REDUCING ENVIRONMENTAL IMPACTS OF THE UPS SYSTEM BASED ON PEM FUEL CELL WITH CIRCULAR ECONOMY

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Abstract

In this paper an environmental impacts of a 3 kW uninterruptible power supply system with polymer membrane fuel cell (FCH-UPS) was evaluated with a life cycle assessment (LCA) method. The analysis was focused on the analysis of the end of life (EOL) scenarios that will help to reduce environmental impacts during manufacturing stage. Numerical model of the FCH-UPS was developed using Gabi software. The scope of analysis was cradle-to-grave with functional unit 1 kWh of produced electric energy. In operating phase two geographical locations are compared where hydrogen is produced with electrolysis on-site. Three EOL scenarios were analysed: base, feasible and realistic scenario. With realistic EOL scenario in average a 72% reduction of all environmental impacts in the manufacturing phase was achieved. EOL phase of 3kW FCH-UPS represents low environmental impact compared with other phases in the entire life cycle of observed system. CO₂ emissions of 3 kW FCH-UPS system was 239 g CO₂ per 1 kWh of produced electricity if operating in Norway and 4040 g CO₂ per 1 kWh in Morocco due to electricity grid mix. Results show that with circular economy, recycling and reuse of the materials in EOL phase, an average reduction of 66 % in all environmental impact indicators could be achieved in entire life cycle of a 3kW FCH-UPS system operated in Norway.

Keywords: Life cycle assessment (LCA), hydrogen technologies (HT), end of life assessment (EOLA), polymer exchange membrane fuel cell (PEMFC), uninterruptible power supply (UPS), circular economy

1 INTRODUCTION

Uninterruptible power supply (UPS) system could provide clean, conditioned and uninterruptible power to the sensitive loads such as airlines computers, data centres, communication systems, telecommunications grids and medicals support systems in hospitals etc. [1]. For reliable operation without grid blackouts, electrical energy is needed all the time, without interference. Because of the complexity of electrical grid system, the probability of the electricity blackouts is not negligible. In these cases the UPS systems provide reliable constant voltage and constant frequency [2]. Conventional UPS systems consist in most cases from battery stacks. UPS with batteries as storage source provides good performance during grid interruption and blackout by supplying instant backup energy. However, batteries cannot provide backup for a very long period of time and have limited charge/discharge cycles. Actually, battery-backed UPS with emergency power generation is based on rapid start diesel engines for longer backup operation. Those also come up with some negative characteristics, such as low energy density (see Figure 1), short life time, strict working temperature range, high-cost maintenance and hazardous effect to the environment [3]. Batteries also contain toxic heavy metals such as cadmium, mercury, and lead which may cause serious environmental issues [4]. To mitigate those drawbacks, many researchers have been working on alternative power sources to replace battery based UPS systems. Fuel cell (FC) is better than traditional internal combustion engines (ICE) for electricity generation in many aspects, such as: high energy density, high efficiency and zero pollution during operation. It is an ecological necessity and a technological challenge to reduce dependence on oil by using alternative fuels, improving the energy efficiency of the existing technologies and developing low carbon technologies such as fuel cell and hydrogen (FCH) technologies [5]. That is why FCH systems are becoming one of the candidates for the next generation of energy producers [6]. UPS systems for electricity generation, which are based on FCH technologies (FCH-UPS), are limited mostly by fuel (hydrogen) availability. At normal operation FCH-UPS are able to operate without special maintenance 10 years and more [7]. In contrary to ICE-UPS systems they have almost no moving parts which lower the maintenance costs and emit no noise during operation. In addition, the conversion of chemical energy of fuel into electricity occurs via effective electrochemical

processes. The energy efficiency of the FCH-UPS is higher compared to the ICE-UPS at wide range of capacity [8]. FCH technology is seen as a great opportunity to reduce environmental impacts in respect to environmental protection and sustainability due to less harmful emissions for people's health compared to ICE-UPS systems. One of the major challenges for FCH-UPS is the decrease of the high costs of main components (e.g. FC) in order to reduce lifecycle costs to more competitive levels [9].

Figure 1: Energy and power density for UPS system, [4]

As stated above the FCH-UPS system has several advantages over conventional UPS systems, such as longer backup time, higher efficiency, higher energy and power density, longer lifespan, lower maintenance cost and environmental soundness [10]. In addition FCH-UPS systems are considered feasible to be integrated into advanced energy supply systems on large scale [11,12]. The three subsystems: hydrogen production system, hydrogen storage tank and FC have the ability to convert electric energy into hydrogen based chemical energy, store it, and convert it back into electricity when needed. If hydrogen is produced from renewable energy sources (RES), such a system emits small amounts of emissions in its operational phase. However, in other phases of its life cycle: raw materials production, manufacturing, transport and end of life, it is expected to have certain environmental impact. Currently almost half of the hydrogen used all over the world comes from steam reforming of natural gas (48%), 29% from liquid hydrocarbons, 18% from coal and just 4 % is produced with electrolysis [13].

Figure 2: Advanced energy system with H_2 infrastructure, [14]

Figure 2 shows the advanced energy system in the future energy supply, where redundant electrical energy is converted into hydrogen with electrolysis. With FCH-UPS system the conversion back to electricity is possible when needed. But such an advanced energy system have intermittent and very fluctuating operating load conditions (on-off cycles, variable loads, ramps, etc.), which lead to different degradation mechanisms within FCH technologies. This degradation mechanisms cause shorter lifespan, lower efficiency, lower power and consequently higher overall environmental impact in the entire life cycle of the FCH system [15–18].

To proper assess environmental impacts of an FCH-UPS system a life cycle assessment (LCA) method should be used that is a standardised technique to determine the environmental impacts associated with all stages of a product's life. It can serve to improve a product's environmental profile, compare it to incumbent technology or help to make environmental labels and declarations.

LCA method was successfully used by other authors to analyse environmental impacts for various FCH technologies in different energy systems. Ghandehariun with Kumar [19] assessed environmental impacts associated with hydrogen production through water electrolysis using the electricity generated from a wind power plant. Kumar with Verma [20] evaluate life cycle greenhouse gas emissions in H₂ production from underground coal gasification with and without carbon capture and sequestration. The environmental performance of hydrogen and electricity production by supercritical water reforming of glycerol was evaluated by Galera with Gutiérrez Ortiz [21]. Valente et al. [22] analysed the correlation between global warming potential (GW) and acidification potential (A) of hydrogen energy systems and its validity to estimate the harmonised environmental A indicator. Evangelisti et al. [23] presented a comprehensive life cycle assessment of a fuel cell vehicles focused on its manufacturing phase and compared with the production of battery electric vehicle and an internal combustion engine vehicle. The use and disposal phase were also included in the analysis and results show that for GW in the end of life phase has negligible impact in entire life cycle. Similar study to Evangelisti et al. was done by Lombardi et al. [24]. Garraín and Lechón [25] are one of the few who studied comparison of environmental impacts in the manufacturing process and recycling for end of life strategies of a polymer electrolyte membrane (PEM) fuel cell mounted in a cargo bike in the GW, energy use and A indicators. As far as the analysis of the LCA method of FCH-UPS systems is concerned, there have not been many studies so far. Mori et al. [26] analysed the impacts of an UPS system based on FCH technologies from extraction of raw materials to the end of operation phase, using renewable energy sources for hydrogen production. The study shows that the use of FCH-UPS could reduce environmental impacts of electricity generation and distribution. Agostini et al. [27] presented the study in the framework of the EU project SSH2S, a solid-state hydrogen storage tank - fuel cell system as Auxiliary Power Unit (APU) for a light duty vehicle. The aim of the study was to assess environmental impacts of the APU and conclusions show that APU systems using tanks based on solid-state hydrogen storage materials have similar environmental performances than compressed gas systems. However, Agostini et al. pointed out that the inclusion of the end of life stage and recycling of materials may result in different conclusions for environmental impacts of an APU system.

From the literature review it could be seen that several authors analysed FCH technologies in UPS applications with LCA method, but without emphasizing EOL phase with possible circular economy principle. Contrary to those studies this paper evaluates environmental impacts from cradle to the grave of FCH-UPS system with three EOL scenarios as recommended by guidance document for performing LCA on FCH technologies from EU project FC-HyGuide (G.A. 256328 and 256850) [28,29]. 3 kW FCH-UPS system (shown in Figure 3), produced by Electro Power Systems from Torino, is the main objective of this study. Main components included in the study are: air blower, external heat exchanger, hydrogen recirculation blower, PEM fuel cell stack, air humidifier, controls and regulation system and other balance of plant (BoP) components needed. Main cabinet and lead batteries are manufactured in different locations across Europe. In the study all components were modelled according to detailed manufacturer's data and numerical models also for all BoP components were set up.

Figure 3: Left: Fuel cell and developed BoP; Right: FluMaBack 3kW FCH-UPS system, [7]

The main contribution of this research is environmental impact assessment of the 3 kW FCH-UPS system from extraction of raw materials all the way to the end of life phase. With this paper the importance of circular economy (reuse and recycling) of FCH technologies was shown.

Furthermore, the presented issue in this research is the main goal of the undergoing EU project HyTechCycling founded by FCH JU (G.A. 700190) [30], where the importance of reusing, recycling and remanufacturing of critical, rare, expensive and geostrategic materials in FCH technologies is evaluated with the help of recycling industry and manufacturers in details. Results presented in the paper will be used for future research about new recycling and new dismantling technologies applied to FCH technologies, [31].

2 LIFE CYCLE ASSESSMENT OF 3 KW FCH-UPS

LCA method is the most comprehensive method for evaluating the environmental impact of the product in its all life cycle stages. The LCA method evaluates material and energy inputs, outputs and potential environmental impacts of a product during its lifetime. It consists of four stages: the definition of the goal and scope; the life cycle inventory (LCI) analysis, which is the construction of the product's life cycle model, where all relevant mass and energy flows are quantified; the life cycle impact assessment (LCIA), that is the evaluation of the environmental relevance of these flows and finally the interpretation of results. LCA study in this paper was made according to FC-HyGuide document [28] and ISO standards 14040 and 14044, [32,33].

2.1 The goal and the scope of the study

The goal and scope define the exact questions that the analysis will try to answer, and set its spatial, temporal, and technological boundaries. The product's function is defined and quantified by the functional unit and in this study the functional unit is 1 kWh of produced uninterrupted electricity. The type of analysis was cradle-to-grave (from production of raw materials to end of life scenarios - EOL). The goal of the study was to determine environmental impacts of the 3kW FCH-UPS and evaluate those impacts at different phases: manufacturing, transportation, operation and end-of-life (EOL). Two utilization sites, one in northern Africa (Marrakesh, Morocco) and one in northern Europe (Oslo, Norway), were used for evaluation of operational phase environmental impacts. The study is physically limited to the FCH-UPS system, while the manufacturing of the hydrogen production facility was not included. The system's physical boundaries include the all UPS's subsystems. Transport via railway, cargo ship and truck has been included in LCA models. Operation phase is considered to be 10,000 h which is approximately 10 years' time. In the LCA model the maintenance of the system is excluded. Finally, three different EOL scenarios were analysed.

2.2 LCA model of FCH-UPS system

The model of FCH-UPS system is shown in Figure 4, with all material and energy inputs. A top-to-bottom principle was used to model the system, which contains: materials and energy inputs, seven manufacturing processes (FC, air blower, hydrogen blower, external chiller, humidifier, battery stack and additional components), nine transport processes, two operation processes and three EOL scenarios for each operating site. Model was set up on four layers with plan nesting technique in Gabi software. All parts in manufacturing phase were modelled according to detailed manufacturer's data presented in public document, [7]. In the EOL phase landfill, reuse and recycling strategies were used in three EOL scenarios.

Figure 4: General LCA model of 3 kW FCH-UPS system with boundaries

3 LIFE CYCLE INVENTORY (LCI) ANALYSIS

In LCI analysis all input and output flows are translated into contribution to the chosen environmental impact categories. In the study all virgin material mass flows, used for BoP components manufacturing processes, are included. Also, emissions during the phases of materials extraction, manufacturing, transport, operation and end of life were included. Data consist of primary data gathered on the basis of manufacturers' masses of materials as inputs in manufacturing processes of BoP components. Secondary data, which are generic databases (Gabi professional, Ecoinvent 3.1) [34,35], are used in all cases where primary data are not available. The basic technical data of analysed 3kW FCH-UPS system are presented in table 1.

Table 1: Basic technical data of 3kW FCH-UPS system

	FluMaBack 3kW
Dimensions / Weight	100 x 100 x 100 / 500 kg
Electrical power	3 kW
Thermal power	NA
Fuel cell	PEM fuel cell
Electrolyte	Nafion™
Efficiency	0.5
Rated voltage output	24 V
Rated el. current output	125 A
Temperature range	up to 65 °C
Lifetime	10,000 h
Fuel	Hydrogen, 99.99 % purity
Fuel consumption (at 3 kWe)	0.0883334 kg/ kWh

3.1 Manufacturing phase

For manufacturing phase detailed data was provided by manufacturers for all components and parts. General mass LCI data for 3 kW FCH-UPS is presented in Table 2. All other data for each UPS component are presented in public available study from EU funded project FluMaBack, [7].

Table 2: Summarized data of LCI analysis for 3kW FCH-UPS

GENERAL	mass	unit
External heat exchanger	23	kg
<u>Air Blower</u>	<u>2.210</u>	<u>kg</u>
rotor	0.282	kg
stator	0.483	kg
impellers	0.152	kg
return channels	0.139	kg
housing, electronics, other	1.153	kg
<u>Hydrogen Blower</u>	<u>1.890</u>	<u>kg</u>
rotor	0.241	kg
stator	0.325	kg
impellers	0.048	kg
covers, volute, housing, motor	1.186	kg
protection		
screws, nuts, small parts	0.014	kg
electronics	0.075	kg
<u>UPS Assembly, Turin</u>	<u>165.130</u>	<u>kg</u>
cabinet	141.500	kg
compressors, fans, pumps	1.500	kg
DC/DC converter	8.180	kg
control panel	1.400	kg
cables	4,000	kg
cooling fan	5,000	kg

pressure regulator	0.550	kg
Valves-Fittings-Piping	3.000	kg
Humidifier	1.975	kg
3 kW FC	28.000	kg
Battery stack	60.800	kg
MASS OF FCH-SYSTEM	283.005	kg

3.2 Operation and hydrogen production

One of the objectives in this study was the comparison of the FCH-UPS system operation at two geographical sites with different electrical energy mixes that are needed for production of hydrogen with electrolysis on-site. Manufacturing of hydrogen production facility was not included in the LCA model. In the case of Morocco the energy grid mix consists from: coal (43%), oil (24%), natural gas (23%), hydro (7%) and wind power (2%). On the contrary, in Norway, 95 % of energy grid mix consists of electricity produced by hydro power plants.

Table 3: LCI table for H₂ production

H ₂ production method	Energy input (for 1 kg H ₂)	Mass (for 1 kg of H ₂)	Remarks
Electrolysis (NO – grid mix)	52.5 kWh	9 kg of water	RES (hydro): 95 %
Electrolysis (MO – grid mix)	52.5 kWh	9 kg of water	RES (hydro + wind): 9 %

3.3 Transport

Transportation modelling has two segments: transportation of the BoP components from manufactures of components to the final assembly site in Torino and transportation of finished FCH-UPS system to the utilization site (Norway and Morocco) with cargo ship, railway and trucks.

3.4 End of life assessment (EOLA) scenarios

For systems with hydrogen technologies different end of life strategies can be considered after the end of lifetime. These processes are reuse, recycle or landfill of materials. If no information regarding materials is available the worst case scenario is applied, which according to HyGuide is landfilling [36]. In this study the landfill scenario was used as a base case scenario. According to the waste management hierarchy, landfilling is the least preferable option and should be limited to the minimum. Furthermore landfilling is an unwanted option for the disposal strategies of FCH technologies, but it is still the most common. All materials of 3kW FCH-UPS system are presented in Table 4 and in the case of base scenario 100% are landfilled.

Table 4: List of all materials in 3kW FCH-UPS system

3kW FCH-UPS FluMaBack		
Material	Mass [g]	Mass [kg]
Steel	163242.52	163.24252
Copper	12341.30	12.3413
Aluminium	19133.50	19.1335
Plastic bonded ferrite	453.00	0.453
Plastics	21166.31	21.16631
Silicon	230.00	0.23
Electronics	815.00	0.815
Tin-lead alloy	39520.00	39.52
Sulfuric acid 96%	4936.00	4.936
Carbon	9768.00	9.768
Nafion	482.40	0.4824
Platinum	17.60	0.0176
Water	10864.00	10.864

The second EOL scenario is feasible scenario, which represents the highest theoretical reuse and recycling possibilities for all materials in the FCH-UPS system. Feasible scenario drastically lowers the input of new materials in the manufacturing phase. In the feasible scenario 68% of reuse and 32% of recycling for all materials was considered (Table 5). The feasible scenario is technically difficult to implement, because manufacturers are not motivated to collect their components after the end of their lifetime on one hand and the complexity of recycling of some specific critical materials on the other hand. Specific guidelines and standards for recycling of FCH technologies do not exist yet. However, the goal of undergoing EU project HyTechCycling [30] is to deliver recommendations and guidelines for EOL phase for the FCH technologies and that is the motivation why we also introduced the third scenario.

Table 5: List of reused and recycled materials for feasible scenario

Feasible EOL scenario					
Reuse			Recycle		
Material	Mass [kg]	Share [%]	Material	Mass [kg]	Share [%]
Aluminium	16.9340	88.5	Aluminium	2.2000	11.5
Copper	6.4413	52.2	Copper	5.9000	47.8
Steel	163.2425	100.0	Plastics	16.8990	79.8
Plastics	4.2673	20.2	Tin-lead alloy	39.5200	100.0
Electronics	0.8150	100.0	Sulfuric acid 96%	4.9360	100.0
Plas. Bon. F.	0.4530	100.0	Water	10.8640	3.8
Silicon	0.2300	100.0	Carbon	9.7680	100.0
Total reuse	192	68.0	Nafion	0.4824	100.0
			Platinum	0.0176	100.0
			Total recycle	91	32.0

Third scenario is realistic EOL scenario and is somewhere in-between the first two scenarios. Realistic scenario represents the highest expected amount of reused and recycled materials and components in the FCH-UPS system according to available recycling and dismantling technologies from recycling industry and manufacturers. In the realistic scenario the reuse of main housing and components with easy dismantling procedure (50% of all mass) was considered and 41% of materials with easy recycling strategies were recycled. Other 9% represents landfilling of small electronic devices and components of the FC, because of the missing data or specific guidelines/legislation for dismantling and recycling of FCH technologies. Masses of the materials for realistic scenario are presented in Table 6. In Table 7 all mass flows used in the EOL scenarios are summarized.

Table 6: List of reused and recycled materials for realistic scenario

Realistic EOL scenario								
Reuse			Recycle			Landfill		
Material	Mass [kg]	Share [%]	Material	Mass [kg]	Share [%]	Material	Mass [kg]	Share [%]
Aluminium	1.12	0.4	Aluminium	17.9610	6.4	Aluminium	0.0530	0.0
Steel	140.18	49.7	Copper	9.5418	3.4	Copper	2.5000	0.9
Plastics	0.14	0.0	Plastics	13.2670	4.7	Steel	4.1056	1.5
Electronics	0.14	0.0	Tin-lead alloy	39.5200	14.0	Plastics	8.0604	2.9
Total reuse	142	50	Sulfuric acid 96%	4.9360	1.7	Plas. Bon. F.	0.4530	0.2
			Water	10.8640	3.8	Carbon	9.7680	3.5
			Silicon	0.2300	0.1	Nafion	0.4824	0.2
			Platinum	0.0176	0.0	Electronics	0.6750	0.2
			Steel	18.9569	6.7	Total landfill	26	9

Table 7: Summary of end of life scenarios for 3kW FCH-UPS system

EOL scenario	Base	Feasible	Realistic
1. Landfill	283kg (100%)	/	26 kg (9%)
2. Reuse	/	192kg (68%)	142 kg (50%)
3. Recycle	/	91kg (32%)	115 kg (41%)

4 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The Life Cycle Impact Assessment (LCIA) helps interpret emissions and resource consumption data that are associated with a product's life cycle in terms of environmental burdens, human health, and resources. The European Platform on LCA provides guidance and data to facilitate LCIA, [37]. For this study the life cycle numerical model was created using GaBi ts software [38,39], which converts the LCI data according to ISO 14040. All environmental impact indicators [40] were analysed according to the CML2001 environmental impact assessment methodology, [41].

Figure 5: Framework of impact categories for characterisation modelling at midpoint and endpoint levels, [37]

CML 2001 is midpoint LCIA methodology with levels of midpoint indicators presented in Figure 5. Within CML 2001 LCIA methodology different global, regional and local environmental midpoint impact indicators were analysed:

Global indicators:

- CML2001 - Jan. 2016, Abiotic Depletion (**AD** elements) [kg Sb eq.]
- CML2001 - Jan. 2016, Global Warming Potential (**GW** 100 years) [kg CO₂ eq.]
- CML2001 - Jan. 2016, Ozone Layer Depletion Potential (**OD**, steady state) [kg R11 eq.]

Regional indicators:

- CML2001 - Jan. 2016, Acidification Potential (**A**) [kg SO₂ eq.]

Local indicators:

- CML2001 - Jan. 2016, Eutrophication Potential (**E**) [kg Phosphate eq.]
- CML2001 - Jan. 2016, Human Toxicity Potential (**HT**) [kg DCB eq.]
- CML2001 - Jan. 2016 v, Photochemical Ozone Creation Potential (**POC**) [kg Ethene eq.]

The results were analysed in terms of chosen environmental indicators, and major contributors to environmental impacts were identified.

5 RESULTS AND DISCUSSION

In the first part of discussion environmental indicators for manufacturing, transportation and operational phase were calculated according to the constructed LCA model presented in Figure 6. In the first part base case EoL scenario, which is landfilling, was taken into account. The second part is focused on comparison of different EoL scenarios of FCH-UPS, contribution to circular economy and reduction of environmental impacts during manufacturing phase because of reuse and recycling of materials. For each EoL scenario the comparison with the base case (landfilling) scenario was made for entire life cycle of the 3kW FCH-UPS system.

5.1 Manufacturing phase

For manufacturing phase the constructed LCA model is presented in Figure 6, where all relevant mass and energy flows were modelled according to LCI data and boundary conditions.

EPS Flumaback 3 kW system - final manufacturing

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

Figure 6: Final LCA model of 3kW FCH-UPS

Results for relative contributions in the manufacturing phase are presented in Figure 7 and more detailed data are shown in Table 8.

Table 8: Relative contribution values of environmental impact for manufacturing phase

	AD	A	E	GW	HT	OD	POC
air blower	18.1 %	4.4 %	24.4 %	3.5 %	17.0 %	0.1 %	4.4 %
H₂ blower	2.8 %	1.1 %	3.8 %	1.2 %	4.5 %	0.0 %	1.1 %
battery	23.7 %	23.3 %	5.7 %	23.0 %	2.5 %	0.0 %	21.1 %
humidifier	0.0 %	0.2 %	0.1 %	0.4 %	0.4 %	0.0 %	0.3 %
external climate	0.1 %	2.8 %	0.7 %	4.4 %	6.6 %	0.0 %	3.8 %
FC stack	19.5 %	43.0 %	10.7 %	35.9 %	20.8 %	99.5 %	31.4 %
cabinet	0.0 %	14.0 %	4.3 %	21.4 %	3.1 %	0.0 %	26.1 %
auxiliary components	35.8 %	11.3 %	50.3 %	10.2 %	45.1 %	0.3 %	11.7 %
Total absolute value	0.177 kg Sb eq.	11.4 kg SO ₂ eq.	3.4 kg PO ₄ eq.	2180 kg CO ₂ eq.	2160 kg DCB eq.	0.0046 kg R11 eq.	0.775 kg Eth. eq.

In the manufacturing process the main impacts come from FC, battery and the cabinet. For indicators E and HT potential the main impacts come from auxiliary components and air blower. Environmental impact is high due to the high mass of steel used in the case of cabinet. In the case of FC and battery high energy consumption in the form of electricity and the use of critical materials during the manufacturing process are very important parameters that have big influence on all environmental indicators. HT potential is the highest in the case of auxiliary components and fuel

cell due to hazardous materials used in electronics of auxiliary components and platinum in FC. The most influential material in almost all environmental impacts criteria (except OD) is platinum, despite its small mass (17.6 g) in 3kW FCH-UPS system. The highest impact in ozone depletion (OD), 90% of all OD potential of the system, comes from Nafion® membrane manufacturing process, which is used to produce PEM fuel cells membranes.

Figure 7: Environmental impacts of FCH-UPS components in manufacturing phase

The list of critical and large quantity materials in 3kW FCH-UPS system with high impacts are presented in Table 9. Platinum as critical material has the biggest share of impact in acidification potential due to the large emissions of sulphur oxides produced during the extraction of the material. In OD criteria almost total OD comes from Nafion manufacturing. The highest impacts for electronic equipment is in AD, E and HT impact indicators. The highest impact in GW in manufacturing phase comes from materials with large quantities such as steel, aluminium and plastics.

Table 9: List of critical and large quantity materials in 3kW FCH-UPS system

Material	Quantity [kg]	CML2001	Material	Quantity [kg]	CML2001
Critical materials			Large quantities		
Platinum	0.0176	ALL except OD	Steel	163.24	GW
Nafion	0.482	GW, OD	Aluminium	19.13	GW, HT
Electronic equipment	0.815	AD, E, GW, HT	Plastics	21.166	GW

5.2 Transportation and operation phase

Operation of FCH-UPS at two different locations was analysed. For that reason two transportation LCA models were set up for transport of FCH-UPS system from Torino to operational site (Figure 8 and Figure 9).

- Northern Europe: Oslo, Norway (truck – ship – truck)
- Northern Africa: Marrakesh, Morocco (truck – container ship – truck)

a.) Manufacturing + transport to North EU (Oslo, NOR)

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

Figure 8: LCA model of transportation to Northern EU

b.) Manufacturing + transport to North Africa (Morocco, Marrakech)

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

Figure 9: LCA model of transportation to Northern Africa

In Figure 11 relative contributions of manufacturing, transport and operation are presented for base case scenario. In operation phase electrolysis on-site was used for hydrogen production process. LCA model of operation phase for Norway is presented in Figure 10. For Morocco operation phase the hydrogen is also produced with electrolysis. The difference compared to Norway is electricity grid mix used that is in Morocco fossil fuel based and in Norway hydropower based.

EPS Flumaback 3kW system - operation (electrolysis, NO grid mix)

Process plan: Reference quantities
The names of the basic processes are shown.

Figure 10: LCA model of operation phase for 30,000 kWh_e (Oslo, Norway)

From results it is evident that the operating phase is very influential compared to the manufacturing and transportation phase, especially at Morocco operational site. Environmental impacts due to operation are mainly influenced by the electricity grid mix of the country (MO and NO). Transport has almost negligible influence in all environmental impact criteria. In the case of Morocco the operational phase has a much bigger impact as in the Norway case due to fossil fuel (91%) based electricity grid mix. On contrary in the Norway the most influential phase is manufacturing phase for most environmental impact criteria (except for GW potential). Electricity grid mix in Norway comes 95% from RES (hydro power) and therefore has a very small influence in operational phase.

Figure 11: Environmental impact indicators for manufacturing, transportation and operation of FCH-UPS

For manufacturing, transport and operation phase the calculation of GW emissions for 1kWh of generated electricity was done. Results show that the CO₂ emissions were 239 g of CO₂ eq. per 1 kWh_e for Norway and 4040 g for Marocco operation site. In Figure 12 comparisons of CO₂ emission per 1 kWh_e for several electricity generation technologies (global averages, [42]) are shown. It is evident that 1kWh of electricity produced with 3 kW FCH-UPS system that is installed in Norway has significantly lower CO₂ emission than electricity from fossil fuels. On the contrary if the same system is installed in Marocco, the impact is almost 17 times bigger.

Figure 12: CO₂ emissions for 1kWh of produced electricity by different technologies

5.3 EOL assessment scenarios for FCH-UPS

Three EOL scenarios were chosen: base (landfilling), feasible and realistic scenario. In the LCA models different amounts (or ratios) of recycled, reused and landfilled materials were used, all according to each of the EOL scenario. Figure 13 shows LCA model for realistic EOL scenario. Three EOL scenarios are defined and presented above in Tables 4-7.

EOLA Scenario 3 + manufacturing

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

Figure 13: Numerical model of Realistic EOL scenario

Results show that recycling and reusing of materials in the EOL phase the reduction of environmental impacts could be achieved in the manufacturing phase. Figure 14 shows the relative reduction of environmental impacts during the manufacture phase, where each of the EOL scenarios is normalized to the base case scenario (landfill). Results of the realistic scenario show that in average a 72% reduction of all analysed environmental indicators could be achieved in the manufacturing phase. The OD potential indicator is excluded in the realistic scenario because there are not enough data available for Nafion recycling, which has is the main contributor in OD indicator. With the feasible scenario a 75% reduction of CO₂ emissions, compared to base case EOL scenario, could be achieved and even higher reductions in other environmental impact indicators. Different processes and strategies in the EOL phase have different environmental impacts. That is why the relative comparison of environmental impacts was made for different EOL processes compared with the manufacturing phase.

Figure 14: Reduction of environmental indicators in manufacturing phase according to EOL scenarios

Table 10 shows results of relative contributions in all environmental impact criteria for manufacturing and EOL processes. In this case operational phase is excluded to get better understanding of manufacturing and EOL phase environmental impacts. Reuse process is considered without any environmental impact. Results show that in the case of the feasible scenario the recycling process has in average 64% lower environmental impacts than manufacturing phase.

Table 10: Relative contribution of EOL processes compared with manufacturing phase

Base	AD	A	E	GW	HT	OD	POC
Manufacturing [%]	100	99.8	99.8	99.8	100	100	99.7
Landfill [%]	0	0.2	0.2	0.2	0	0	0.3
Total value	0.177 [kg Sb eq.]	12.308 [kg SO ₂ eq.]	3.424 [kg PO ₄ eq.]	2172 [kg CO ₂ eq.]	1767.2 [kg DCB eq.]	0.004 [kg R11 eq.]	0.882 [kg Eth. eq.]
Feasible	AD	A	E	GW	HT	OD	POC
Manufacturing [%]	78.6	74.7	80.6	94.9	71.6	98.1	74.4
Recycling [%]	21.4	25.3	19.4	5.1	28.4	1.9	25.6
Total value	0.00095 [kg Sb eq.]	2.605 [kg SO ₂ eq.]	0.184 [kg PO ₄ eq.]	565 [kg CO ₂ eq.]	42.6 [kg DCB eq.]	0.00046 [kg R11 eq.]	0.136 [kg Eth. eq.]
Realistic	AD	A	E	GW	HT	OD	POC
Manufacturing [%]	99.5	81.6	97	95.4	97	99.8	83.4
Landfill [%]	0	0.1	0.1	0.1	0	0	0.1
Recycling [%]	0.5	18.3	2.9	4.5	2.9	0.2	16.4
Total value	0.0429 [kg Sb eq.]	3.792 [kg SO ₂ eq.]	1.344 [kg PO ₄ eq.]	1008 [kg CO ₂ eq.]	426.9 [kg DCB eq.]	0.00456 [kg R11 eq.]	0.2315 [kg Eth. eq.]

In general the goal of the circular economy, and hence also of this study, is to show the possibility of lowering environmental impacts in entire life cycle of FCH-UPS with different EOL scenarios. In Table 11 absolute values for environmental impact indicators for EOL scenarios are shown for Morocco operational site. Results are presented for entire life cycle (manufacturing, transportation to operational site, utilization and EOL scenario) of 3kW FCH-UPS system.

Table 11: Absolute values of 3kW FCH-UPS in entire life cycle operating in Morocco

	AD [kg Sb eq.]	A [kg SO ₂ eq.]	E [kg PO ₄ eq.]	GW [kg CO ₂ eq.]	HT [kg DCB eq.]	OD [kg R11 eq.]	POC [kg Ethene eq.]
Base	0.181	361.8	38.3	121215	7790	0.0046	23.129
Feasible	0.005	352.3	35.0	119596	5668	0.0005	22.448
Realistic	0.047	353.4	36.2	120041	6090	0.0046	22.530

The results presented in Figure 15 show that in the case of Morocco the reduction of environmental impacts could be achieved mainly in the operational phase (hydrogen production with electrolysis with fossil fuel based electricity), except in AD criteria which has the biggest impact in the manufacturing phase.

Figure 15: Relative comparison of EOL scenarios for entire life cycle of FCH-UPS system (Morocco)

EOL and manufacturing phase have almost negligible environmental impacts compared with operation phase. In this case EOL processes have low impact on environmental indicators in entire life cycle.

Nevertheless in the case of Morocco the average reduction of all analysed environmental impact indicators are 23% (from 1% in GW to 97% in AD) for feasible EOL scenario and 18% (from 1% GW to 74% AD) for realistic EOL scenario.

Table 12: Absolute values of 3kW FCH-UPS in entire life cycle operating in Norway

	AD [kg Sb eq.]	A [kg SO ₂ eq.]	E [kg PO ₄ eq.]	GW [kg CO ₂ eq.]	HT [kg DCB eq.]	OD [kg R11 eq.]	POC [kg Ethene eq.]
Base	0.196	16.9	4.3	7185	2319	0.0046	1.177
Feasible	0.020	7.3	1.0	5566	197	0.0005	0.496
Realistic	0.062	8.5	2.2	6011	619	0.0046	0.578

Figure 16: Relative comparison of EOL scenarios for entire life cycle of FCH-UPS system (Norway)

In the case of Norway the operation phase has significant lower influence on environmental impacts compared with manufacturing, transport (see Figure 11) and EOL (see Table 10) phases as in the case of Morocco. The data from Table 12 and Figure 16 show the reduction of environmental impacts for feasible and realistic scenario compared to base scenario. In the case of Norway the EOL phase has bigger effect on reduction of total environmental impacts in manufacturing phase and in entire life cycle. In average 66% (23% GW to 92% HT) reduction of all analysed environmental indicators for feasible and 51% (16% GW to 73% HT) reduction for realistic scenario could be achieved with circular economy in the entire life cycle of 3kW FCH-UPS system. Figure 17 shows CO₂ emissions per 1kWh_e of generated electricity and compared with other electricity generation technologies. Analysis of CO₂ emissions per 1kWh_e electricity was made for the entire life cycle of 3kW FCH-UPS system. From results it could be seen that in the case of Norway operational site 22% reduction of CO₂ emissions could be achieved with feasible scenario and 16% with realistic scenario. For Morocco operational site the reduction for both scenarios is around 1% which is very small and confirms the importance of operational phase and the influence of hydrogen production methodology in whole life cycle of technologies.

If we want to reduce environmental impacts in the whole life cycle of the FCH-UPS system with circular economy, operational and manufacturing phase have to be considered. With proper and well approached end of life strategies for recycling and reuse of virgin materials, a big reduction of environmental impacts could be achieved in manufacturing phase. This is the reason why proper guidelines and legislation must be applied in the future for the FCH technologies systems, to achieve lowest possible environmental impacts and contribute to sustainable development of these technologies.

Figure 17: CO₂ emissions for entire life cycle with EOL scenarios per 1kWh_e

The outcome of the results compared with other studies show that end of life assessment with circular economy is an important step towards sustainable energy supply. Despite the fact that the EOL phase and circular economy proves to be important for lowering environmental impacts of FCH technologies, it has not been so often analysed in other studies. Critical comparing results from other relevant studies we can conclude:

Evangelisti et al [23] compared environmental impacts of all phases in entire life cycle of FCV and get similar results as in this paper, that the EOL phase has negligible effect on environmental impacts compared with operation and manufacturing phase. Furthermore for GW impact in manufacturing phase they show that the main contribution comes from FC 46% (with hydrogen tank) and in this study the FC contribution is 35,9% (hydrogen production and storage are excluded).

Some parallels could be made from results of Garraín and Lechón [25] analysis of environmental impact assessment related to the manufacturing and disposal stage of PEMFC. Results for acidification indicator show that the main impact comes from platinum, aluminium and copper. It is noteworthy that the use of recycled platinum and copper is especially important towards the reduction of acidification. In this paper we obtained similar data for platinum, from which we can see high impact from critical materials e.g. platinum despite small mass in absolute sense. They also stated that if all metals with high quantity were recycled, global warming emissions could be reduced and fossil energy use could be drastically lowered. The results show that metals (their production and processing) and plastics are the main contributors to the global warming and fossil energy use related impact categories. Similar conclusion can be made for 3kW FCH-UPS system for realistic and feasible scenario, where we assumed reuse and recycling of large quantity metals and critical materials. Results of this EOL scenario show also the reduction of all environmental indicators including GW and fossil energy use.

6 CONCLUSIONS

A fuel cell based UPS system (FCH-UPS) was analysed with LCA method in its manufacturing, transportation, operation and end of life (EOL) phase. Two operating sites were included in the operational phase, one in Norway and the other in Morocco. Hydrogen in operational phase was produced on-site with electrolysis and local electricity grid mix. The study shows that the main environmental impacts come from operational and manufacturing phases. One of the key measures for reducing total environmental impacts is the implementation of circular economy of the materials in the EOL phase, but the operation and manufacturing phase must be considered. When EOL phase is compared just to the manufacturing phase, the EOL phase has much lower environmental impact. Three EOL scenarios were analysed: base (100% landfill), feasible (32% recycle, 68% reuse) and realistic (9% landfill, 50% reuse and 41% recycle). With realistic scenario an average of 51% reduction of all environmental impacts and 72% reduction in the manufacturing phase, compared to base case EOL scenario, could be achieved in the case of Norway. Other results show:

- In manufacturing phase the biggest share of environmental impacts comes from manufacturing of battery, FC stack and the cabinet.
- The most influential material is Pt (considered also as critical material) in all environmental impact indicators except OD. The highest impact in OD criteria comes from Nafion.
- Transport has almost negligible influence in all analysed environmental indicators.
- Operational phase is very influential in the entire life cycle and in Morocco case represents more than 90 % of all environmental impacts. This is due to fossil fuel based electricity mix used for hydrogen production. The production of hydrogen with electrolysis in Norway has much lower environmental impact due to electricity mix that comes 95 % from hydropower.
- CO₂ emissions of 3kW FCH-UPS system per 1kWh_e is 239 gCO₂ per kWh_e if operated in Norway and 4040 gCO₂ per kWh_e if operated in Morocco.
- For feasible scenario results show that when comparing manufacturing and EOL phase, the EOL phase has in average 64% lower environmental impacts than manufacturing phase.
- For Morocco operational site the reduction of all analysed environmental indicators in the entire life cycle of 3kW FCH-UPS system are in average 23% for feasible scenario and 18% for realistic scenario.
- In the case of Norway operational site the reduction of all analysed environmental indicators in the entire life cycle of 3kW FCH-UPS system are in average 66% for feasible scenario and 51% for realistic scenario.
- With the analysis of CO₂ emissions per 1kWh_e of generated electricity for entire life cycle of the system with three EOL scenarios results show that by implementing the circular economy in average 16% reduction could be achieved for Norway utilisation site by following the realistic scenario. For feasible EOL scenario the result was 22% reduction. For Morocco the reduction was negligible.

Regarding the intensive R&D efforts in the field of FCH technologies manufacturing and operation their energy efficiencies are expected to further improve in the future. That will lower environmental impacts of the FCH-UPS systems in the operational phase, but as presented in the study the major contribution to overall environmental impacts will be the hydrogen production method. In order to reduce the overall environmental impacts thoughtful planning and awareness is needed when implementing the hydrogen technologies into the existing power production systems.

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