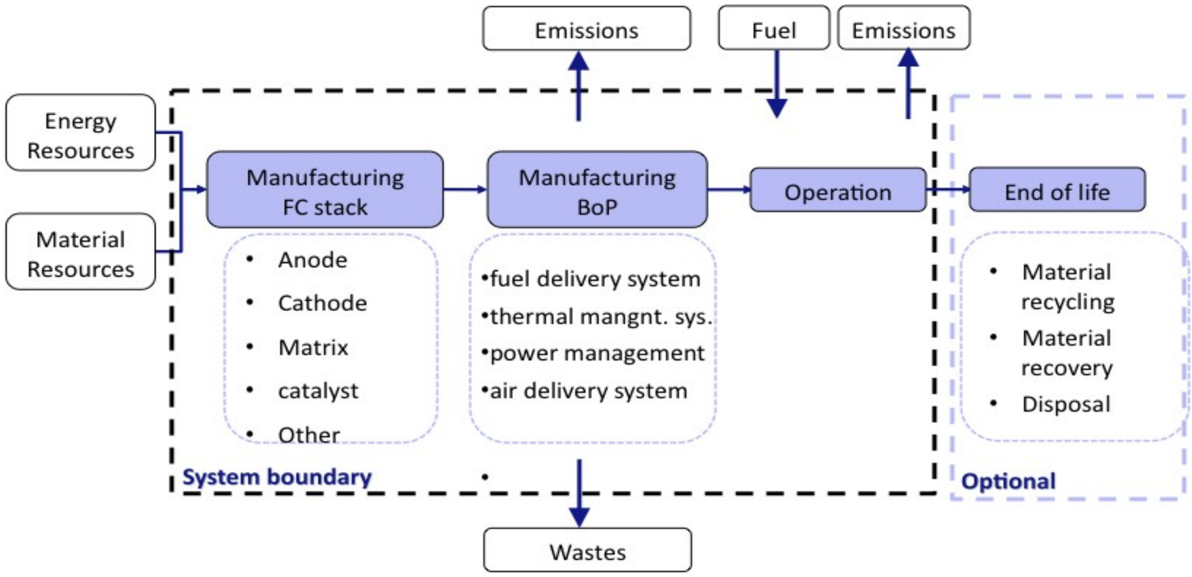

Figure 2. System boundaries and processes for fuel cell systems suggested in the FC-Hy guide for fuel cells. (Masoni and Zamagni, 2011)

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

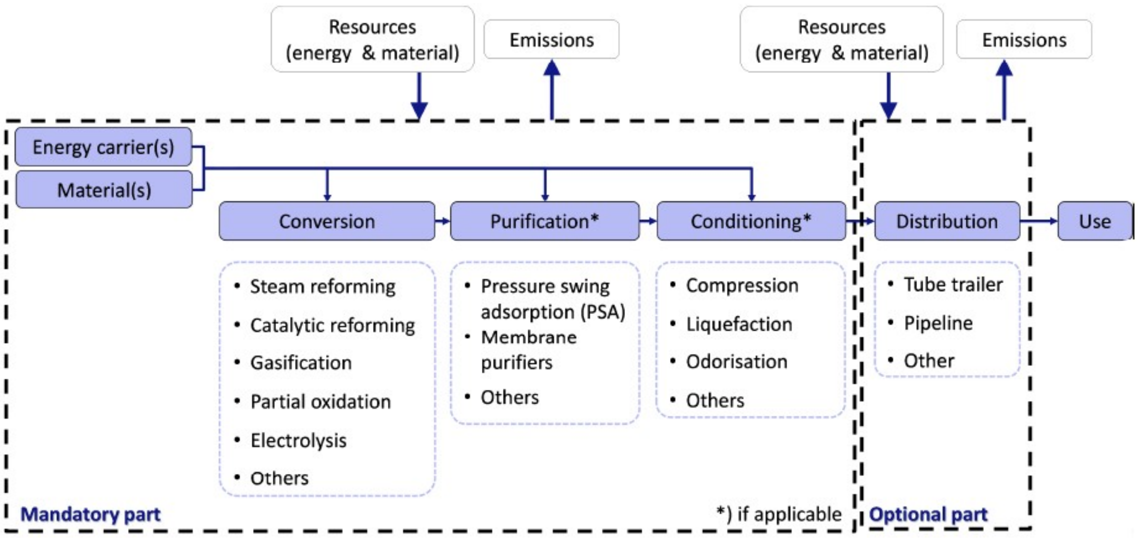

Figure 3 System boundaries and processes for the hydrogen delivery chain suggested in the FC-Hy guide for hydrogen production systems (Lozanovski et al. 2011).

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. If data gaps arise, they must be clearly documented and explained how they are handled.

3. Description of the study

3.1 Reformed Ethanol Fuel Cell System (REFCS)

The Reformed Ethanol Fuel Cell System (REFCS) developed in this project consisted of four units: the fuel cell system, Pressure Swing Absorption -unit (PSA-unit), fuel processor (reformer) and complete system integration. The concept of the system is explained in more detail by Sarsama et al. (2017). The components of all units and the materials used in them were collected to an excel file by all project partners. *Powercell Sweden Ab* and *Genport srl* provided data for the fuel cell system, *University of Porto* collected data for the PSA unit, *The Fraunhofer ICT-IMM* was responsible for delivering data for the fuel processor, and finally VTT provided data for the complete system integration. The material composition of the REFCS was then calculated based on the collected data. The bill of materials (BOM) can be seen in

Table 2. There were some materials that were listed in the BOM but for which there was no production data available. These are written in red text in the table below. The total amount of missing materials was c.1,4 kg, which is less than 0,2 % of all the materials used in REFCS.

Table 2. Bill of material of REFCS. The red numbers describe materials which had no production data available.The numbers may not match because of the roundings.

Materials	Fuel Cell System production	Fuel processor production	PSA unit production	Complete system integration	Amount in kg
Metals					617,0
steel, chromium steel	13,3	46,3	34,1	311,7	405,4
aluminium	53,8	6,6	5,9	18,4	84,6
steel, low-alloyed	59,8	0	0,4	0,1	60,3
copper	53,0	0	1,5	0,7	55,2
brass	10,8	0	0	0	10,8
pig iron	0,6	0	0	0	0,60
aluminium oxide	0	0,086	0	0	0,086
platinum	0,020	0,004	0	0	0,024
rhodium	0	0,001	0	0	0,001
nickel, 99.5%	0	0,002	0	0	0,002
alumel	0	0	0	0,002	0,002
chromel	0	0	0	0,002	0,002
Batteries					68,0
battery, Li-ion, rechargeable, prismatic	68	0	0	0	68,0
Plastics					68,4
polyvinylchloride	25,3	0	0	0	25,3
polyethylene, high density	0	0	0	24	24,0
polypropylene	11,6	0	0,5	1,8	13,8
epoxy resin insulator, Al2O3	0	0	3,0	0,6	3,6
Polyetherimide	0,7	0	0	0	0,7
polycarbonate	0,7	0	0	0	0,7
POM	0,2	0	0	0	0,2
nylon 6	0,1	0	0	0	0,1
Electronics / electrical components					12,2
printed wiring board, through-hole mounted, unspecified, Pb free	7,6	0	0,4	0,7	8,7
pump, 40W	0	0	0	3,4	3,4
Others					48,5
activated silica	0	24,7	0	0	24,7
silicone product	11,5	0	0	0	11,5
ethylene glycol	5	0	0	0	5,0
activated carbon	0	0	4,6	0	4,6
carbon felt	0,7	0	0	0	0,7
textile, woven cotton	0,5	0	0	0	0,5
DI resin	0,5	0	0	0	0,5
tetrafluoroethylene	0,3	0	0,04	0,13	0,5
glass fibre	0,3	0	0	0	0,3
synthetic rubber	0,2	0	0	0	0,2
graphite	0	0	0,05	0,01	0,06
carbon black	0,06	0	0	0	0,06
cerium concentrate, 60% cerium oxide	0	0,01	0	0	0,01
TOTAL WEIGHT					814,2

In addition to the material composition used for the REFCS, the use stage of the system was also considered in the study. There were two different usage scenarios, which are described in chapters 3.3 and 3.4. In both cases the REFCS uses raw bioethanol (in 95% solution) as a fuel, thus production of it was considered as well. According to the simulation model the system consumed 0,94 kg absolute ethanol per hour at 2 kW power (Wichert 2017). Thus the total amount of ethanol used during the 20 000 h usage time equals to **18 800 kg ethanol**. Similarly, the 20 000 h with 2 kW power equals to **40 000 MWh** produced during the assumed life time of the REFCS.

The raw ethanol used is made from biobased materials. Thus all carbon dioxide emissions (1,896 kg CO_2/h) that are released during the use are biogenic, and no fossil CO_2 emissions are released during the use stage of the REFCS. There are no nitrogen oxides formed during the process due to low enough temperatures and catalytic combustion. Similarly no sulphur emissions occur. Also particulate emissions were assumed to be zero since the fuel processor burners were operated with air excess (Wichert 2017).

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. The life cycle of the REFCS was built to and calculated with an LCA calculation tool called SULCA. The flowsheet of the REFCS can be seen in Figure 4.

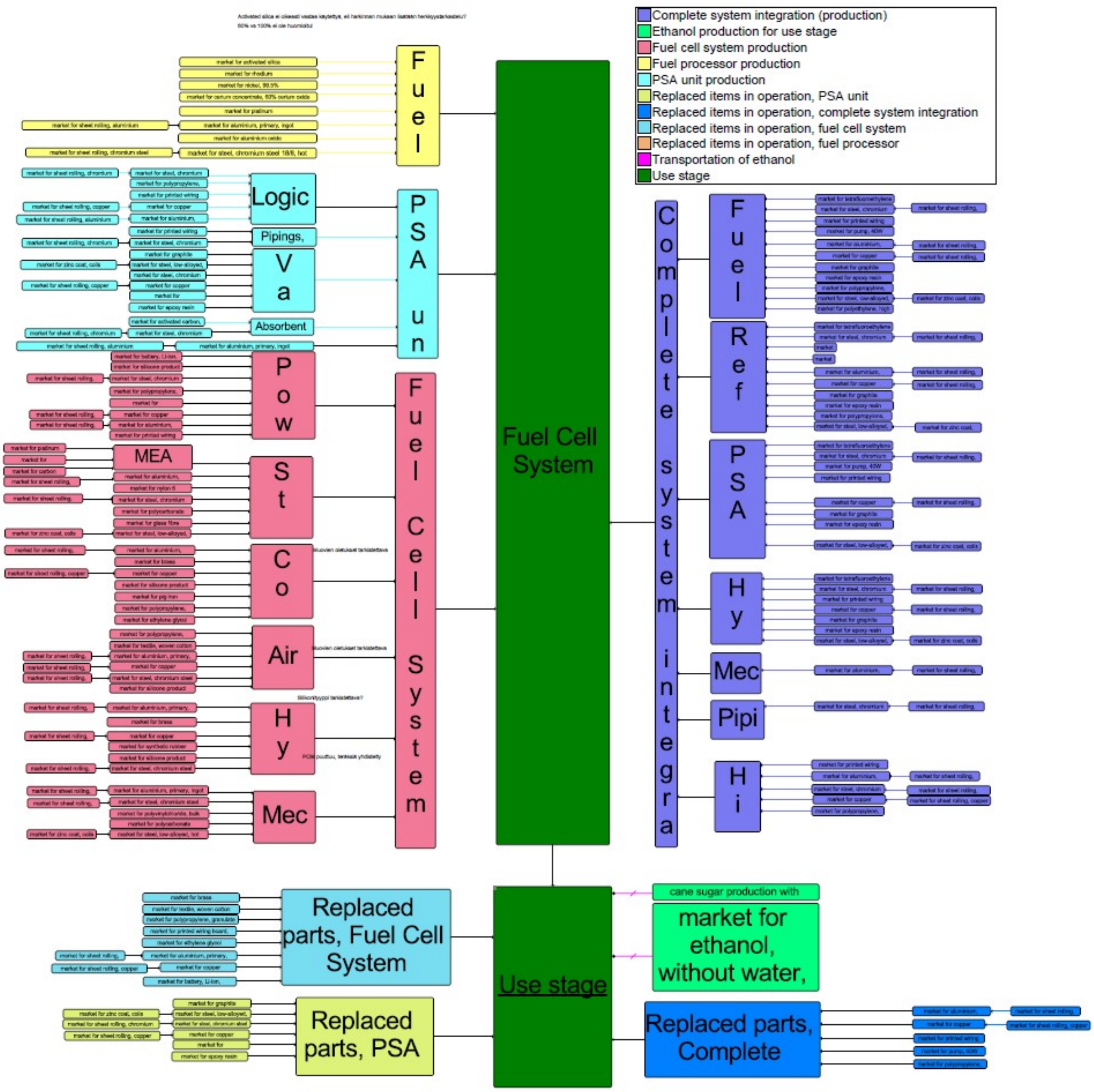

Figure 4. The flowsheet of the REFCS system in off-grid scenario.

The data for material production was collected from commercial database Ecoinvent 3.3. The allocation method used was "Allocation, at the point of substitution". The data was collected during the spring/summer 2017.

The transportation of the materials/components and of the REFCS equipment were not considered in the study due to the expected small importance. However, the transportation of ethanol was taken into account, assuming 100 km distance with 3,5-7,5 metric ton lorry.

3.2 Diesel generator as comparison

The REFCS was compared to a diesel generator. The data for the diesel generator was collected from the Ecoinvent 3.3 database. Since there were no generators with exactly 2 kW of electrical power output, a generator with 18,5 kW power output was scaled down to represent a 2 kW generator. This was done by scaling down the manufacturing inputs, fuel consumption, and emissions by a factor of 2/18,5. The lifetime of the diesel generator was kept the same.

The life cycle of the diesel generator included production of the generator, production of diesel used during the lifetime and the use stage, where the diesel was combusted in the generator. The transportations of the materials/components and of the diesel generator were not considered in the study due to the expected small importance. However, the transportation of diesel was taken into account, assuming 100 km distance with 3,5-7,5 metric ton lorry. Similarly to the REFCS 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.

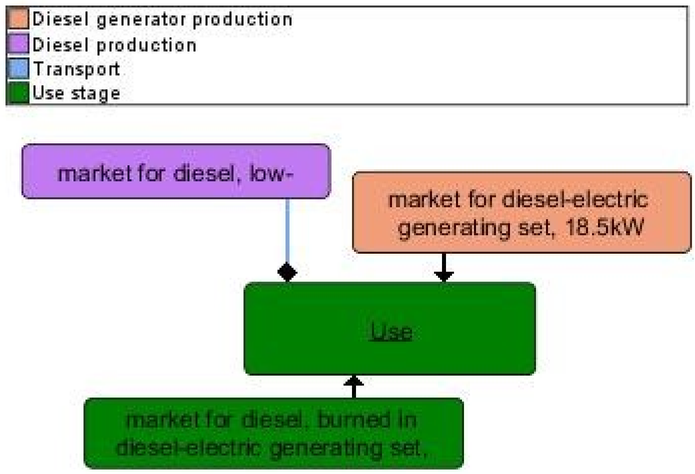

Figure 5. Flowsheet of the diesel generator.

3.3 Off-grid scenario

In the off-grid scenario the REFCS was assumed to be used as a constant power provider in an area where electricity is not readily available. Such a location could exist e.g. in many developing countries. For this study the location was assumed to be somewhere in remote Australia. The operation duration was selected to be 20 000 h, producing in total 40 MWh of electricity, which was the functional unit of this study. Since the components of the REFCS have different lifetime expectancies from 5000 h to 40 000 h, those components that were expected to last for less than 20 000 h needed to be replaced with new similar items in the calculation. The total materials that needed replacement during the 20000 h operation are listed in

Table 3.

Table 3. Materials used for replacing parts of the REFCS.

Materials	Amount in kg
Metals	11,6
aluminium, primary, ingot	9,1
copper	1,3
brass	0,8
steel, chromium steel 18/8, hot rolled	0,4
steel, low-alloyed, hot rolled	0,02
Batteries	68,0
battery, Li-ion, rechargeable, prismatic	68,0
Plastics	2,0
polypropylene, granulate	1,9
epoxy resin insulator, Al2O3	0,1
Electronics / electrical components	1,5
pump, 40W	1,4
printed wiring board, through-hole mounted, unspecified, Pb free	0,1
Others	18,0
ethylene glycol	15,0
textile, woven cotton	1,5
DI resin	1,5
graphite	0,002
tetrafluoroethylene	0,001
TOTAL WEIGHT OF REPLACED MATERIALS	101,2

Raw ethanol was used as a fuel for the REFCS. Since the use stage is typically of high importance with products that have long usage duration, the impact from different raw materials (i.e. feedstocks) in ethanol production was decided to be tested. The off-grid scenario was thus calculated firstly with market ethanol, that describes the typical global ethanol market with several raw material used in the production stage. Secondly, the most typical ethanol raw material in Australia was used, namely ethanol produced as a by-product from cane sugar production (Biofuels Association of Australia, 2017).

Transportation of the REFCS equipment to the usage location was left out of the study due to the fact that the delivery happens only once and thus the impact can be expected to be negligible. However, the transportation of ethanol was considered and was assumed to be 100 kilometres by 3,5-7,5 metric ton lorry. The use location was assumed to be in such area that it might not necessarily be possible to be reached with a heavier vehicle. In addition, the storage possibilities for ethanol may also be limited.

3.4 Back-up scenario

The second scenario considered a situation where REFCS is used as a back-up power supply in case of power black-outs. In this case, the REFCS was assumed to be used for 100 h per year, again in Australia, for 20 years. This equals to 2000 usage hours in total. With 2 kW power the total energy produced during the 20 years was thus 4 MWh. The REFCS equipment was assumed to last as it is due to small usage hours, so no replaced parts were considered. The transportation of ethanol was considered and was assumed to be the same as in the off-grid scenario, i.e. 100 kilometres by 3,5-7,5 metric ton lorry.

4. Results of the LCA

4.1 Off-grid scenario results

The results of the impact assessment calculations of the 40 MWh of power produced with REFCS and diesel generator are presented in the following tables. The impact assessment method used was the CML method, updated in August 2016 (CML 2016). 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 4 represents the impact assessment results of REFCS with market ethanol used,

Table 5 describes the results of REFCS with ethanol from cane sugar production used, and Table 6 shows the results for diesel generator.

As can be seen from the results, the ethanol production plays an important role in the results. Ethanol from cane sugar production has a smaller impact than the market ethanol, which is produced with several different methods. The differences of impacts from these two ethanol options are presented in Table 7.

Table 4. Impact assessment results of REFCS with market ethanol used in off-grid scenario (case 1).

	AP [kg SO_2 eq.]	**GWP [kg CO_2 eq.]**	**EP [kg PO_4--- eq.]**	**POCP [kg ethylene eq.]**	**ADP, elements [kg antimony eq.]**	**ADP, fossil fuels [MJ]**
Ethanol production for use stage	139,90	16640,00	60,06	5,44	0,06	145000,00
Fuel cell system production	79,80	3068,00	31,63	4,11	0,36	42220,00
PSA unit production	2,41	327,50	1,10	0,15	0,01	4091,00
Fuel processor production	13,74	522,90	1,99	0,67	0,02	6988,00
Replaced items in operation, fuel cell system	7,04	613,90	4,48	0,36	0,05	8906,00
Replaced items in operation, PSA unit	0,03	3,69	0,02	0,00	0,00	43,73
Replaced items in operation, fuel processor	0,00	0,00	0,00	0,00	0,00	0,00
Replaced items in operation, complete system integration	0,28	24,17	0,18	0,02	0,00	330,80
Complete system integration (production)	12,40	2120,00	4,06	0,78	0,05	27350,00
Transportation of ethanol	2,50	980,40	0,58	0,16	0,00	14370,00
Use stage	0,00	0,00	0,00	0,00	0,00	0,00
Total life cycle	258,10	24300,00	104,10	11,69	0,56	249300,00

Table 5. Impact assessment results of REFCS with ethanol from cane sugar production used in off-grid scenario (case 2).

	AP [kg SO_2 eq.]	GWP [kg CO_2 eq.]	EP [kg PO_4--- eq.]	POCP [kg ethylene eq.]	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]
Ethanol production for use stage	104,10	11030,00	46,30	1,88	0,04	63090,00
Fuel cell system production	79,80	3068,00	31,63	4,11	0,36	42220,00
PSA unit production	2,41	327,50	1,10	0,15	0,01	4091,00
Fuel processor production	13,74	522,90	1,99	0,67	0,02	6988,00
Replaced items in operation, fuel cell system	7,04	613,90	4,48	0,36	0,05	8906,00
Replaced items in operation, PSA unit	0,03	3,69	0,02	0,00	0,00	43,73
Replaced items in operation, fuel processor	0,00	0,00	0,00	0,00	0,00	0,00
Replaced items in operation, complete system integration	0,28	24,17	0,18	0,02	0,00	330,80
Complete system integration (production)	12,40	2120,00	4,06	0,78	0,05	27350,00
Transportation of ethanol	2,50	980,40	0,58	0,16	0,00	14370,00
Use stage	0,00	0,00	0,00	0,00	0,00	0,00
Total life cycle	222,30	18700,00	90,34	8,13	0,54	167400,00

Table 6. Impact assessment results of diesel generator in off-grid scenario.

	AP [kg SO_2 eq.]	GWP [kg CO_2 eq.]	EP [kg PO_4--- eq.]	POCP [kg ethylene eq.]	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]
Diesel generator production	13,02	2046,00	5,18	0,80	0,06	24780,00
Diesel production	51,83	5423,00	6,93	3,34	0,00	505900,00
Transport of diesel	1,28	500,60	0,29	0,08	0,00	7336,00
Use stage	421,20	30660,00	74,32	8,73	0,00	2085,00
Total life cycle	487,30	38630,00	86,73	12,95	0,07	540100,00

Table 7. Environmental impacts of the ethanol production options used in the study. Values are per 1 kg of ethanol.

	AP [kg SO_2 eq.]	GWP [kg CO_2 eq.]	EP [kg PO_4--- eq.]	POCP [kg ethylene eq.]	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]
Market ethanol production	0,007439	0,8853	0,003195	0,0002892	0,000003166	7,711
Ethanol as by-product from cane sugar production	0,005535	0,5869	0,002463	0,0001002	0,000001902	3,356

The results are also presented in figures (Figure 6 to Figure 11), in which the life cycle is divided into four stages: production of the REFCS or diesel generator, including the replaced parts; production of the fuel (ethanol or diesel), transport of the fuel, and finally the use stage. As could be expected when electricity is produced, the production of the fuel is of high importance on all cases except in the impact category of depletion of elementary resources. The REFCS creates fewer impacts than the diesel generator when climate change, acidification, photochemical oxidation and depletion of fossil fuel resources are considered. The diesel generator based electricity is more environmentally friendly in the impact categories of eutrophication potential and depletion of elementary resources.

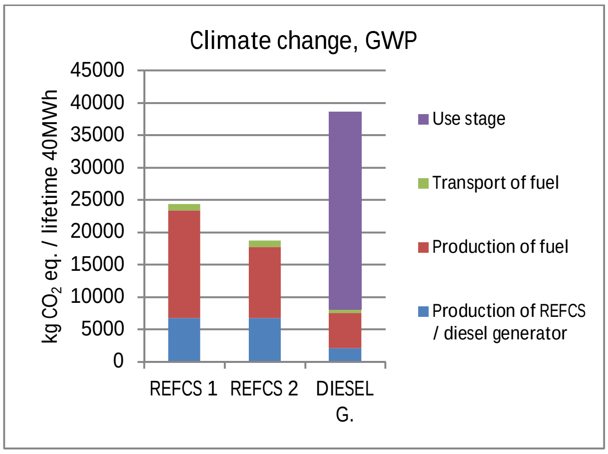

Figure 6. Global warming potential results of the off-grid scenario.

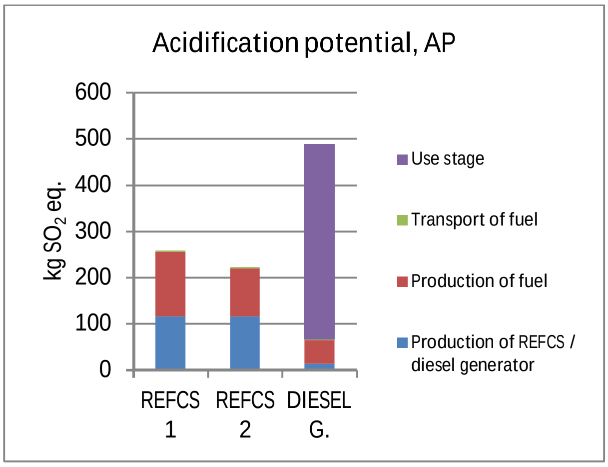

Figure 7. Acidification potential results of the off-grid scenario.

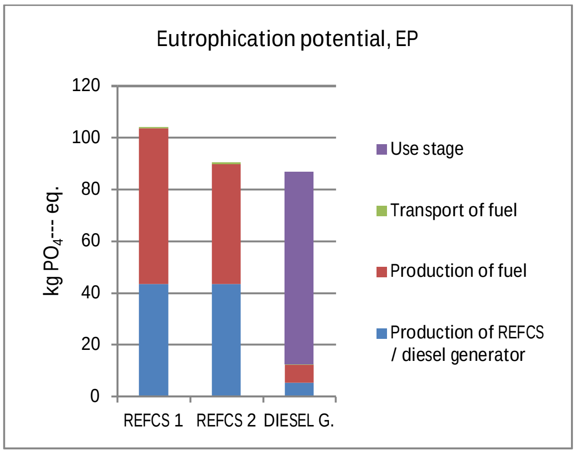

Figure 8. Eutrophication potential results of the off-grid scenario.

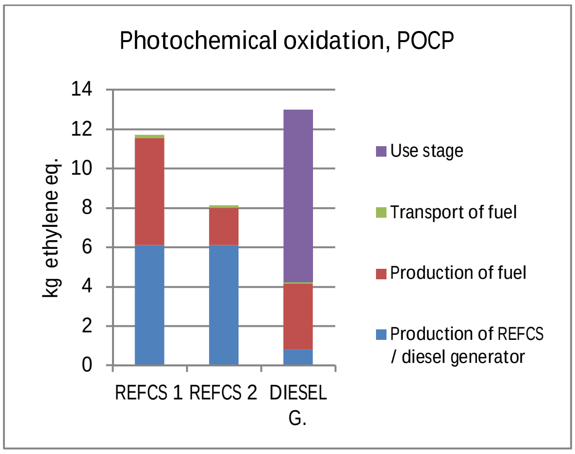

Figure 9. Photochemical oxidation potential results of the off-grid scenario.

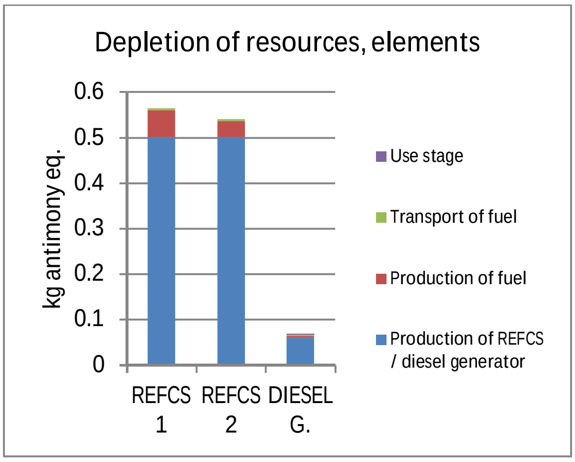

Figure 10. Depletion of element resources results of the off-grid scenario

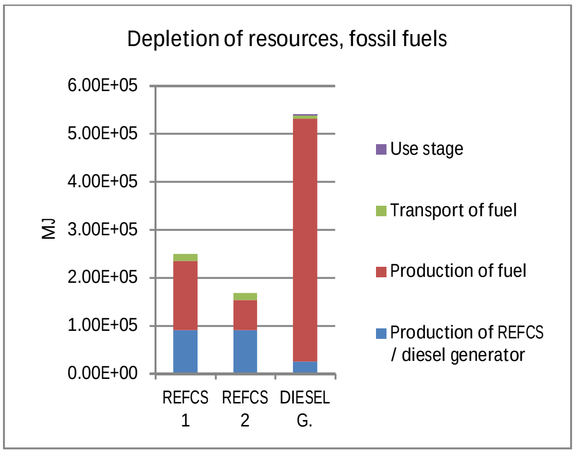

Figure 11. Depletion of fossil fuel resources results of the off-grid scenario.

The shares of impacts from life cycle stages in each impact category are presented in more detail below in Figure 12 for REFCS with market ethanol and Figure 13 for REFCS with ethanol from cane sugar production. The Fuel cell system production is of high importance especially in the depletion of elementary resources –category, since it includes electronics and rare metals (e.g. platinum). However, the production of the fuel – ethanol – is very important in all other impact categories except in the depletion of elementary resources –category.

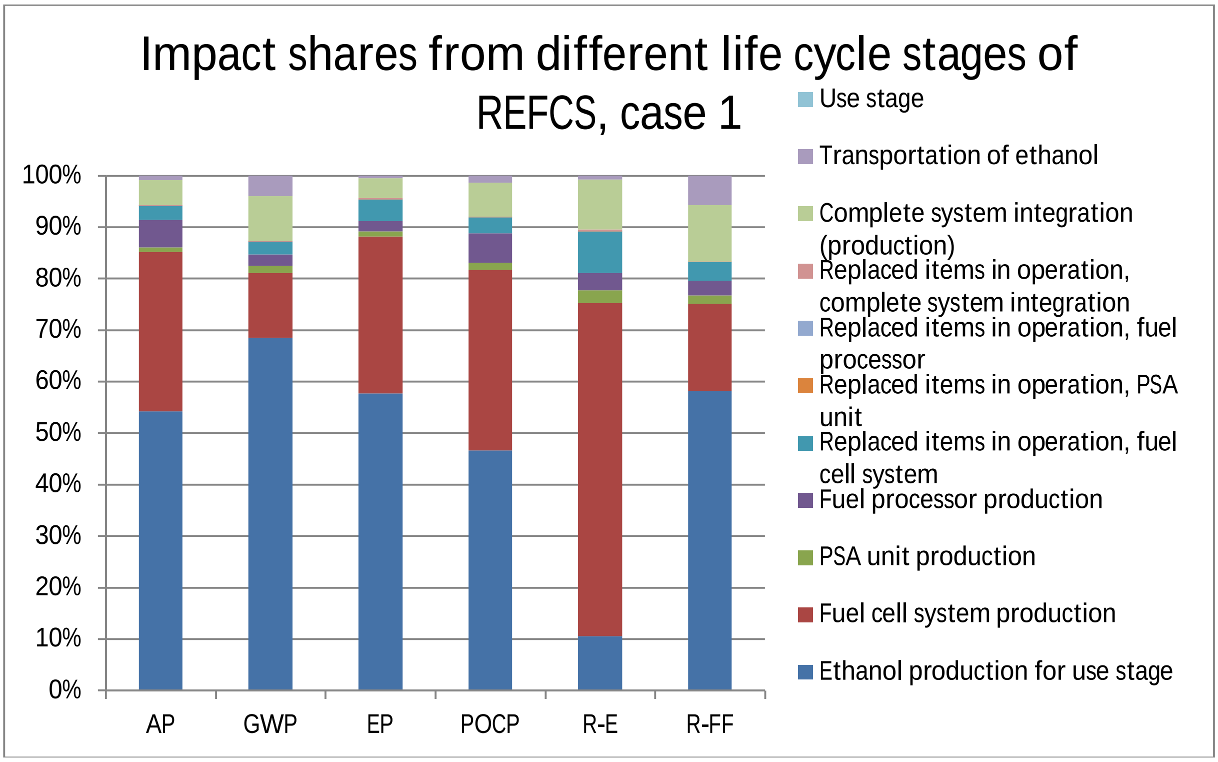

Figure 12. The shares of impacts from different life cycle stages of REFCS with market ethanol used in off-grid scenario (case 1).

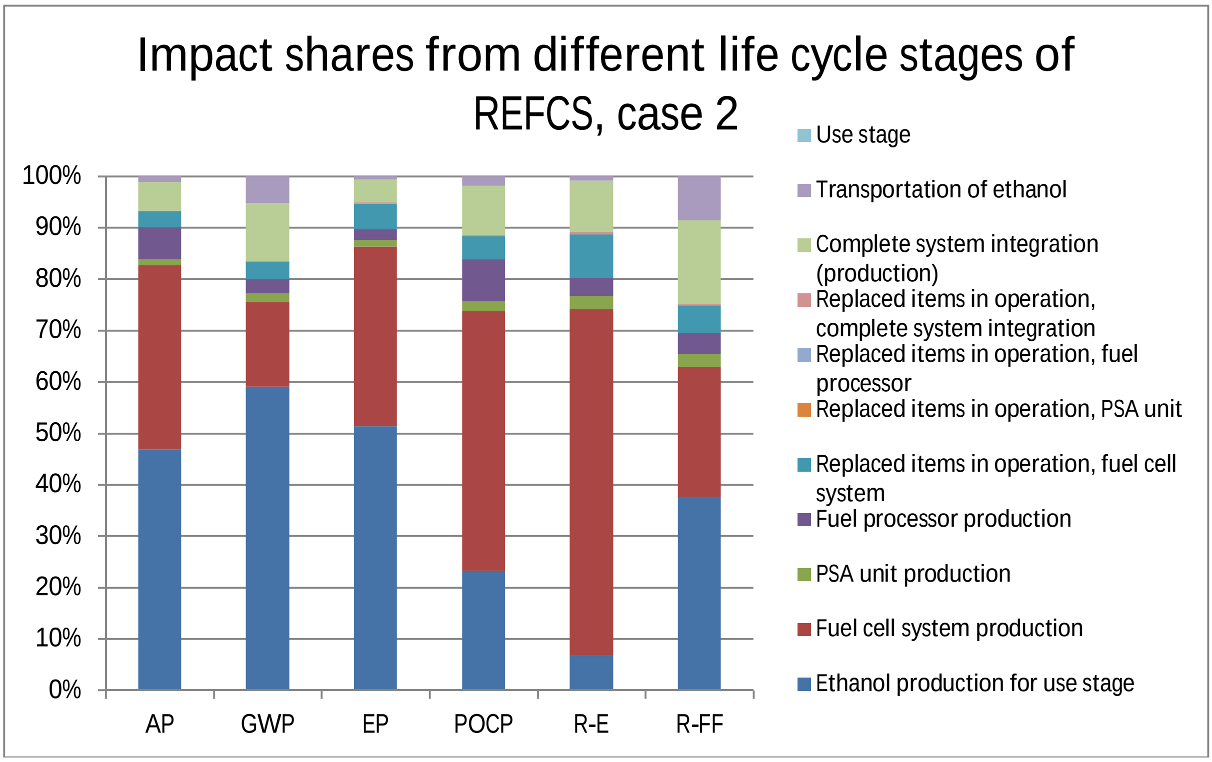

Figure 13. The shares of impacts from different life cycle stages of REFCS with ethanol from cane sugar production used in off-grid scenario (case 2).

Figure 14 shows the relative results of the three cases when compared to the diesel generator. The impacts from the diesel generator case are approximately twofold in the acidification category, in the global warming category and in the depletion of the fossil fuel resources category compared to the REFCS cases. The photochemical oxidation potential is also a bit lower in the REFCS cases. However, the diesel generator saves elementary resources, since the REFCS causes 8 times higher elementary resource depletion (note: the bar is fully shown in the figure). The diesel generator also causes a bit less eutrophication than the REFCS cases. The use of cane sugar based ethanol also decreases the environmental impacts compared to the market ethanol.

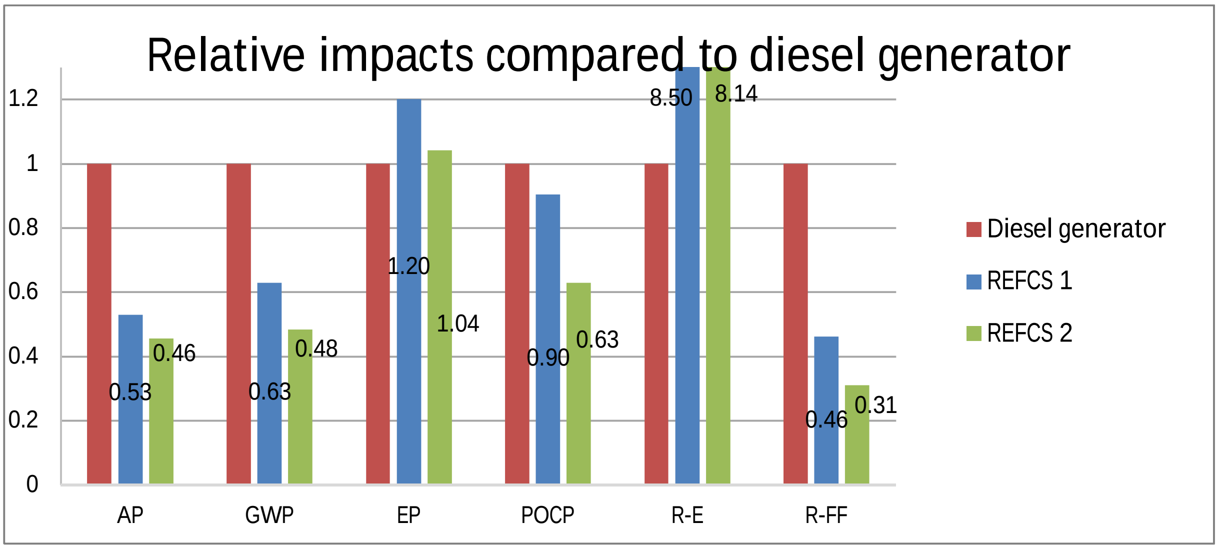

Figure 14. The relative impact assessment results of all three cases studied in the off-grid scenario, compared to the diesel generator.

4.2 Back-up scenario results

The results of the impact assessment calculations of 4 MWh of electricity produced with REFCS and diesel generator are presented in the following tables. The results include acidification potential, global warming potential, eutrophication potential, photochemical oxidation (summer smog) potential and abiotic depletion of elementary and fossil fuel resources.

Table 8 represents the impact assessment results of REFCS with market ethanol used, Table 9 describes the results of REFCS with ethanol from cane sugar production used, and Table 10 shows the results for diesel generator. As can be seen, the ethanol from cane sugar production has smaller impact than market ethanol, which is produced with several methods. This result was similar to the off-grid study. However, in this scenario, the impacts from the diesel generator are smaller than those of REFCS in all studied impact categories.

Table 8. Impact assessment results of REFCS with market ethanol used in back-up scenario (case 1).

	AP [kg SO_2 eq.]	GWP [kg CO_2 eq.]	EP [kg PO_4--- eq.]	POCP [kg ethylene eq.]	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]
Ethanol production for use stage	13,99	1664,00	6,01	0,54	0,01	14500,00
Fuel cell system production	79,80	3068,00	31,63	4,11	0,36	42220,00
PSA unit production	2,41	327,50	1,10	0,15	0,01	4091,00
Fuel processor production	13,74	522,90	1,99	0,67	0,02	6988,00
Complete system integration (production)	12,40	2120,00	4,06	0,78	0,05	27350,00
Transportation of ethanol	0,25	98,04	0,06	0,02	0,00	1437,00
Use stage	0,00	0,00	0,00	0,00	0,00	0,00
Total life cycle	122,60	7801,00	44,84	6,27	0,46	96590,00

Table 9. Impact assessment results of REFCS with ethanol from cane sugar production used in back-up scenario (case 2).

	AP [kg SO_2 eq.]	GWP [kg CO_2 eq.]	EP [kg PO_4--- eq.]	POCP [kg ethylene eq.]	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]
Ethanol production for use stage	10,41	1103,00	4,63	0,19	0,00	6309,00
Fuel cell system production	79,80	3068,00	31,63	4,11	0,36	42220,00
PSA unit production	2,41	327,50	1,10	0,15	0,01	4091,00
Fuel processor production	13,74	522,90	1,99	0,67	0,02	6988,00
Complete system integration (production)	12,40	2120,00	4,06	0,78	0,05	27350,00
Transportation of ethanol	0,25	98,04	0,06	0,02	0,00	1437,00
Use stage	0,00	0,00	0,00	0,00	0,00	0,00
Total life cycle	119,00	7240,00	43,46	5,91	0,46	88400,00

Table 10. Impact assessment results of diesel generator in back-up scenario.

	AP [kg SO_2 eq.]	GWP [kg CO_2 eq.]	EP [kg PO_4--- eq.]	POCP [kg ethylene eq.]	ADP, elements [kg antimony eq.]	ADP, fossil fuels [MJ]
Diesel generator production	13,02	2046,00	5,18	0,80	0,06	24780,00
Diesel production	5,18	542,30	0,69	0,33	0,00	50590,00
Transport of diesel	0,13	50,06	0,03	0,01	0,00	733,60
Use stage	42,12	3066,00	7,43	0,87	0,00	208,50
Total life cycle	60,45	5705,00	13,34	2,02	0,06	76310,00

The results are again also presented in figures (Figure 15 to Figure 20), in which the life cycle is divided into four stages: production of the REFCS or diesel generator, including the replaced parts; production of the fuel (ethanol or diesel), transport of the fuel, and finally the use stage. Since in this scenario less electricity is produced due to the back-up use of the equipment, the production of the fuel is of less importance compared to the off-grid scenario. On the contrary, the production of the equipment has even a greater role in all impact categories. The diesel generator case is the most environmentally friendly case in all impact categories in this scenario.

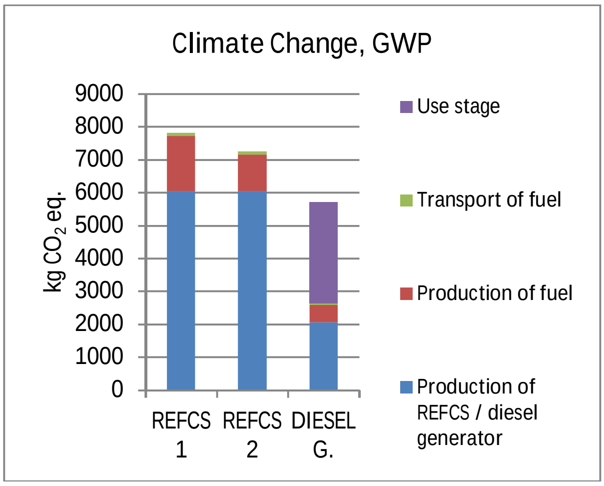

Figure 15. Global warming potential results of the back-up scenario.

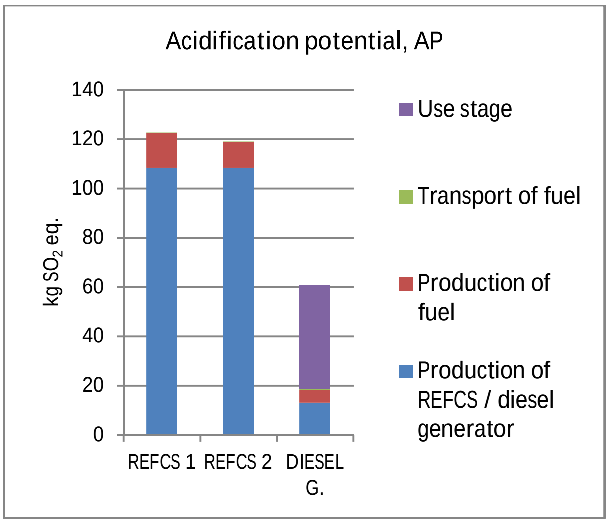

Figure 16. Acidification potential results of the back-up scenario.

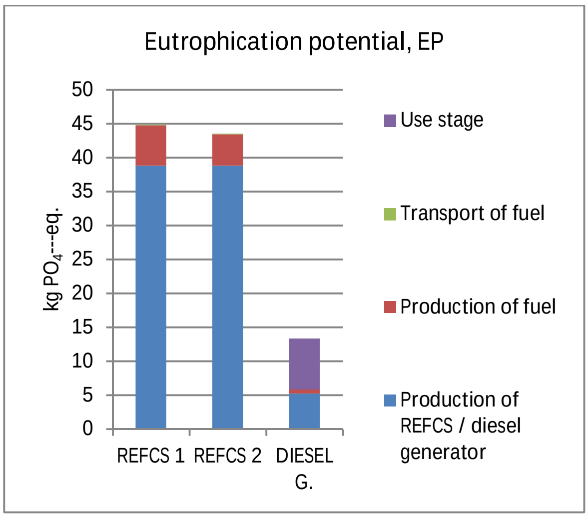

Figure 17. Eutrophication potential results of the back-up scenario.

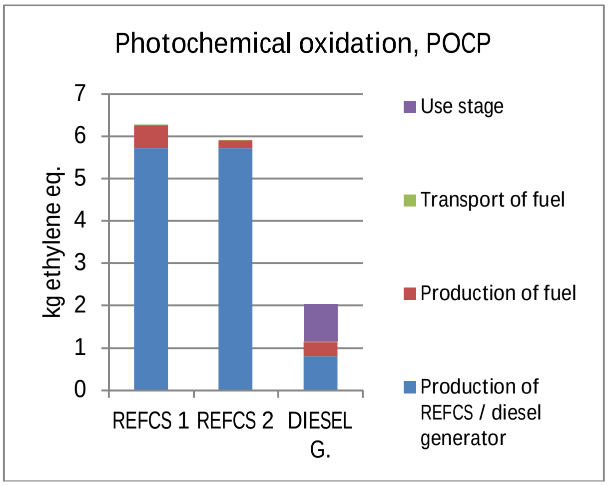

Figure 18. Photochemical oxidation potential results of the back-up scenario.

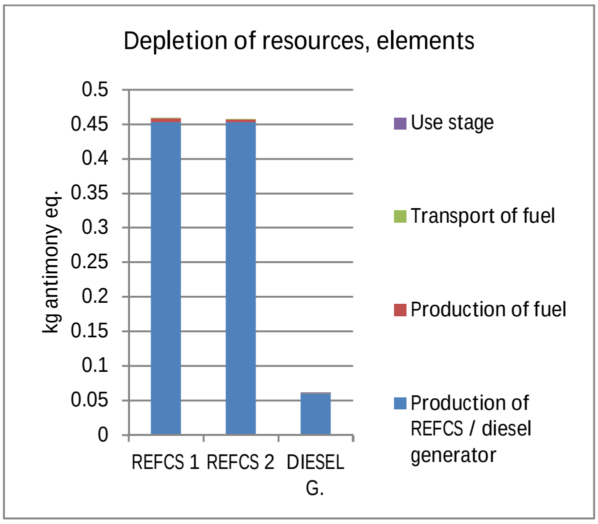

Figure 19. Depletion of element resources results of the back-up scenario.

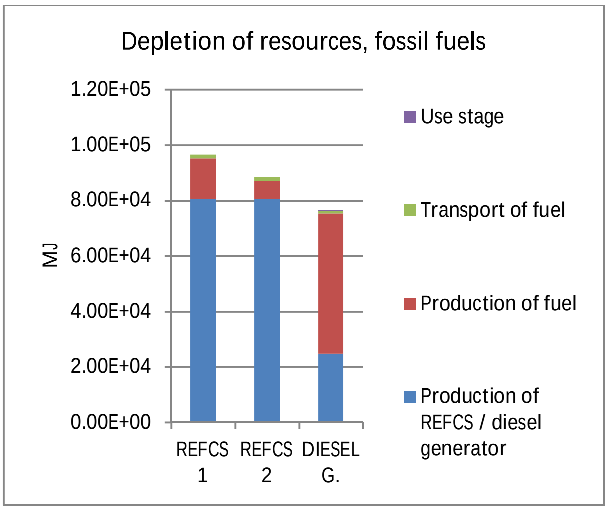

Figure 20. Depletion of fossil fuel resources results of the back-up scenario

The shares of impacts from more detailed life cycle stages in each impact category are presented below in Figure 21 for REFCS with market ethanol and Figure 22 for REFCS with ethanol from cane sugar production. The Fuel cell system production is of high importance in all categories, since it includes electronics and rare metals (e.g. platinum). However, the production of the fuel – ethanol – is less important since it is used less in this scenario. It should be noted also, that there is no need for replaced parts in the REFCS equipment in this scenario.

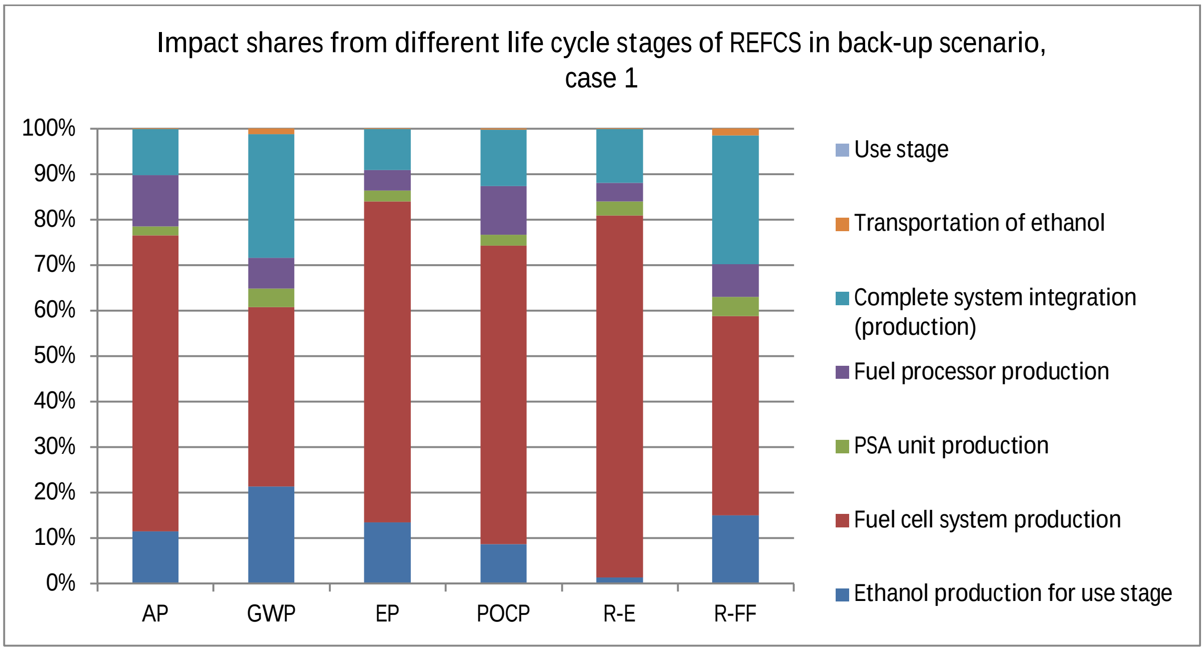

Figure 21. The shares of impacts from different life cycle stages of REFCS with market ethanol used in back-up scenario (case 1).

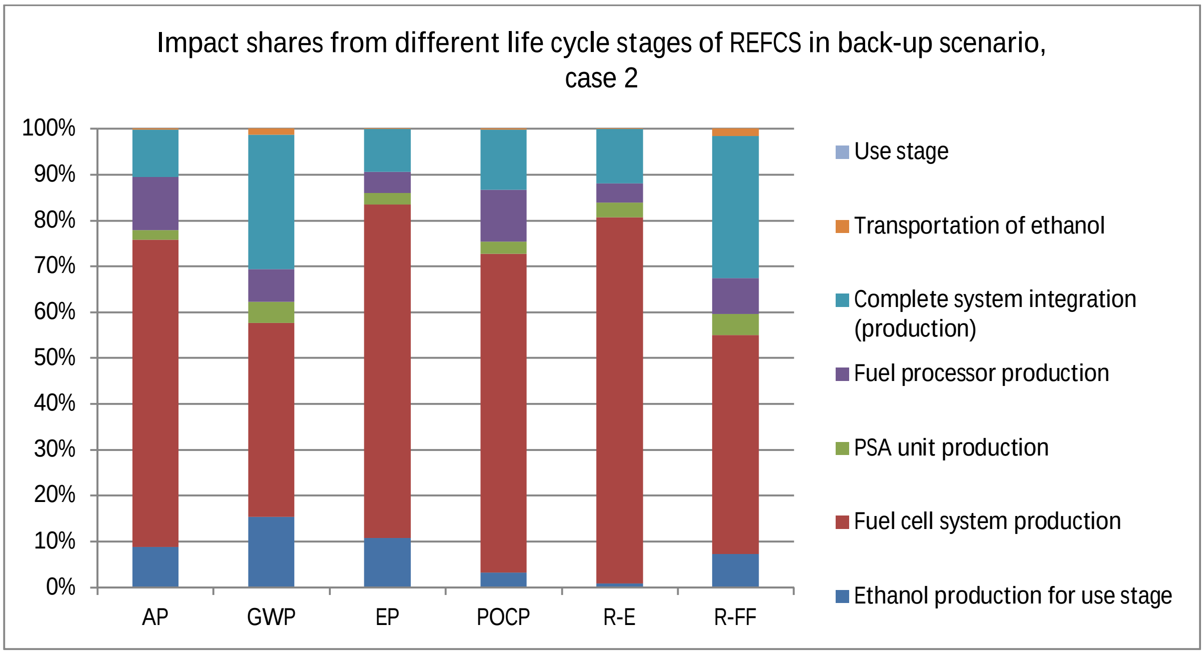

Figure 22. The shares of impacts from different life cycle stages of REFCS with ethanol from cane sugar production used in back-up scenario (case 2)

Figure 23 shows the relative results of the three cases, when diesel generator is the reference case. The impacts from the diesel generator case are smaller in all categories.

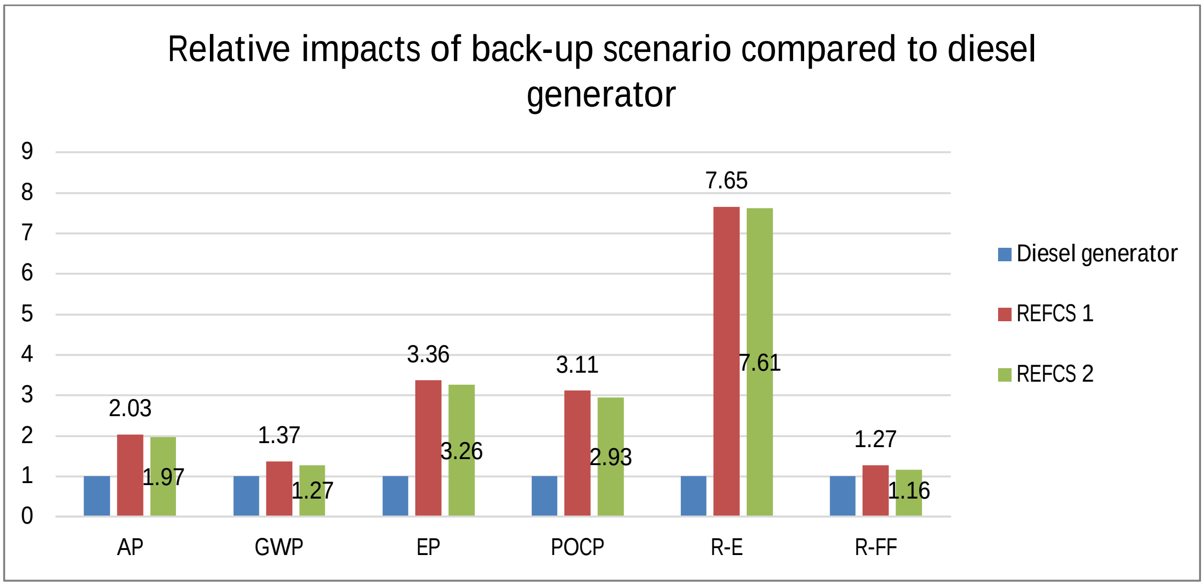

Figure 23. The relative impact assessment results of all three cases studied in the back-up scenario, compared to the diesel generator.

Since the impacts of the REFCS in the back-up scenario were higher than the impacts of the diesel generator, the break-even point for the two systems was estimated for the global warming potential. When the fuel consumption and electricity production in both cases were increased to create c. 8,5 MWh, the GWP impact from the diesel generator exceeded the impact from the REFCS system, i.e. the higher impact from REFCS manufacturing is canceled by the benefits of using bioethanol instead of diesel. This break-even point would equal to c. 213 h of usage per year instead of the 100 h of usage evaluated in the scenario.

5. Discussion, conclusions and recommendations

When the results of both off-grid and especially back-up scenarios are studied, it is easy to see that the production of REFCS is of higher importance than the production of the diesel generator. This is due to the fact that the REFCS equipment being developed in this project is only at prototype stage, meaning that the system was built for the first time. It is very likely, that once the REFCS is fully ready to be commercialized, the amount of materials used is decreased, e.g. by optimizing the steel components' wall thicknesses etc. Thus, the impact from the REFCS production would be smaller. However, as the REFCS technology uses rare materials such as catalysts, it is foreseen that the impact of manufacturing the system is very unlikely to go below that of the diesel generator. Thus, to reduce the overall impact, the benefits come mainly through higher efficiency and low impact of the fuel use itself.

As said, depletion and mining of rare elements is a large factor in the manufacturing of the fuel cell system and fuel processor. In this study, recycling and allocation of environmental burden of the recycled materials to the following life cycles was left out. For stationary fuel cell stacks, up to 90 % of the elements could be recovered. (Pehnt 2001). The same recovery percentage could be applied also for fuel processor reactors. In addition, large amounts of metals and plastics could be recycled with small effort. Allocation to materials going to recycling would decrease the impacts from the REFCS production stage remarkably, depending on the allocation method used. This would decrease the impacts from the REFCS production stage, and improve the environmental benefits further when compared to the diesel generator.

Another consideration is that even though the REFCS has only a 2 kW continuous power output, the Fuel cell system (FCS) is sized to produce 7 kW of net power. Also this somewhat exaggerates the resources required for the manufacturing, and if the system would be designed for 2 kW output, the impact of manufacturing would be significantly reduced. In fact, it can be stated that the material and energy needed for the FCS production (and maintenance) would then be only 30 % of the current value (2/7=0.286≈0.3). This would play a major role especially in the back-up scenario, where the production of fuel cell system creates 40-80 % of the impacts, depending on the category studied. This scaling of the fuel cell system would actually decrease the impacts from the REFCS cases so remarkably that the climate change impact would be equal to the diesel generator in the market ethanol case and 10% lower for the by-product ethanol case, when 4 MWh is produced (back-up case). Also, the acidification potential impact would be of the same level for REFCS cases and diesel generator, and the impact in fossil fuel depletion would be lower for the REFCS cases than for the diesel generator. The depletion of elementary resources would also drop by 50 % compared to the case presented earlier in this report. This scaling of the FCS combined to the recycling of materials would improve the environmental aspects of REFCS compared to the diesel generator, especially in the back-up scenario.

The production of ethanol is also of high importance. The ethanol used in the analysis was market bioethanol, not necessarily crude bioethanol. If ethanol is manufactured from waste streams, the CO_2-eq. emissions are lower. This may have a large effect on the use stage, if no farmland is actively being used for the ethanol production. The Ecoinvent database has several different ethanol production options, of which the lowest climate impact belongs to “ethanol production from sugar beet molasses”, which has a carbon footprint of c. 0,35 kg CO_2 eq. / kg ethanol. This would bring the climate impact even further down from market ethanol (c. 0,89 kg CO_2 eq. / kg ethanol) and from by-product ethanol from cane sugar production (c. 0,59 kg CO_2 eq. / kg ethanol). Conflict of interest between food production and land area is evident on first generation biofuels, where arable land is reserved for fuel production. In second generation biofuels, in addition to waste streams, the feedstock may be some other type of biomass that is produced in land areas not suitable for crop production.

One thing that was not considered in this study but what could be important is the preservability of diesel vs. ethanol. Since the storage time of the fuels affects the frequency of how often fuels should be delivered to the usage location, it can also have an effect on the environmental impacts. According to some sources (e.g. Bp Australia limited 2005), diesel stays useable when stored for 12 months or longer at an ambient of 20 ºC, but only 6-12 months at an ambient temperature higher than 30 ºC, which could be the case in the scenarios of this project since the location is in Australia. On the other hand, ethanol should be useable for years and years if sealed properly and not being in contact with air. In remote areas where the REFCS or diesel generators would be used in off-grid applications, the fuels could be stored for a long time, and this aspect should also be considered when selecting the equipment for power applications.

All in all, REFCS has many benefits compared to the diesel generator in off-grid application, especially since no recycling of the materials at the end-of-life stage was yet taken into consideration. Recycling would allocate some of the environmental burden to the recycled materials and decrease the burden related to REFCS production. Thus, it can be said that in off-grid applications, REFCS is a good choice compared to diesel generator. However, due to higher use of resources in the manufacturing, using the REFCS for a pure back-up application is not a good option even though the impacts from the REFCS production are probably exaggerated in the scenarios, as explained in the beginning of this chapter. Instead, especially in Europe, where hydrogen infrastructure is available, the diesel generator should also be compared to using only the Fuel Cell system with hydrogen as fuel. In addition, using biodiesel in a diesel genset is one viable option that should be investigated more. However, with biodiesel, local particle and NO_x emissions are still a problem. Electrochemical fuel conversion does not produce harmful local emissions, which would allow it to be used in cities, where using large scale diesel back-up power is forbidden. Also construction sites using power tools could benefit from the absence of local harmful emissions.

REFERENCES

Alvarez, S., Carballo-Penela, A., Mateo-Mantecón, I. and Rubio, A. 2016. Strengths-Weaknesses-Opportunities-Threats analysis of carbon footprint indicator and derived recommendations. Journal of Cleaner Production 121 (2016), pp.238-247 http://www.sciencedirect.com/science/article/pii/S0959652616001736 [Accessed 09.05.2016]

Biofuels Association of Australia 2017. How is ethanol made? http://biofuelsassociation.com.au/biofuels/ethanol/how-is-ethanol-made/ [Accessed 04.09.2017]

Bp Australia limited (2005). Fuel News, Long term storage of diesel. https://www.bp.com/content/dam/bp-country/en_au/media/fuel-news/long-term-storage-diesel.pdf [Accessed 06.11.2017]

BSI PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution (BSI), London, UK (2011) 38 pp. [ISBN 978 0 580 71382 8] http://shop.bsigroup.com/upload/shop/download/pas/pas2050.pdf

CML-IA, 2016. CML-IA Characterisation Factors. http://www.cml.leiden.edu/software/data-cmlia.html [Accessed 23.11.2017]

Fang, K. and Heijungs, R. 2015. Investigating the inventory and characterization aspects of footprinting methods: lessons for the classification and integration of footprints. Journal of Cleaner Production 108 (2015) part A, pp.1028-1036 http://www.sciencedirect.com/science/article/pii/S0959652615008197 [Accessed 09.05.2016]

Goedkoop, M. J., Heijungs, R., Huijbregts, M., De Schryver. A., Struijs, J., & Van Zelm, R., ReCiPe. (2008). A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level (1st ed.). In Report I: Characterisation. http://www.rivm.nl/dsresource?objectid=8ed17c8e-a370-437f-afc7-3004b6cce2bc [Accessed 01.11.2017]

ISO/TS 14067 2013. Greenhouse gases. Carbon footprint of products. Requirements and guidelines for quantification and communication.

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

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

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Lozanovski, A., Schuller, O., and Faltenbacher, M., (2011) Guidance document for performing LCA on hydrogen production systems. http://www.fc-hyguide.eu/documents/10156/HY_Guidance_Document.pdf [Accessed 06.11.2017]

Masoni, P. and Zamagni, A. 2011. Guidance document for performing LCA on fuel cells. http://www.fc-hyguide.eu/documents/10156/FC_Guidance_Document.pdf [Accessed 06.11.2017]

Pehnt, M. 2001. Life-cycle assessment of fuel cell stacks. International Journal of Hydrogen Energy 26 (2001), pp. 91-101.
http://www.sciencedirect.com/science/article/pii/S0360319900000537

Sarsama, J., Nissilä, M., Koski, P., Kaisalo, N., and Tallgren, J. (2017). Deliverable 6.5 Hazop report. EU- project PEMBeyond - PEMFC system and low-grade bioethanol processor unit development for back-up and off-grid power applications. http://pembeyond.eu/deliverables/D6.5%20HAZOP%20report.pdf [Accessed 06.11.2017]

Wichert, M. 2017. Emailed information from Martin Wichert, 22.3.2017.