New technologies and strategies for fuel cells and Hydrogen Technologies in the phase of recycling and dismantling

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WP4 LCA for FCH technologies considering new strategies & technologies in the phase of recycling and dismantling

D4.3 Case studies with new strategies in dismantling and recycling stage

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Executive Summary

In the following document case studies for observed technologies (PEMWE, AWE, PEMFC and SOFC) are presented in manufacturing, operational and end of life (EoL) stage. Data for manufacturing and operational stage were obtained with the help of industry partners. It is important to emphasize that most of the gathered data are proprietary data which cannot be publicly shared in detail. Life cycle assessment (LCA) models were set up in Gabi Thinkstep software environment with generic data use from Gabi ts and Ecoinvent 3.5 database. Functional unit used was 1 kWh of exergy: in the case of fuel cell electricity and in the case of electrolyser chemical energy of hydrogen.

After setting life cycle inventory (LCI) of manufacturing and operational phase, materials constituting each observed technology were evaluated according to deliverable D2.1, [1]. For each material the possible EoL processes were defined according to D2.2, [2]. LCA was done according to methodology specified in D4.1,[3] and partial results presented in D4.2, [4]. Analysis was done in several steps for each technology:

- The first step was to analyse the manufacturing stage and impacts of materials used. The environmental impacts were compared for different subsystems of observed technologies and/or particular materials.
- After manufacturing phase was evaluated it was compared to the operational stage to see the influence of manufacturing stage and to get impacts of functional unit throughout the lifetime of observed technology.
- Third step was to analyse the impact of EoL scenario where manual dismantling, reuse, energy extraction and recycling processes were used. Recycling processes were defined according to literature and available processes in generic databases.

There are specific LCA case studies with data from different manufacturers so it is a challenge to make general comments for each observed technology, however we can conclude the following:

- In LCI phase material lists could be obtained from manufacturers, but a lot of post processing of bill of material is needed prepare the data for LCA modelling;
- Usually no data is available in energy consumption for manufacturing stage, therefore impacts in manufacturing stage are a bit under rated.
- Operational phase can be defined quite well if operational data come from long term measurements. In other cases manufacturers define nominal operating point with constant production and consumption. That is an ideal case so impacts are under rated.
- In operational phase it is good to include maintenance, but it has no relevant influence on results and can be neglected in most cases. It is also rare for manufacturers to give these data.
- In EoL phase no guidelines and small amount of comprehensive studies are published, therefore a lot of time is invested in searching and studying basic EoL processes to define LCI. In addition, for critical materials there are rarely well defined processes of material recovery available. Therefore similar processes are used or new processes are modelled on the basic of scientific papers.
- Where no data is available landfill is used as suggested in HyGuide project from the past, [5].

In *manufacturing stage* we confirmed a big importance of critical materials. With possible reduction of required masses of critical materials in manufacturing phase, a big reduction of environmental impacts is expected.

In *operational phase* of electrolysers wind power is proven to be the most suitable to power electrolysers and using photovoltaics (PV) is also very reasonable. Hydropower was not included

since it is used in the base load of electro energetic systems and in our opinion is not appropriate for use in energy storage. Operational phase becomes more relevant in total environmental impacts with longer life time of the system. That means that energy source for technology operation is of great importance to minimize the impacts of operational phase.

In EoL phase the reduction of environmental impacts in manufacturing phase comes in a small scale from reuse of main cabinets/containers and the use of energy from energy extraction. But the biggest share of reduction comes from secondary materials used in manufacturing stage. Scenarios in the study are set to be optimistic, so results in reality could be slightly worse. But with this approach we showed a large potential in EoL strategies to reduce environmental impacts in manufacturing phase of FCH technologies.

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Abbreviations

AWE	Alkaline Water Electrolyser
BoP	Balance of Plant
EL	Electrolyser
ELCD	European reference Life Cycle Database
EoL	End of Life
EoLA	End of Life Assessment (Analysis)
EPLCA	European Platform on Life Cycle Assessment
FC	Fuel Cell
FCH	Fuel Cell and Hydrogen
FCH-JU	Fuel Cell and Hydrogen Joint Undertaking
HDPE	High Density Polyethylene Granulate
ILCD	International Reference Life Cycle Data System
LCA	Life Cycle Analysis
LCC	Life Cycle Costs
LCDN	Life Cycle Data Network
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MEA	Membrane Electrode Assembly
NG	Natural Gas
PEEK	Polyether ether ketone
PEM	Polymer Electrolyte Membrane
PEMEC	Polymer Electrolyte Membrane Electrolyser Cell
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PEMWE	Polymer Electrolyte Membrane Water Electrolyser
PFSA	Perfluorosulphonic acid (Nafion)
PGM	Platinum group metals
PTFE	Polytetrafluoroethylene (Teflon)
PM	Precious Metals
PV	Photovoltaics
RES	Renewable Energy Sources
SOFC	Solid Oxide Fuel Cell
TM	Transition Metal

1. Introduction

In order to assess environmental impacts of EoL phase in FCH technologies case studies of observed technologies have to be set up to give us realistic results regarding the environmental impacts of EoL processes. Data obtained for each technology has to be obtained from manufacturers if possible. In the case of present study data was provided from industrial actors in the field of FCH technologies.

1.1 Background

In the report *Assessment of critical materials and components in FCH technologies* that was done in the scope of work package 2 (***Regulatory analysis, critical materials and component identification and mapping of recycled technologies***) critical materials represented in FCH technologies were identified with the help of upgraded EU criticality methodology, [1]. After identification of materials the most relevant current and possible future EoL processes were identified and described in deliverable *Existing EoL technologies applicable to FCH products*, [2]. Novel EoL processes were identified in deliverables *New EoL technologies applicable to FCH products*, [6] and *New EoL strategies for FCH products*, [7].

In the first part of work package 4 (***LCA for FCH technologies considering new strategies & technologies in the phase of recycling and dismantling***) the LCA methodology and approach was defined in *LCA approach in the EoL cycle of FCH technologies,* [3]. After that life cycle assessment of represented materials in FCH technologies was assessed in terms of environmental impacts of each material in deliverable *LCA of materials represented in FCH technologies*, [4]. CML2001 methodology was used with global, regional and local environmental indicators, [8].

1.2 Goal and the scope of the work

The ***goal*** of this report:

- Is to define EoL processes for EoL phase of observed FCH technologies: AWE, PEMWE, PEMFC and SOFC. In order to construct LCI processes have to be defined according to data from industry actors and/or from literature.
- To assess environmental impacts using midpoint CML2001 life cycle impact assessment methodology.
- To compare environmental impacts of manufacturing, operational and EoL phase.
- To assess possible recycling strategies of observed technologies.

The scope of the study is cradle to grave with emphasis on EoL phase. In EoL phase relevant EoL processes for all materials in each observed technology are used. ***Functional unit*** of the observed technologies is 1 kWh of exergy to enable comparison of technologies.

1.3 Limitations

The basic physical and methodological limitations are:

- LCA methodology was used to assess environmental impacts:
  - CML2001 life cycle impact methodology
  - From cradle to grade
  - Gabi Thinkstep software environment
  - Gabi ts and Ecoinvent 3.5 generic databases
- LCA is limited to the case studies of observed technologies:
  - AWE, PEMWE, PEMFC and SOFC.
- Materials provided by industry partners and FCH technologies manufacturers.

1.4 Structure of the document

- In the introduction part of 1st chapter the background of the work is described and linked to work done so far. Goals and the scope are defined and limitations stressed out.
- 2nd chapter shortly summarizes used LCA methodology that was used in assessment and was described in details in previous deliverables.
- In the 3rd chapter LCI is set up according to data obtained from manufacturers and on the basis of literature, papers and assumptions.
- In 4th chapter results are presented and discussed for all life cycle phases and for all technologies.
- In 5th chapter the main conclusions are presented and in chapter 6 the references.

2. LCA approach used

2.1 CML2001 life cycle impact assessment methodology

LCA is a methodological tool used to quantitatively analyse the life cycle of products/activities. ISO 14040 and 14044 provide a generic framework, [9], [10]. Once goal and scope of the study are determined, all relevant data are collected the scope of inventory assessment and a life cycle assessment method are defined, numerical models set up and a balance calculated. This result is usually a very long list of emissions, consumed resources, etc. The interpretation of this list is difficult, but life cycle Impact Assessment (LCIA) procedure is designed to help with this interpretation, [11], [12].

The basic approach in the HyTechCycling project will be the midpoint approach with CML2001 LCIA methodology.

Global indicators

- Global Warming Potential (GWP 100 years) [kg CO2 eq.]
- Abiotic Depletion (ADP elements) [kg Sb eq.]
- Abiotic Depletion (ADP fossil) [MJ]
- Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]

Regional indicators

- Acidification Potential (AP) [kg SO2 eq.]
- Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]
- Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]

Local indicators

- Eutrophication Potential (EP) [kg Phosphate eq.]
- Human Toxicity Potential (HTP inf.) [kg DCB eq.]
- Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]
- Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]

2.2 LCA approach in manufacturing stage of technologies

In manufacturing stage of observed technologies the approach is very straight forward. After receiving data from the industry partners, life cycle inventory table is created with masses of each material used in manufacturing stage. In addition energy input (electricity) for manufacturing is used where available.

After materials are identified suitable production processes for these materials are identified in Gabi ts database and Ecoinvent 3.5 database. Masses of materials are set according to LCI table for each technology. Environmental balance is calculated and results are presented with environmental indicators of CML2001 LCIA methodology.

Where available also testing of the stack and the overall unit before operation is included in manufacturing stage. Testing is a onetime event.

2.3 LCA approach in operating stage of technologies

In operating stage first of all life time has to be defined. According to data from industry partners energy balance is defined for electrolysers (PEMWE and AWE):

- Energy needed for electrolysis – electricity (EU 28 mix).
- Amount of produced hydrogen in the case of fuel cells.
- Consumption of all gases and liquids needed in operation phase.
- Consumption of spare parts if available.
- Number of stack replacements in the whole life time of each system.

2.4 LCA approach in EoL phase

When discussing EoL phase in FCH technologies we put the operational phase out of the scope. The influence of operational stage in the whole life time is prevailing, so in EoL phase we will discuss only manufacturing and EoL phase and try to link them.

In the EoL phase there are several possible strategies after the first stage that is **manual dismantling** of the whole system:

(1) Reusing – RU
(2) Recycling – REC
(3) Energy extraction – EE
(4) Landfill – LF

(1) **Reusing of parts (RU)** is according to advisory board very unlikely since after many years of use phase (10 – 20 years for all observed technologies) many parts are damaged or technologies meanwhile improved so much that “old” parts are not useful anymore. But some big parts for outside systems as container could be reused and in environmentally ambitious scenario reuse of that part should be introduced.

(2) **Recycling (REC)** is done in all cases where possible to extract secondary material that can be used in some cases instead of virgin material, in other cases could be used in other products. Processes from Gabi ts and Ecoinvent 3.5 were used in many cases of recycling.

(3) **Energy extraction (EE)** is actually incineration process in which we get credits in the form of electricity and heat. Electricity can be used in the same process and model as a back loop or electricity input is reduced according to electricity extracted from EE. Heat generation in EE is evaluated according to CML2001 and impacts are subtracted in manufacturing stage. That means this heat is used in some other process.

(4) **Landfill (LF)** is used in the case of all materials where there is no recycling and energy extraction possible. Landfill is also the process used in the case when no data regarding EoL process is available. That is also the suggestion of HyGuide document, [5].

For each technology the starting point of EoL strategy planning starts with LCI table, where all materials are listed with their masses. As stated before the whole system first is submitted to manual dismantling, after that different processes are applied. Processes correspond to material types (plastic, steel, nonferrous metals, critical materials, etc.). After recycling there can be two strategies of EoL phase environmental impacts evaluation:

i. We can avoid the input of virgin material in manufacturing stage – with that, manufacturing stage will have lower environmental impacts because of less virgin materials use, but some additional impact will come from EoL phase.

ii. We can manufacture secondary materials that are not usable in manufacturing of observed technologies, but are usable in other products. So we have to add EoL stage environmental impact, but subtract environmental impact of materials production for other products.

2.4.1 Steps in LCA of EoL phase

1. Manual dismantling of the system.
2. In the case of outdoor systems container will be reused in all cases: repainted and reused.
3. Define EoL processes for each material in LCI manufacturing table of observed technology.
4. Set up EoL processes with proper input/output masses according to masses of materials in each observed technology.
5. Calculate environmental balance of EoL processes.
6. Post process results and adapt (reduce) input masses of virgin materials in manufacturing stage.
7. Subtract impacts of manufacturing of allocated secondary materials from total impacts of EoL phase.

After modelling all EoL processes we get environmental impact of EoL processes and masses of secondary materials that can be used as input flows in manufacturing stage. We have two possibilities:

i. Reduce masses of input virgin materials in manufacturing phase or
ii. Calculate the environmental impact of avoided virgin material and subtract the impact from total impact of manufacturing stage in observed environmental indicators.

We will use second option because all the FCH systems are modelled in a form of multiple subsystems. And there is no data available about how much of virgin material (i.e. steel) we can reduce in which system.

To calculate the effect of EoL on manufacturing phase we have to **sum manufacturing phase and EoL phase environmental impacts** and **subtract environmental impact of avoided masses of virgin materials** listed in Table 9: Secondary materials available for manufacturing process after EoL phase of AWE.

3. LCI of observed technologies

In this chapters life cycle inventory tables are presented in terms of materials use. Data was obtained from various stakeholders involved in HyTechCycling project. It is important to emphasize that most of the gathered data are proprietary data which cannot be publicly shared in detail, e.g. masses are given in percentages of total mass, platinum group metals (PGM) are aggregated etc.

3.1 Alkaline water electrolyser - AWE

3.1.1 Manufacturing and testing phase of AWE

General data of AWE outdoor unit is

- In **MANUFACTURING** stage subsystems are modelled separately: CH (chiller), CLC (closed loop cooling), CP (control panel), DWS (demi water supply), GGS (gas generation system- stack included), HPS (hydrogen purification system), IA (instrument air), N2P (nitrogen panel), OH (outdoor housing).
- Outdoor AWE system is modelled in 20 feet container. Paint for container is also included in the LCA manufacturing model.
- LCA models are set up with data provided from advisory board with the use of generic data from Gabi ts and Ecoinvent 3.5 database.
- Before operation **TESTING** and **FIRST FILL** are also included. The stack is tested for 14 hours and for that 641.6 kWh of electricity is needed and at the end the whole system is tested for 24 h which consumes 1920 kWh of electricity. Testing is one-time process.
- **OPERATION** is modelled for 1 year operation with possible extension to the whole lifetime of 20 years. In operation phase spare parts in every year are included, all solvents needed for operation and electricity consumption for hydrogen and oxygen production.
- Power of the system is 50 kW system, with 30 start-ups per year and production of 1.46 kg H_2/h. Average load is 30 %.

Table 1: Masses of subsystems

SUM OF WEIGHT - SUBSYSTEMS	MASS, KG	MASS, %
CH - **CHILLER**	140.979	1%
CLC - **CLOSED LOOP COOLING**	624.9698	7%
CP - **CONTROL PANEL**	950	10%
DWS - **DEMI WATER SUPPLY**	146.5075	2%
GGS - **GAS GENERATION SYSTEM**	1463.76	15%
HPS - **HYDROGEN PURIFICATION SYSTEM**	303.4905	3%
IA - **INSTRUMENT AIR**	95.5009	1%
N2P - **NITROGEN PANEL**	11.63204	0%
OH - **OUTDOOR HOUSING**	5811.717	61%
GRAND TOTAL	**9548.557**	100%

In manufacturing phase the LCA model is set up so all subsystems are modelled separately. In addition in manufacturing stage AWE stack and whole unit testing is included before putting the system into operation.

IMPORTANT: Electricity consumption is included just in the case of testing, but NOT in the case of pure manufacturing, where just list of materials are included.

Table 2: LCI table of AWE subsystems

MASSES OF MATERIALS IN KG	CH	CLC	CP	DWS	GGS	HPS	IA	N2P	OH
CARBON STEEL	59.50	203.42	390.00	5.10	411.07	0.00	68.00	0.00	5520.10
CARBON STEEL SHEET	0.00	0.00	245.00	0.00	0.00	3.43	0.00	0.00	9.61
STAINLESS STEEL SHEET	0.14	1.26	0.00	0.45	0.06	1.08	1.51	0.06	0.00
STAINLESS STEEL	51.90	58.81	0.00	15.81	828.19	218.46	22.46	9.17	97.35
ALUMINIUM	4.25	197.76	36.00	2.30	12.93	13.25	0.06	0.72	0.14
TRANSITION METAL	12.75	125.35	244.00	3.02	11.68	0.69	0.01	0.06	120.43
GLASS	0.05	0.00	0.00	0.15	0.38	0.36	0.10	0.02	0.00
BRASS	1.28	2.23	0.00	0.20	0.00	0.00	0.00	0.00	0.00
TRANSITION METAL	0.00	0.00	0.00	0.00	60.00	0.00	0.00	0.00	0.00
PGM	0.00	0.00	0.00	0.00	0.13	0.02	0.00	0.00	0.00
STYRENE DIVINYLBENZENE COPOLYMER	0.00	0.00	0.00	46.20	0.00	0.00	0.00	0.00	0.00
POLYESTER	0.00	0.15	0.00	23.82	0.98	0.40	0.01	0.06	0.01
THERMOPLASTICS	10.71	26.54	35.00	6.09	119.84	0.10	0.00	0.00	16.76
PVC	0.00	0.61	0.00	3.41	12.89	2.40	2.18	1.20	4.26
CERAMIC	0.00	0.00	0.00	0.00	0.00	31.35	0.00	0.00	0.00
SILICA	0.00	0.00	0.00	23.00	0.00	30.80	0.00	0.00	0.00
PP	0.40	4.68	0.00	12.87	5.16	1.14	0.00	0.34	0.06
FLUOROSCENT LAMP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	42.32
EPDM	0.00	0.00	0.00	0.00	0.04	0.02	0.00	0.00	0.00
NBR	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.11
ZINK	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18
BRONZE	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00
CAST IRON	0.00	3.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POLYURETANE	0.00	0.00	0.00	0.00	0.00	0.00	1.12	0.00	0.00
ABS	0.00	0.00	0.00	0.00	0.42	0.00	0.00	0.00	0.42
POLYAMIDE (PA)	0.00	0.00	0.00	0.35	0.00	0.00	0.00	0.00	0.00
CARBON	0.00	0.00	0.00	3.53	0.00	0.00	0.00	0.00	0.00
EXTERIOR PAINT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	165.06

Table 3: Solvents and water for the tests and first fill before regular operation

Material	**Mass, kg**
Demi water consumption cell stack pressure test	100
Demi water consumption test stand rinsing	150
Demi consumption unit pressure test	250
KOH consumption test stand + unit+ first fill	746.7 (4.7+742)
H_2SO_4 *consumption test stand*	1.5
Glycol first fill	222

3.1.2 Operational phase of AWE

In the operational phase we are oriented in consumption of solvents and gases needed for operation, number and masses of spare parts needed in 1 year operation and electricity needed for production of AWE main product that is **HYDROGEN**. The side products are oxygen and heat.

The LCA model for operation is modelled for 1 year operation with possible scale up to the whole life time of the outside unit. The main assumption and data are

- The lifetime of the system is assumed to be 20 years of operation that is the life time of BoP system.
- The stack lasts from 7-10 years. We modelled two replacements of the stack in the whole life time of the unit.
- All spare parts in the operation phase for one year time are listed included in LCA model of operational phase (Figure 1).
- 30 start-ups per year are assumed, that defines materials used just in the start-up procedure which is nitrogen.
- The average load within the year is 30 %.
- Maximum production capacity is 1.46 kgH_2/h.
- Electricity used for production of hydrogen is EU-28 mix as base scenario. LCA model easily allows the change of electricity mix if the influence of electricity mix will be researched. The comparison is made for production of hydrogen with electricity from photovoltaics, wind and lignite as worst case scenario.
- According to energy balance AWE is operating in average at efficiency of 64,556% using the caloric value of hydrogen of 141.8 MJ/kgH_2.

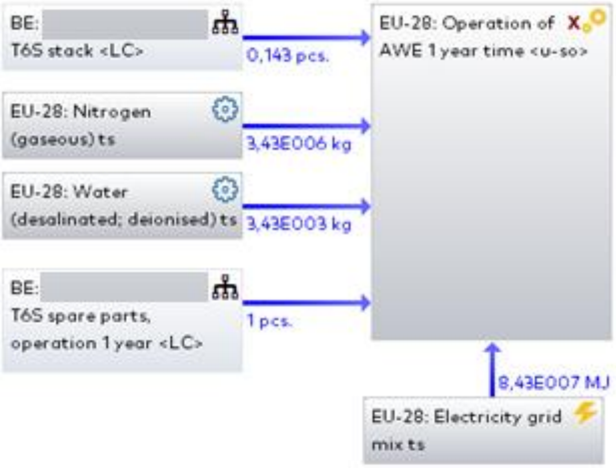


Figure 1: LCA model of operational phase of AWE unit in one year time frame.

Table 4: Spare parts for 1 year operation of AWE T6S whole outside unit.

SPARE PARTS - MATERIAL	1 YEAR, KG
CARBON STEEL	1.4691144
STAINLESS STEEL SHEET	0.0361565
STAINLESS STEEL	11.015475
ALUMINIUM	0.2165016
TRANSITION METAL	0.2117725
GLASS	0.0120522
BRASS	0.0308633
TRANSITION METAL	1.2267504
PGM	0.002658
POLYESTER	0.0232627
THERMOPLASTICS	2.0719497

Table 5: Nitrogen and demi water used for the operational phase for 1 year operation of AWE

CONSUMPTION	VALUE	UNIT	VALUE PER YEAR	
DEMI WATER	17.88	l tap water/kg H2	3430171.072 demi	kg
NITROGEN - GASEOUS	1.5	Nm^3/ start-up	1333.431 Nitrogen	kg
NITROGEN - GASEOUS	0.18	Nm^3/h standby		

Table 6: Production of hydrogen. oxygen and heat

OUTPUT FLOWS	1 YEAR		
HYDROGEN @100% QUALITY RATE	**383688**	**kg**	**useful flow**
OXYGEN @100% QUALITY RATE	191844	kg	to atmosphere
HEAT	**4610130.456**	**kWh**	to atmosphere

Table 7: Electricity needed for system standby/control and hydrogen/oxygen production for 1 year

ENERGY NEEDED FOR OPERATION	1 YEAR	UNIT	COMMENT
ELECTRICITY CONTROL STANDBY	5874.456	kWh	100% heat
ELECTRICITY CONTROL PRODUCTION	4604256	kWh	100 % heat
ELECTRICITY POWER PRODUCTION	18800712	kWh	partly heat

3.1.3 EoL phase of AWE

EoL cycle phase is very important to avoid virgin materials with recycling (plastics, steel, nonferrous metals, etc.), avoid manufacturing of new parts with reuse of undamaged parts of the system (i.e. steel container in the case of outdoor systems), extraction of energy from non-recyclable but materials with high caloric values (some plastics).

In the case of AWE outdoor system the basis of EoL is LCI table (Table 2: LCI table of AWE subsystems). For applying EoL strategy all masses of materials are summed and processes are identified for EoL. Data for AWE EoL case study is presented in Table 8: Materials and EoL approach in AWE technology. Additional comment needed for AWE outdoor systems are

- **OH container system is reused and in manufacturing phase can be avoided:** in OH system there is mainly **steel** from container that can be repainted and reused. There is also some **copper** in the form of cables that is recycled, **stainless steel** is mainly in the form of pipe fittings and fasteners that are also recycled, thermoplastic. Fluorescent lamps are assumed to be reused as only additional parts to be reused in the scope of container.

- **Plastics** in the system is after dismantling mainly put into energy extraction (incineration) and electricity and thermal energy is extracted after incineration process. Part of plastics is recycled and very small part landfilled.
- **Glass, ceramic and silica** is landfilled.
- **PGMs** are recycled with the use of hydrometallurgical processing.
- **Nickel** is also recycled with the rate of 92 % with the use of process treatment of metal part of electronics scrap, in blister-copper, by electrolytic refining.
- **Non-ferrous metals** have high recovery rate. Aluminium is recycled with the process from Gabi ts database Aluminium recycling (2010) from World steel. Copper that has a significant share is recycled with the use of process treatment of metal part of electronics scrap, in blister-copper, by electrolytic refining. Bronze and brass are added to copper mass since materials are similar and more important the mass is almost negligible (3.75 kg vs. 518 kg of Cu).
- **Steel** is recycled. The recycling rate used is 88 % that means the output mass that can be avoided in manufacturing phase is 88 % of input mass in recycling process. In the process of cast iron production 42.84 % scrap is used and 57.16% of pig iron. So using the production process mass allocation of environmental impact is needed.

Table 8: Materials and EoL approach in AWE technology

	DESCRIPTION OF MATERIALS	MASS INPUT, KG	EOL PROCESS	RATE
STEEL	carbon steel, stainless steel, cast iron	2698.05	REC	88%
CARBON	Black carbon	3.53	EE	100%
NON-FERROUS MATERIALS	Aluminum	267.40	REC	96%
	TM	517.99	REC	100%
	Brass	3.70	REC	100%
	TM	0.18	REC	30%
	Bronze	0.05	LF	100%
PLASTICS	copolymer	46.20	EE	100%
	Polyester	25.43	EE	100%
	Thermoplastics	215.05	REC	84%
	PVC	26.96	LF	100%
	Polypropylene	24.64	REC	84%
	EPDM	0.05	EE	100%
	NBR	0.16	EE	100%
	Polyurethane	1.12	EE	100%
	ABS	0.83	EE	100%
	Polyamide (PA)	0.35	EE	100%
PGM	PGM	0.13	REC	50%
	PGM	0.017	REC	90%
TM METALS	TM	60.00	REC	92%
OTHERS	Glass	1.06	LF	100%
	Ceramic	31.35	LF	100%
	Silica	53.80	LF	100%
EXCLUDED	OH steel for container	5627.1	RU	-
	Fluorescent lamp	42.32	RU	-
	exterior paint	165.06	RU	-

Legend: RU – reuse, REC – recycled, EE – energy extraction, LF – landfilled, ND – no data

After EoL phase secondary materials that can be avoided in manufacturing stage are listed in Table 9: Secondary materials available for manufacturing process after EoL phase of AWE.

Table 9: Secondary materials available for manufacturing process after EoL phase of AWE

SECONDARY MATERIALS	MASS, KG
STEEL	831.54
ALUMINIUM	256.71
TM	517.99
BRASS	3.70
BRONZE	0.05
THERMOPLASTICS	180.64
POLYPROPYLENE	20.70
PGM	0.09
TM	55.20

In the process of energy extraction electricity and thermal energy is produced. According to mass of plastics used in EE EoL process **94.94 kWh of electricity and 222.5 kWh of thermal energy** is produced. This energy is used in other processes, but reduction of environmental impacts will be allocated to manufacturing phase.

3.2 Polymer electrolyte membrane electrolyser - PEMWE

General data of PEMWE outdoor unit is

- In **MANUFACTURING** stage subsystems are modelled separately.
  - For CP (control panel), ANA (analyser), DWS (demi water supply) and GGS (gas generation system- stack included) systems data were distributed separately
  - Other systems are more or less the same as in AWE system, so CH (chiller), CLC (closed loop cooling), HPS (hydrogen purification system), IA (instrument air), N2P (nitrogen panel) and OH (outdoor housing) are used from LCA model of AWE system.
- Outdoor PEMWE system is modelled in 20 feet container. Paint for container is also included in the LCA manufacturing model.
- LCA models are set up with data provided from advisory board with the use of generic data from Gabi ts and Ecoinvent 3.5 database.
- Before operation **TESTING** and **FIRST FILL** is also included:
  - 24h of the whole unit testing. Testing is onetime process and requires 1920 kWh of electricity.
- **OPERATION** is modelled for 1 year operation with possible extension to the whole lifetime of 20 years. In operation phase spare parts in every year are included, all solvents needed for operation and electricity consumption for hydrogen and oxygen production.
- Power of the system is 50 kW system, with 30 start-ups per year and production of 1.46 kg H_2/h. Average load is 30 %.

Table 10: Masses of subsystems

SUM OF WEIGHT, PEMWE SUBSYSTEMS	MASS, KG	MASS, %
ANA - ANALYZER	13.47525	0.15%
CH - **CHILLER**	140.979	1.60%
CLC - **CLOSED LOOP COOLING**	624.9698	7.08%
CP - **CONTROL PANEL**	1200	13.60%
DWS - **DEMI WATER SUPPLY**	41.31558	0.47%
GGS - **GAS GENERATION SYSTEM**	580.4279	6.58%
HPS - **HYDROGEN PURIFICATION SYSTEM**	303.4905	3.44%
IA - **INSTRUMENT AIR**	95.5009	1.08%
N2P - **NITROGEN PANEL**	11.63204	0.13%
OH - **OUTDOOR HOUSING**	5811.717	65.87%
GRAND TOTAL	**8823.508**	**100.00%**

In manufacturing phase the LCA model is set up in the manner that all subsystems are modelled separately. In addition in manufacturing stage whole unit testing is included before putting the system into operation.

IMPORTANT: Electricity consumption is included just in the case of testing, but NOT in the case of pure manufacturing, where just list of materials are included.

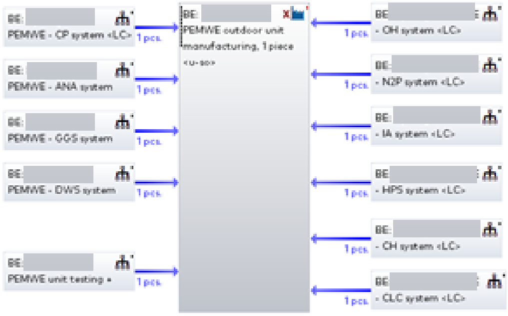


Figure 2: LCA model of PEMWE outdoor unit.

Table 11: LCI table of PEMWE subsystems

MASSES OF MATERIALS IN KG	ANA	CP	DWS	GGS
CARBON STEEL	0	492.6316	0.24	2.86
CARBON STEEL SHEET	0	309.4737	0	0
STAINLESS STEEL SHEET	0.6	0	2.8	13.434
STAINLESS STEEL	4.66125	0	32.585575	496.3402278
CAST IRON	0	0	0	0
ALUMINIUM	1.38	45.47368	0.12	0.598
ALUMINIUM SHEET	0	0	0	1.5833
TM	0.115	308.2105	0	0.3335
GLASS	0	0	0	0.12
BRASS	1.4	0	2.068	9.16425
OTHER TRANSITION METALS (NON PGM)	0	0	0	34.6548
PGM	0	0	0	0.080358937
POLYPROPYLENE	0	0	0.344	2.777665
POLYESTER	0.115	0	0	0.1915
POLY ETHYLENE	0	0	0	0.161
THERMOPLASTICS	0.654	44.21053	0	4.771303261
SILICA	1.9	0	0	0
PEEK	0.7	0	2.068	8.38
POLYAMIDE	1.95	0	0.425	0
STEEL, ELECTRO-GALVANISED	0	0	0.5	0.92
PFTE	0	0	0.16	0.304
EPDM	0	0	0.005	0.154
BRONZE	0	0	0	1.3
TM	0	0	0	2
PVDF	0	0	0	0.3

Legend to the Table 11:

- CP (control panel)
- ANA (analyser)
- DWS (demi water supply)
- GGS (gas generation system- stack included)

Table 12: LCI table of PEMWE subsystems used also in AWE outside unit

MASSES OF MATERIALS IN KG	CH	CLC	HPS	IA	N2P	OH
CARBON STEEL	59.50	203.42	0.00	68.00	0.00	5520.10
CARBON STEEL SHEET	0.00	0.00	3.43	0.00	0.00	9.61
STAINLESS STEEL SHEET	0.14	1.26	1.08	1.51	0.06	0.00
STAINLESS STEEL	51.90	58.81	218.46	22.46	9.17	97.35
ALUMINIUM	4.25	197.76	13.25	0.06	0.72	0.14
TM	12.75	125.35	0.69	0.01	0.06	120.43
GLASS	0.05	0.00	0.36	0.10	0.02	0.00
BRASS	1.28	2.23	0.00	0.00	0.00	0.00
TM	0.00	0.00	0.00	0.00	0.00	0.00
PGM	0.00	0.00	0.02	0.00	0.00	0.00
STYRENE DIVINYLBENZENE COPOLYMER	0.00	0.00	0.00	0.00	0.00	0.00
POLYESTER	0.00	0.15	0.40	0.01	0.06	0.01
THERMOPLASTICS	10.71	26.54	0.10	0.00	0.00	16.76
PVC	0.00	0.61	2.40	2.18	1.20	4.26
CERAMIC	0.00	0.00	31.35	0.00	0.00	0.00
SILICA	0.00	0.00	30.80	0.00	0.00	0.00
PP	0.40	4.68	1.14	0.00	0.34	0.06
FLUOROSCENT LAMP	0.00	0.00	0.00	0.00	0.00	42.32
EPDM	0.00	0.00	0.02	0.00	0.00	0.00
NBR	0.00	0.00	0.00	0.00	0.00	0.11
TM	0.00	0.00	0.00	0.00	0.00	0.18
BRONZE	0.00	0.00	0.00	0.05	0.00	0.00
CAST IRON	0.00	3.80	0.00	0.00	0.00	0.00
POLYURETANE	0.00	0.00	0.00	1.12	0.00	0.00
ABS	0.00	0.00	0.00	0.00	0.00	0.42
ACETAL	0.00	0.00	0.00	0.00	0.00	0.00
POLYAMIDE (PA)	0.00	0.00	0.00	0.00	0.00	0.00
CARBON	0.00	0.00	0.00	0.00	0.00	0.00
EXTERIOR PAINT	0.00	0.00	0.00	0.00	0.00	165.06

Legend to the Table 12

- CH (chiller),
- CLC (closed loop cooling),
- HPS (hydrogen purification system),
- IA (instrument air),
- N2P (nitrogen panel),
- OH (outdoor housing).

3.2.1 Modelling of the PEMWE system

All materials that are not specified (PMG and non PGM transition metals) are modelled as the worst case scenario for materials. PGM are modelled as Platinum and TM materials are modelled as Titanium as the worst case between two options: stainless steel coated with titanium or pure titanium. Because of the lack of data 72 small parts are missing since there is no mass specification data (here listed in groups)*: electrical mounting, fastener, pipe fitting, spare parts, junction box, fire and gas detector, filter process, orifice plates and flanges, gasket, pressure indicator, valve pressure indicator, valve solenoid, pipe part, valve ball, valve safety relief*.

For testing in the case of PEMWE the whole system is tested for 24 h that consumes 1920 kWh of electricity. Only the stack is not tested as in the case of AWE.

Table 13: Solvents and water for the tests and first fill before regular operation of PEMWE

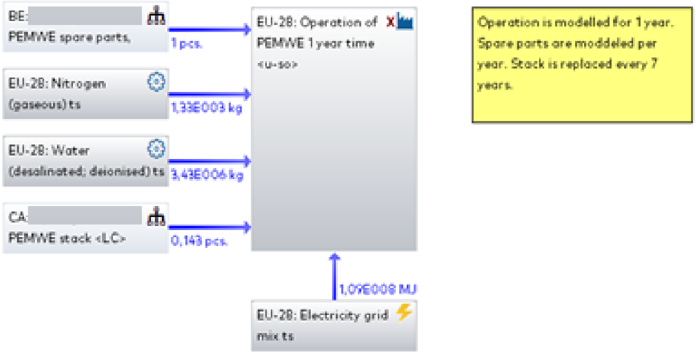
Material	Mass, kg
Demi water consumption cell stack pressure test	100
Demi water consumption unit pressure test	250
Glycol	222

3.2.2 Operational phase of PEMWE

In the operational phase we are oriented in consumption of solvents and gases needed for operation, number and masses of spare parts needed in 1 year operation and electricity needed for production of PEMWE main product that is **HYDROGEN**. The side products are oxygen and heat.

The LCA model for operation is modelled for 1 year operation with possible scale up to the whole life time of the outside unit. The main assumption and data are

- The lifetime of the system is assumed to be 20 years of operation that is the life time of BoP system.
- The stack lasts from 7-10 years. We modelled two replacements of the stack in the whole life time of the unit.
- All spare parts in the operation phase for one year time are listed included in LCA model of operational phase.
- 30 start-ups per year are assumed that define materials used just in the start-up procedure as nitrogen.
- The average load within the year is 30 %.
- Maximum production capacity is 1.46 kgH_2/h.
- Electricity used for production of hydrogen is EU-28 mix as base scenario. LCA model easily allows the change of electricity mix if the influence of electricity mix will be researched. The comparison is made for production of hydrogen with electricity from photovoltaics, wind and lignite as worst case scenario.
- According to energy balance PEMWE is operating in average at efficiency of 49,844% using the caloric value of hydrogen of 141.8 MJ/kgH_2.



Operation is modelled for 1 year. Spare parts are moddeled per year. Stack is replaced every 7 years.

Figure 3: LCA model of operational phase of PEMWE unit in one year time frame.

Table 14: Spare parts for 1 year operation of PEMWE whole outside unit.

SPARE PARTS - MATERIAL	1 YEAR. KG
STAINLESS STEEL SHEET	0.007417
STAINLESS STEEL	0.15601
ALUMINIUM	0.000748
TM	6.24E-05
GLASS	0.002472
BRASS	0.005323
POLYESTER	6.24E-05
SILICA	0.129436

Table 15: Nitrogen and demi water used for the operational phase for 1 year operation of PEMWE

CONSUMPTION	VALUE	UNIT	VALUE PER YEAR	
DEMI WATER	11.92	l tap water/kg H2	4573560.96 demi	kg
NITROGEN - GASEOUS	1.5	Nm³/ start-up	1333.431 Nitrogen	kg
NITROGEN - GASEOUS	0.18	Nm³/h standby		

Table 16: Production of hydrogen. oxygen and heat in PEMWE

OUTPUT FLOWS	1 YEAR		
HYDROGEN @100% QUALITY RATE	**383688**	**kg**	**useful flow**
OXYGEN @100% QUALITY RATE	191844	kg	to atmosphere
HEAT	**10752462**	**kWh**	to atmosphere

Table 17: Electricity needed for system standby/control and hydrogen/oxygen production for 1 year in PEMWE

ENERGY NEEDED FOR OPERATION	1 YEAR	UNIT	COMMENT
ELECTRICITY CONTROL STANDBY	9198	kWh	100% heat
ELECTRICITY CONTROL PRODUCTION	10743264	kWh	100 % heat
ELECTRICITY POWER PRODUCTION	19568088	kWh	partly heat

3.2.3 EoL phase of PEMWE

EoL cycle phase is very important to avoid virgin materials with recycling (plastics, steel, nonferrous metals, etc.), avoid manufacturing of new parts with reuse of undamaged parts of the system (i.e. steel container in the case of outdoor systems), extraction of energy from non-recyclable but materials with high caloric values (some plastics).

In the case of PEMWE outdoor system the basis of EoL is LCI tables (Table 11: LCI table of PEMWE subsystems, Table 12: LCI table of PEMWE subsystems used also in AWE outside unit). For applying EoL strategy all masses of materials are summed and processes are identified for EoL. Data for PEMWE EoL case study is presented in Table 18: Materials and EoL approach in PEMWE technology.

Table 18: Materials and EoL approach in PEMWE technology

	Description of material	***mass, kg***	***EoL process***	***recovery rate***
Steel	**Carbon steel, stainless steel, cast iron, sheets, electro steel**	2167.006	REC	88%
nonferrous materials	**Aluminum**	265.335	REC	96%
	TM	567.949	REC	100%
	Brass	16.14225	REC	100%
	TM	0.18	REC	30%
	Bronze	1.35	REC	100%
plastics	**Polypropylene**	9.741665	REC	84%
	Polyester	0.9365	EE	100%
	Poly Ethylene	0.161	REC	84%
	Thermoplastics	103.7458	REC	84%
	PVC	10.65	LF	100%
	PEEK	11.148	EE	100%
	Polyamide	2.375	EE	100%
	EPDM	0.179	EE	100%
	ABS	0.42	EE	100%
	Polyuretane	1.12	EE	100%
	NBR	0.11	EE	100%
PGM	**PGM**	0.100359	REC	76%
TM	**TM**	36.6548	REC	40%
Others	**Silica**	32.7	LF	100%
	Ceramics	31.35	LF	100%
	Glass	0.65	LF	100%
	PFTE	0.464	LF	100%
	PVDF	0.3	LF	100%
Excluded	**Steel container**	5520.1	RU	-
	Paint	165.06	RU	-
	Fluorescent lamp	42.32	RU	-

Legend: RU – reuse, REC – recycled, EE – energy extraction, LF – landfilled, ND – no data

Additional comment needed for PEMWE outdoor systems are

- **OH container system is reused and in manufacturing can be avoided:** in OH system there is mainly **steel** from container that can be repainted and reused. There is also some **copper** in the form of cables that is recycled, **stainless steel** is mainly in the form of pipe fittings and fasteners that are also recycled, thermoplastic. Fluorescent lamps are assumed to be reused as only additional parts to be reused in the scope of container.
- **Plastics** in the system is after dismantling mainly put into energy extraction (incineration) and electricity and thermal energy is extracted after incineration process. Part of plastics is recycled and very small part landfilled.
- **Glass, ceramic, PFTE, silica and PVDF** are landfilled.
- **Platinum is** recycled with 76 % recovery rate. Process is modelled according to Duclos et al, [13]
- **Titanium** is 39.7% recycled according to [14]. But since there is no exact data regarding the processes in the EoL just avoided environmental impacts due to avoided virgin titanium are included.

- **Non-ferrous metals** have high recovery rate. Aluminium is recycled with the process from gab its database Aluminium recycling (2010) from World steel. Copper that has a significant share is recycled with the use of process treatment of metal part of electronics scrap, in blister-copper, by electrolytic refining. Bronze and brass are added to copper mass since materials are similar.
- **Steel** is recycled. The recycling rate used is 88 % that means the output mass that can be avoided in manufacturing phase is 88 % of input mass in recycling process. In the process of cast iron production 42.84 % scrap is used and 57.16% of pig iron. So using the production process mass allocation of environmental impact is needed.

After EoL phase secondary materials that can be avoided in manufacturing stage are listed in Table 19: Secondary materials available for manufacturing process after EoL phase of PEMWE.

Table 19: Secondary materials available for manufacturing process after EoL phase of PEMWE

SECONDARY MATERIALS	MASS, KG
STEEL	667.87
ALUMINIUM	254.72
TM	567.95
BRASS	16.14
BRONZE	1.35
POLYPROPYLENE	8.18
POLYETHYLENE	0.13524
THERMOPLASTICS	8.18
PGM	0.076273
TM	14.55196

In the process of energy extraction electricity and thermal energy is produced. According to mass of plastics used in EE EoL process **21.30 kWh of electricity and 48.89 kWh of thermal energy** is produced. This energy is used in other processes, but reduction of environmental impacts will be allocated to manufacturing phase.

3.3 Polymer electrolyte membrane fuel cell – PEMFC

In the case of polymer electrolyte fuel cell the outdoor unit of 10 kW is analysed in all phases. The approach is the same as in the case of electrolysers, so the system in manufacturing phase is modelled part by part, operation is modelled just in nominal operating point and in the end of life the same approach is used with EoL processes applied and reuse of secondary materials in manufacturing stage.

Key features of an outdoor system and LCA approach of PEMFC technology are:

- Methanol based fuel cell solution
- No preventive maintenance
- 200 L fuel capacity
- In **MANUFACTURING** stage subsystems are modelled separately: Stack, balance of plant components, packing if the is shipped separately, outdoor cabinet with plastic tank and battery.
- Outdoor PEMFC system is outdoor steel cabinet.
- LCA models are set up with data provided from manufacturer of PEMFC system.
- **OPERATION** is modelled for 1 year operation with possible extension to the whole lifetime of 10 years as defined for PEMFC system. In this time the production of 50,000 kWh is assumed (data of manufacturer). The fuel consumption (60 vol % methanol + 40 vol % deionized water) is assumed to be 0.85 litres/kWh.

3.3.1 Manufacturing phase of PEMFC

The materials and masses of materials for 5 kW PEMFC outdoor system are omitted from this report due to confidentiality reasons.

The electricity used in manufacturing phase is manufacturer's country specific electricity mix. The system is divided in

- PEMFC stack,
- BoP components,
- lead batteries,
- steel cabinet and
- plastic reservoir for methanol/water solution.

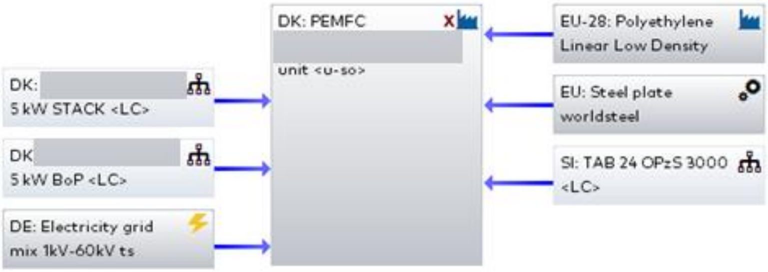


Figure 4: LCA model of manufacturing phase of 5 kW PEMFC cabinet system.

3.3.2 Operational phase of PEMFC

For the operation of 5 kW PEM fuel cell it is assumed that operation is at maximal power the whole life time that is somehow ideal scenario but there is no other data from manufacturer. Since high temperature PEM fuel cells are used the excess heat is used in the process for fuel processing.

The operational phase is defined according to manufacturer data:

- 10000 operating hours in the whole life time.
- PEMFC system operates all the time at nominal power of 5 kW so in the life time 50000 kWh are produced.
- The fuel consumption is 0.85 l/kWh of methanol/water mixture that is 42,500 litres of fuel in the life time of 10000 hours.
- The fuel is the mixture of methanol and water in the ration of 60 vol % of methanol and 40 vol % of deionised water.
- Since methanol could be produced from different sources three sources of methanol production were used: ***methanol mixture globally (reference point), methanol from biomass and methanol from syngas***. With this we can assess the environmental impacts of different methanol production technologies.
- No additional maintenance is assumed in the form of spare parts, solvents/gases usage, stack replacement, etc.

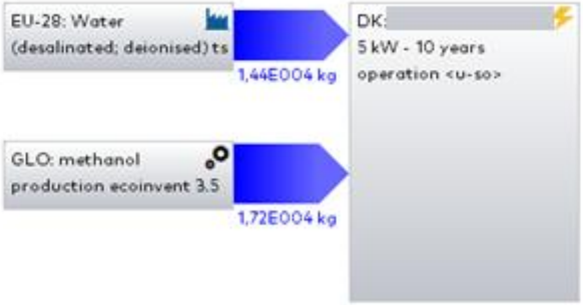


Figure 5: LCA model of manufacturing phase of 5 kW PEMFC cabinet system.

3.3.3 EoL phase of PEMFC

EoL cycle phase is very important to avoid virgin materials with recycling (plastics, steel, nonferrous metals, etc.), avoid manufacturing of new parts with reuse of undamaged parts of the system (i.e. steel container in the case of outdoor systems), extraction of energy from non-recyclable materials with high caloric values (some plastics).

In the case of PEMFC outdoor system the basis of EoL is LCI tables. For applying EoL strategy all masses of materials are summed and processes are identified for EoL. Data for PEMFC EoL case study is presented in Table 20: Materials and EoL approach in PEMFC technology.

Additional comment needed for PEMFC 5 kW cabinet outdoor systems are

- First step is **manual dismantling** of the system.
- **OH container system is reused and in manufacturing can be avoided:** in OH system there is mainly **steel** (150 kg) from container that can be reused.
- **Plastics** in the system is after dismantling mainly put into energy extraction (incineration) and electricity and thermal energy is extracted after incineration process. Part of plastics is recycled and very small part landfilled.
- **Glass, ceramic, PFTE, silica and PVDF** are landfilled.
- **Platinum is** recycled with 76 % recovery rate. Process is modelled according to Duclos et al, [13]
- **Non-ferrous metals** have high recovery rate. Aluminium is recycled with the process from gab its database Aluminium recycling (2010) from World steel. Copper that has a significant share is recycled with the use of process treatment of metal part of electronics scrap, in blister-copper, by electrolytic refining. Bronze and brass are added to copper mass since materials are similar.
- **Steel** is recycled. The recycling rate used is 88 % that means the output mass that can be avoided in manufacturing phase is 88 % of input mass in recycling process. In the process of cast iron production 42.84 % scrap is used and 57.16% of pig iron. So using the production process mass allocation of environmental impact is needed.

After EoL phase secondary materials that can be avoided in manufacturing stage are listed in Table 21.

Table 20: Materials and EoL approach in PEMFC technology

		EOL PROCESS	***RECOVERY RATE***
STEEL	***STEEL (CARBON STEEL, STAINLESS STEEL, IRON)***	REC	88%
NON FERROUS	***TM***	REC	100%
	ALUMINIUM	REC	96%
	LEAD	REC	65%
PLASTICS	***PBI***	EE	100%
	ACRYLONITRILE-BUTADIENE-STYRENE PART (ABS)	EE	100%
	ETHYLENE PROPYLENE DIENE ELASTOMER (EPDM)	EE	100%
	POLYESTER	EE	100%
	POLYPROPYLENE	REC	84%
	POLYURETHANE (PU) [PLASTICS]	EE	100%
	POLYVINYLCHLORIDE	LF	100%
	STYRENE ACRYLONITRILE (SAN)	REC	84%
	LLDPE	REC	84%
ELECTRONICS	***ELECTRONICS***	EE	100%
OTHER	***CARBON***	EE	100%
	SYNTHETIC GRAPHITE	EE	100%
	PTFE, VITON®, SILICONE	LF	100%
	CERAMICS	LF	100%
	PFTE	LF	100%
	INSULATION MATERIAL	LF	100%
	TRIETHYLENE GLYCOL (COOLANT)	REC	100%
PGM		REC	76%
CRITICAL	***PM***	REC	90%
REUSE	***STEEL CABINET***	RU	100%

Legend: RU – reuse, REC – recycled, EE – energy extraction, LF – landfilled, ND – no data, TM – transition metals, PGM – platinum group metals, PM – precious metals

Table 21: Secondary materials available for manufacturing process after EoL phase of PEMFC

SECONDARY MATERIALS
STEEL
TM
ALUMINIUM
LEAD
POLYPROPYLENE
STYRENE ACRYLONITRILE (SAN) [PLASTICS]
LLDPE
PGM
PM

In the process of energy extraction electricity and thermal energy is produced. According to mass of plastics used in EE EoL process **4.58 kWh of electricity and 10.5 kWh of thermal energy** is produced. This energy is used in other processes, but reduction of environmental impacts will be allocated to manufacturing phase.

3.4 Solid oxide fuel cell – SOFC

Solid oxide fuel cell is specific in FCH technologies because it produces electricity and heat at relatively high temperature. So in the case of SOFC is even more important to evaluate results on the unit of exergy.

3.4.1 Manufacturing phase of SOFC

In the case of SOFC we have data just for the 1.5 kW electrical power stack that is presented in Table 22. The materials for BoP components, outdoor cabinet and other auxiliary component are missing. This disables us to compare results of PEMFC and SOFC in terms of environmental impacts per 1 kWe manufactured.

Table 22: Materials for the manufacturing of 1.5 kWe SOFC stack

Material	*Mass, kg*
CERIUM GADOLINIUM OXIDE	0.02
GLASS-CERAMIC	0.7
LANTHANUM STRONTIUM COBALT IRON MIXED PEROVSKITES	0.83
NICKEL OXIDE	0.7
YSZ - YTTRIA-STABILIZED ZIRCONIA	0.6
FERRITIC STAINLESS STEEL	18
MANGANESE COBALTITE-MNCO2O4	0.1
SUM, STACK (1.5 KWE)	**20.95**

The biggest challenge in SOFC technology in manufacturing phase represents the lack of generic data in the case of SOFC technology. That was stressed out already in deliverable D4.2 LCA of materials represented in FCH technologies: HyTechCycling, [4], where availability of LCI data in generic databases were analysed.

Table 23: Availability of SOFC technology materials in GaBi ts and Ecoinvent databases

material	**Availability**	**generic data**
cerium gadolinium oxide	as substitute[4] purchasable[2]	CN cerium oxide agg ts-Gabi extension database vi: precious metals 2019 {ad982149-8f14-4c72-8722-ef3ac2181784}
glass-ceramic	Available	EU-28 glass ceramic production
nickel oxide	New process[3]	nickel available in in Ecoinvent
ysz - yttria-stabilized zirconia	as substitute[4]	RoW zirconium oxide production agg Ecoinvent 3.5 2011: Manufacture of basic chemicals 4. 05. 2019 {1f86e3a2-fe38-4e48-8f40-cb00570d1d6c}
ferritic stainless steel	available	EU-28 stainless steel cold rolled coil (430) p-agg eurofer eurofer 4. 05. 2019 annealed and pickled & skin passed, ferritic, electric arc furnace route production mix, at plant|17% chromium {1fc27f09-4535-4398-a157-8ae2eccb5d73}
manganese cobaltite-MnCo2O4	unavailable	manganese available in Ecoinvent, cobalt available in Ecoinvent

[1] Ecoinvent 3.5.

[2] Extension database: precious metals.

[3] To model new material (production process) out of basic materials/chemicals.

[4] In the case of substituted material the approval of chemical experts is desired or needed.

3.4.2 Operating phase of SOFC

In the operating phase hydrogen consumption, electricity and heat generation are the main data regarding operating phase. Maintenance, spare parts and non-optimal operation all lead to higher specific consumption; however in many cases they can be neglected.

The data for 1.5 kW stack in manufacturing phase are:

- stationary operation at 1.5kWe
- natural Gas: 4.5 Nl/min
- air: 190 Nl/min
- H_2O ca. 1 l/h (deionised)

3.4.3 EoL of SOFC

The methodology of an approach in EoL phase for SOFC is the same as in the case of other observed technologies. The gap in the case of SOFC is that we cannot evaluate the effect of EoL processes and the avoided impacts in manufacturing stage due to the following facts:

- There is absence of information regarding end of life processes for majority of materials in the SOFC technology.
- With no secondary data of materials also avoided environmental impacts could not be assessed.

4. Results and discussion

Results are presented for all technologies in the following order.

- First environmental impacts of *manufacturing stage* are presented.
- After *operational stage* is evaluated and compared with manufacturing stage.
- EoL phase is evaluated toward to manufacturing stage, where environmental impacts are avoided because of secondary materials available after recycling processes and energy extracted (electricity/heat) in incineration processes.

One of the main results that enable comparison of different technologies (electrolysers, fuel cells) of different sizes is the impact per 1 kWh of exergy (hydrogen/electricity) that is produced within technology life time.

4.1 Alkaline water electrolyser (AWE) results

4.1.1 Manufacturing phase – AWE results

In manufacturing phase we will analyse the shares of environmental impacts of different components in total environmental impact:

- GGS system where critical materials (PGM) are present has a large share in all environmental impact indicators.
- OH system has relative small share, nevertheless most of its mass is steel (5.8 tons)

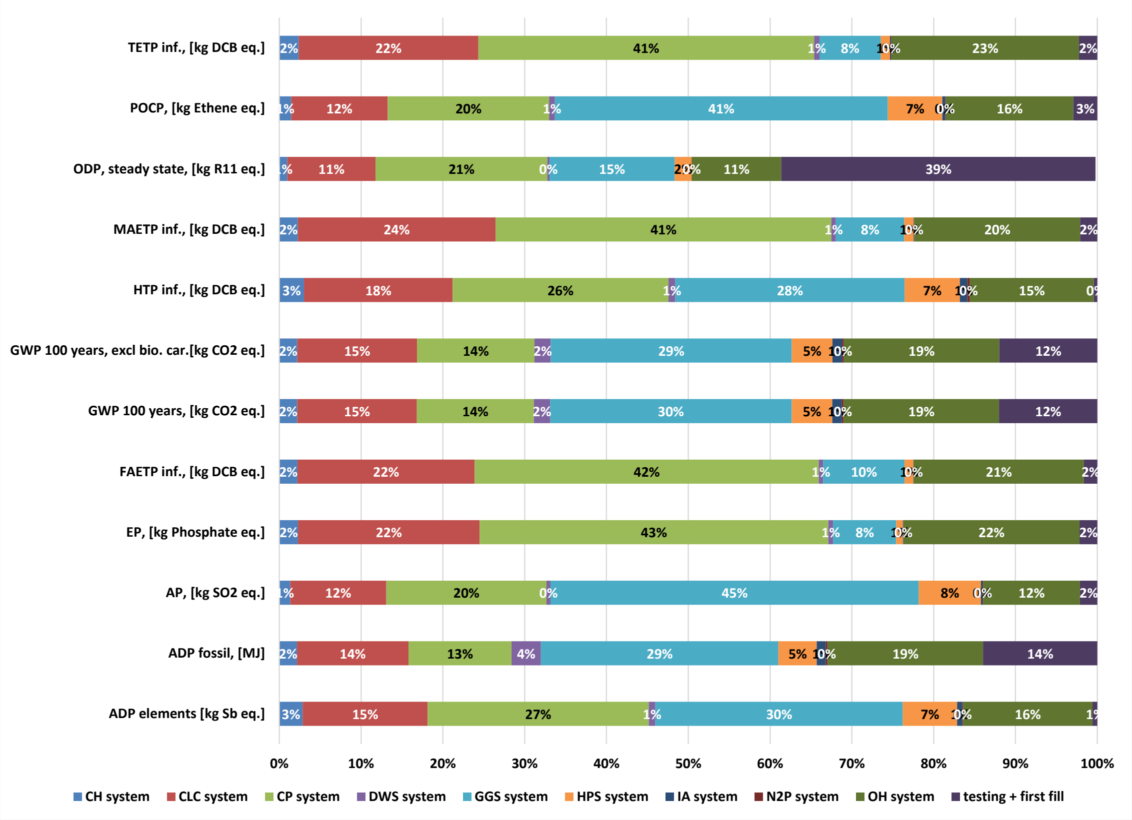


Figure 6: The share of each sub system of AWE in total CML2001 environmental indicators.

- CP system has relevant share in all impact indicators. The mass of the system is almost 1 ton.
- Systems with small mass and with no critical materials involved (CH, DWS, N2P, IA, HPS) have relatively small share in total environmental impacts in manufacturing phase of AWE.

Table 24: Absolute values of environmental indicators in manufacturing phase of AWE outdoor unit

	ADP elem. [kg Sb eq.]	ADP fossil, [MJ]	AP, [kg SO2 eq.]	EP, [kg Phosphate eq.]	FAETP inf., [kg DCB eq.]	GWP 100 years, [kg CO2 eq.]	HTP inf., [kg DCB eq.]	MAETP inf., [kg DCB eq.]	ODP, steady state, [kg R11 eq.]	POCP, [kg Ethene eq.]	TETP inf., [kg DCB eq.]
TOT	**1.67**	**2.3E+05**	**484**	**153**	**3.9E+04**	**2.0E+04**	**2.6E+05**	**1.16E+08**	**0.00027**	**23.4**	**518**
CH system	0.0476	5.08E+03	6.47	3.5	871	432	7.86E+03	2.61E+06	2.65E-06	0.339	12.3
CLC system	0.256	3.19E+04	56.8	33.9	8.50E+03	2.89E+03	4.71E+04	2.80E+07	2.92E-05	2.76	114
CP system	0.452	2.95E+04	94.9	65.1	1.65E+04	2.82E+03	6.85E+04	4.75E+07	5.68E-05	4.61	213
DWS system	0.0136	8.45E+03	2.27	0.915	213	392	2.20E+03	6.59E+05	7.15E-07	0.167	3.42
GGS system	0.506	6.80E+04	218	11.8	3.91E+03	5.83E+03	7.27E+04	9.64E+06	4.14E-05	9.51	38.9
HPS system	0.111	1.10E+04	36.8	1.23	416	979	1.76E+04	1.34E+06	5.63E-06	1.56	5.87
IA system	0.0106	2.57E+03	0.952	0.0676	7.01	234	2.29E+03	4.46E+04	-5.56E-07	0.0858	0.617
N2P system	0.0017	547	0.275	0.0303	7.15	41.8	844	3.78E+04	1.48E-08	0.0151	0.298
OH system	0.265	4.45E+04	57.4	32.9	8.17E+03	3.75E+03	3.93E+04	2.35E+07	2.96E-05	3.64	119
testing + first fill	0.0096	3.27E+04	10.2	3.3	6.38E+02	2.37E+03	1.12E+03	2.41E+06	1.04E-04	0.684	11.6

4.1.2 Operation phase – AWE results

In the operation phase also the 2 time replacement of the stack is included with all spare parts needed within one year. Electricity from (i) EU 28 mix is used for hydrogen production. To analyse the impact of different electricity mixes in hydrogen production with AWE we used also:

(ii) electricity from photovoltaic
(iii) electricity from wind
(iv) electricity from lignite

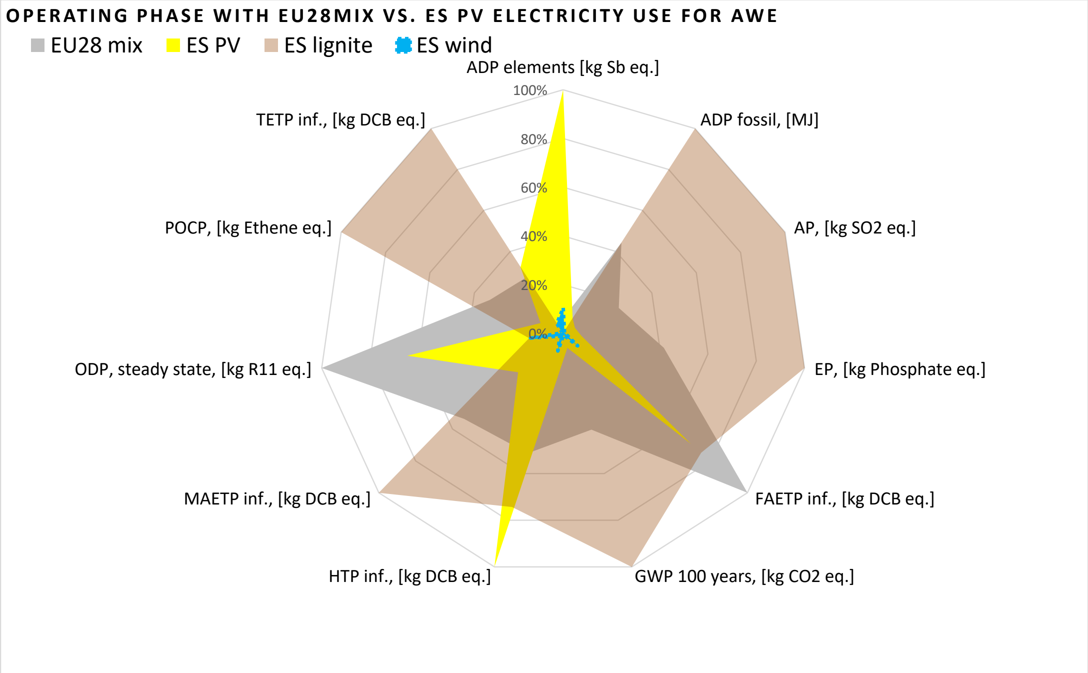


Figure 7: The relative comparison of different scenarios (electricity source) of hydrogen production with AWE unit.

Electricity from lignite is the worst environmental case, after this electricity from EU 28 mix, photovoltaics (taken as ES PV mix) and wind (see Figure 7). Wind (taken as ES electricity mix) is by far the best environmentally oriented solution in hydrogen production. Photovoltaics as renewable energy sources (RES) has significant environmental impact in categories linked with extensive use of silicates in panels manufacturing phase (ADP elements, ODP, HTP, and TETP).

When comparing the shares of manufacturing stage and operational stage it is evident that operational stage is prevailing because of high electricity consumption. In Figure 8 the manufacturing stage is compared with **only 1 year** of AWE operation and we can see that only in the case of ES wind electricity for H_2 production the share of environmental impacts of manufacturing stage reaches in average 49 % of total environmental impacts. In other three cases the share of environmental impacts of operational phase is in average:

- EU28 electricity mix: 81 %
- ES lignite electricity operation: 82 %
- ES PV electricity operation: 79 %
- ES Wind electricity operation: 51 %

Figure 8: Comparison of manufacturing phase of AWE system with operation of 1 year with hydrogen production from all four observed electricity sources.

If we analyse 20 year operation the operational share is even more prevailing in total environmental impacts. The shares of operation phase in total environmental impacts of manufacturing + operational phase are:

- EU28 electricity mix: 97 %
- ES lignite electricity operation: 96 %
- ES PV electricity operation: 96 %
- ES Wind electricity operation: 86 %

In general, if electricity from RES is used for hydrogen generation with AWE unit wind electricity has in average lower environmental impacts compared to PV.

To be able to compare results of manufacturing and operational phase to other technologies we use results from cradle to end of operation for AWE outdoor unit to produce 1 kWh of hydrogen exergy in form of chemical energy (Table 25). The upper calorific value of hydrogen (141 MJ/kg) was taken for calculation.

Table 25: Environmental impacts from cradle to end of operation after 20 years for AWE outdoor unit per 1 kWh of hydrogen exergy

	20 years operation, AWE				
IMPACTS/1 kWh exergy H2	**EU28**	**ES PV**	**ES lignite**	**ES wind**	**NG reforming**
ADP elements [kg Sb eq.]	3.516E-07	5.709E-06	1.75E-08	6.00E-07	1.79E-08
ADP fossil, [MJ]	6.8160789	1.1123967	15.41792	1.48E-01	4.78
AP, [kg SO2 eq.]	0.0018278	0.00039	0.0072801	4.09E-05	0.000115
EP, [kg Phosphate eq.]	0.0001719	3.18E-05	0.0004114	4.67E-06	0.0000149
FAETP inf., [kg DCB eq.]	0.0015523	0.0011156	0.001195	2.42E-04	0.0000862
GWP 100 years, [kg CO2 eq.]	0.6465266	0.0973321	1.5682469	1.24E-02	0.269
HTP inf., [kg DCB eq.]	0.0368523	0.070995	0.0529973	6.16E-03	0.0185
MAETP inf., [kg DCB eq.]	77.800343	35.585154	144.63003	2.87E+00	0.219
ODP, steady state, [kg R11 eq.]	4.175E-12	3.011E-12	1.356E-12	1.34E-12	2.07E-17
POCP, [kg Ethene eq.]	0.0001145	3.528E-05	0.0003468	1.69E-06	0.0000175
TETP inf., [kg DCB eq.]	0.0004689	0.0005502	0.0017022	8.38E-05	0.00000473

In Table 25 absolute impacts of all scenarios for operation of AWE system for 20 years including manufacturing phase are included. Results are calculated to 1 kWh of hydrogen exergy and compared with natural gas (NG) reforming from Germany. It seems that electrolysis with AWE system and wind electricity is the only competitive with NG reforming from environmental point of view.

4.1.3 EoL results - AWE

To present results in EoL phase some comments have to be made in addition to data presented in chapters ***LCA approach in EoL phase*** and ***EoL phase of AWE***:

- To show benefits of EoL phase operational phase is not included in the analysis;
- 1st step in EoL phase is **reuse** of parts (main container that is repainted);
- Remaining equipment is ***manually dismantled***;
- After dismantling EoL processes are applied as recycling processes, landfill, incineration, etc.
- Secondary materials are available after recycling processes to be used in manufacturing phase.
- Energy produced (electricity, heat) in EoL processes (incineration) is used in manufacturing stage

From above comments it is clear that avoided environmental impacts in manufacturing phase come from secondary materials and extracted energy used in manufacturing phase.

In diagram in Figure 9 the effect of EoL scenario as described in previous chapters is presented. After manufacturing stage the value of indicators is set to 100 %:

After applying first step of EoL (reuse of container) the environmental indicators are slightly lowered (in average 3 %) but after applying EoL processes and use of secondary materials instead of virgin materials in manufacturing phase the real effect of EoL phase is showed. Lowering of environmental impact indicators is in average almost 60 %.

It is very important to properly recycle all critical materials. Treating them as hazardous waste (combination of incineration/landfill), which is the worst case scenario, the effect of EoL phase would not be as significant as in case of recycling.

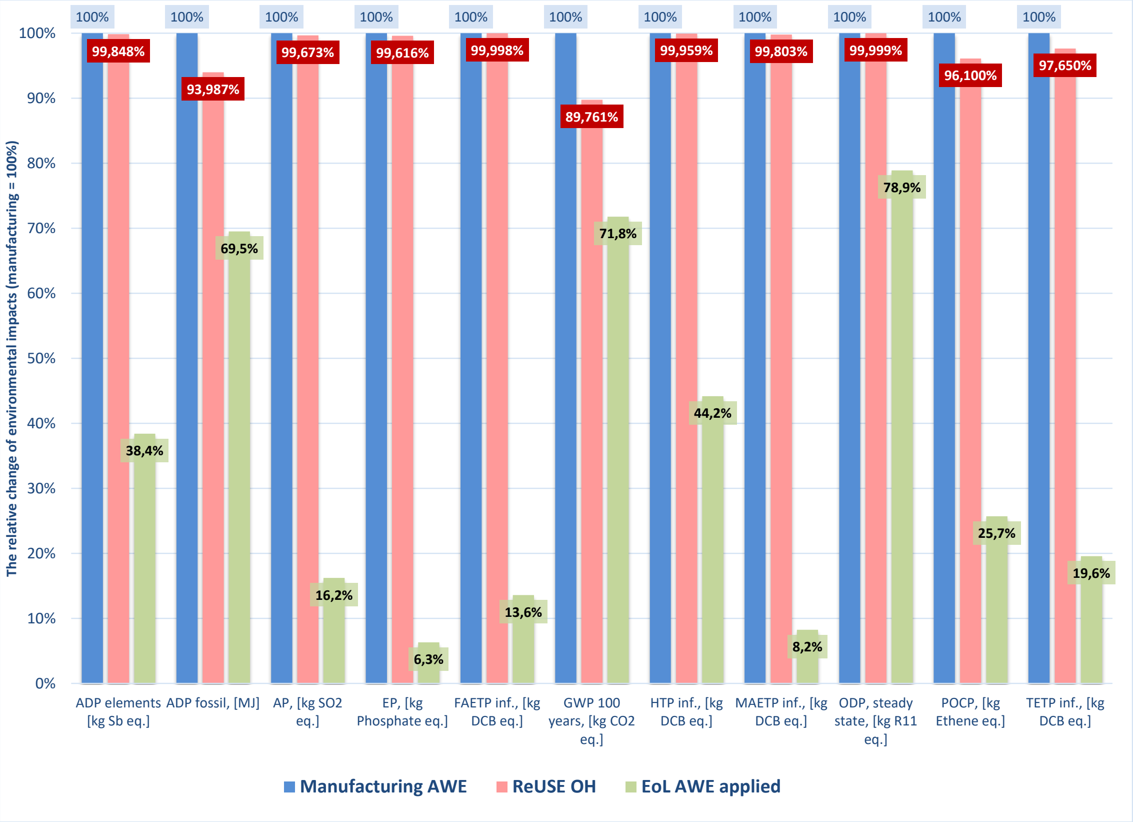


Figure 9: The effect of EoL phase on the manufacturing phase of AWE outdoor unit.

4.2 Polymer electrolyte membrane water electrolyser (PEMWE) results

4.2.1 Manufacturing phase – PEMWE results

In manufacturing phase we will analyse the shares of environmental impacts of different components in total environmental impact. In PEMWE 4 subsystems (ANA, CP, DWS, and GGS) are different from AWE unit; other (CH, CLC, HPS, IA, N2P and OH) are the same auxiliary systems:

- GGS system where critical materials (PGM) and transient metals (TM) materials are present has a large share (in average 27 %) in all environmental impact indicators.
- CP (control panel) system has in average the share of 31 % that is partly due to mass of 1.2 tons and materials involved.
- CLC system has in average the share of 16 % in total environmental impacts.
- OH system has relative small share (in average 17 %) nevertheless most of its mass is steel (5.8 tons).

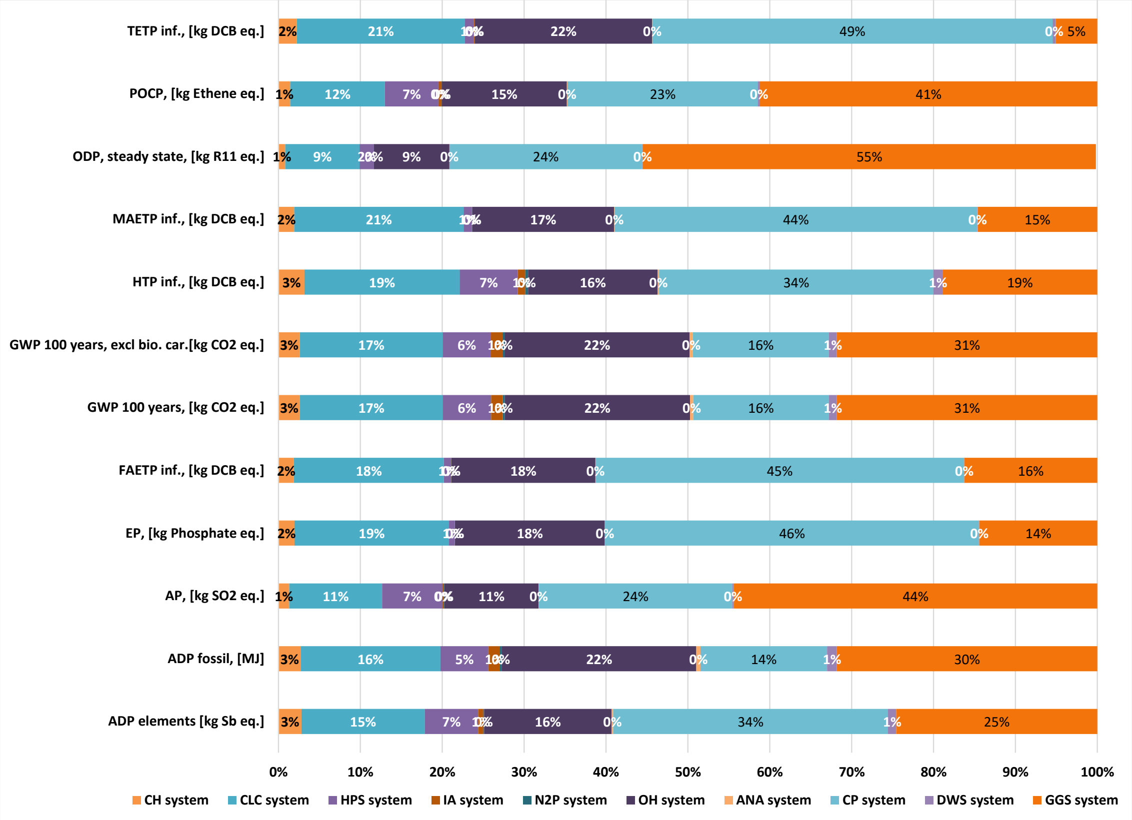


Figure 10: The share of each sub system of PEMWE in total CML2001 environmental indicators in manufacturing phase.

- Systems with small mass and with no critical materials involved (CH, DWS, ANA, N2P, IA, HPS) have relatively small share in total environmental impacts in manufacturing phase of PEMWE.

Table 26: Absolute values of environmental indicators in manufacturing phase of PEMWE outdoor unit

	ADP elem. [kg Sb eq.]	ADP fossil, [MJ]	AP, [kg SO2 eq.]	EP, [kg Phosphate eq.]	FAETP inf., [kg DCB eq.]	GWP 100 years, [kg CO2 eq.]	HTP inf., [kg DCB eq.]	MAETP inf., [kg DCB eq.]	ODP, steady state, [kg R11 eq.]	POCP, [kg Ethene eq.]	TETP inf., [kg DCB eq.]
TOT	**1.7**	**2.0E+05**	**501**	**180**	**4.64E+04**	**1.72E+04**	**1.7E+04**	**2.48E+05**	**1.35E+08**	**0.000321**	**24**
CH	0.0476	5.08E+03	6.47	3.5	871	432	433	7.86E+03	2.61E+06	2.65E-06	0.339
CLC	0.256	3.20E+04	56.8	33.9	8.50E+03	2.89E+03	2.90E+03	4.71E+04	2.80E+07	2.92E-05	2.76
HPS	0.111	1.10E+04	36.8	1.23	4.16E+02	9.79E+02	9.81E+02	1.76E+04	1.34E+06	5.63E-06	1.56
IA	0.0106	2.57E+03	0.952	0.0676	7.01	234	234	2.29E+03	4.46E+04	-5.56E-07	0.0858
N2P	0.00166	5.47E+02	0.275	0.0303	7.15E+00	4.18E+01	4.18E+01	8.44E+02	3.78E+04	1.48E-08	0.0151
OH	0.265	4.45E+04	57.4	32.9	8170	3750	3760	3.93E+04	2.35E+07	2.96E-05	3.64
ANA	0.00308	9.76E+02	0.302	0.0518	8.9	66.2	66.1	4.92E+02	5.83E+04	2.84E-08	0.0197
CP	0.571	29000	118	82.1	20900	2740	2760	83200	6.00E+07	7.58E-05	5.55
DWS	0.0167	2.22E+03	0.981	0.0635	1.34E+01	1.66E+02	1.66E+02	2.74E+03	6.37E+04	2.01E-07	0.0554
GGS	0.418	5.97E+04	222	25.9	7550	5.27E+03	5.29E+03	4.70E+04	1.98E+07	0.000178	9.83
Testing +first fill	0.000569	13300	1.14	0.173	4.47	635	634	45.9	83600	4.52E-09	0.129

4.2.2 Operation phase – PEMWE results

Here the environmental impacts of **operational phase** which includes maintenance are analysed. Electricity from (i) EU 28 mix is used for hydrogen production. To analyse the impact of different electricity mixes in hydrogen production with AWE we used also:

(v) electricity from photovoltaics (PV)
(vi) electricity from wind (Wind)
(vii) electricity from lignite (Lignite)

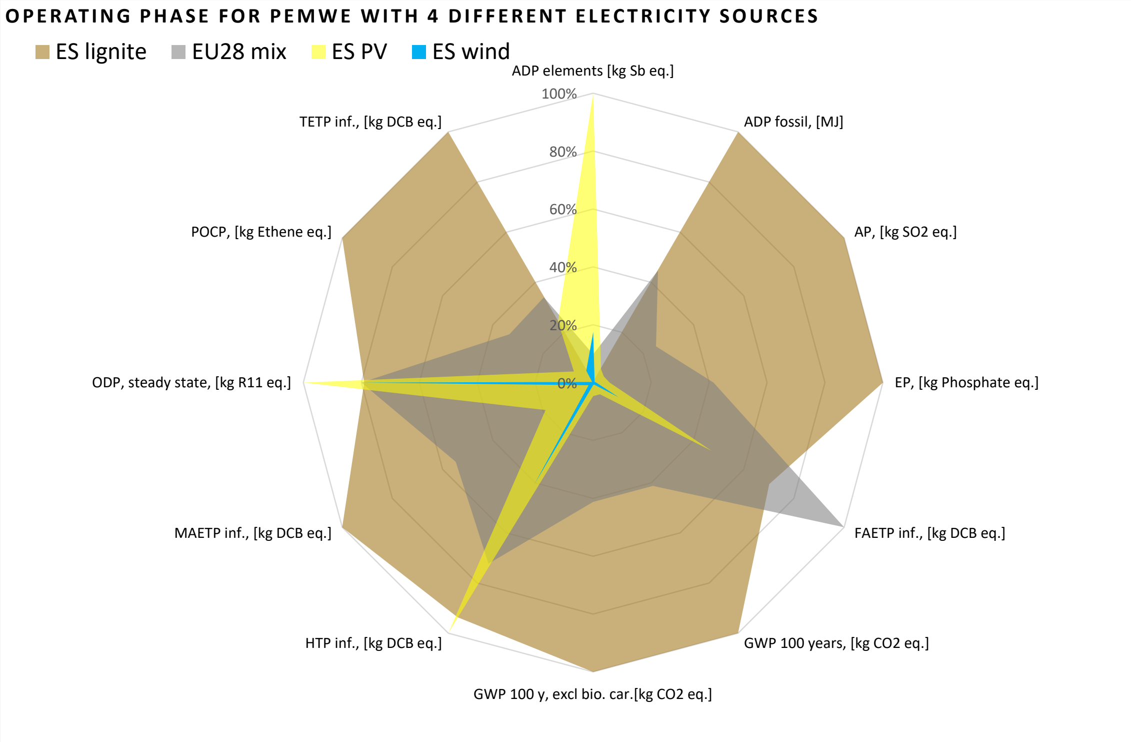


Figure 11: The relative comparison of different scenarios (electricity source) of hydrogen production with PEMWE unit.

Electricity from lignite is the worst environmental case, after this electricity from EU 28 mix, photovoltaics (taken as ES PV mix) and wind (see Figure 11). Wind (taken as ES electricity mix) is by far the best environmentally oriented solution in hydrogen production. ODP is still relevant in the case of wind scenario, but the *reason is manufacturing phase* (materials involved in the system) which also affects the results of operational phase. Photovoltaics as RES has significant environmental impact in categories linked with extensive use of silicates in panels manufacturing phase (ADP elements, ODP, HTP, and TETP).

When comparing the shares of manufacturing stage and operational stage it is evident that operational stage is prevailing because of high electricity consumption. In Figure 12 the manufacturing stage is compared with only 1 year of PEMWE operation and we can see that only in the case of ES wind electricity for H_2 production the share of environmental impacts of manufacturing stage reaches in average 43 % of total environmental impacts. In other three cases the share of environmental impacts of operational phase is in average:

- EU28 electricity mix: 82 %
- ES lignite electricity operation: 83 %
- ES PV electricity operation: 79 %
- ES Wind electricity operation: 49 %

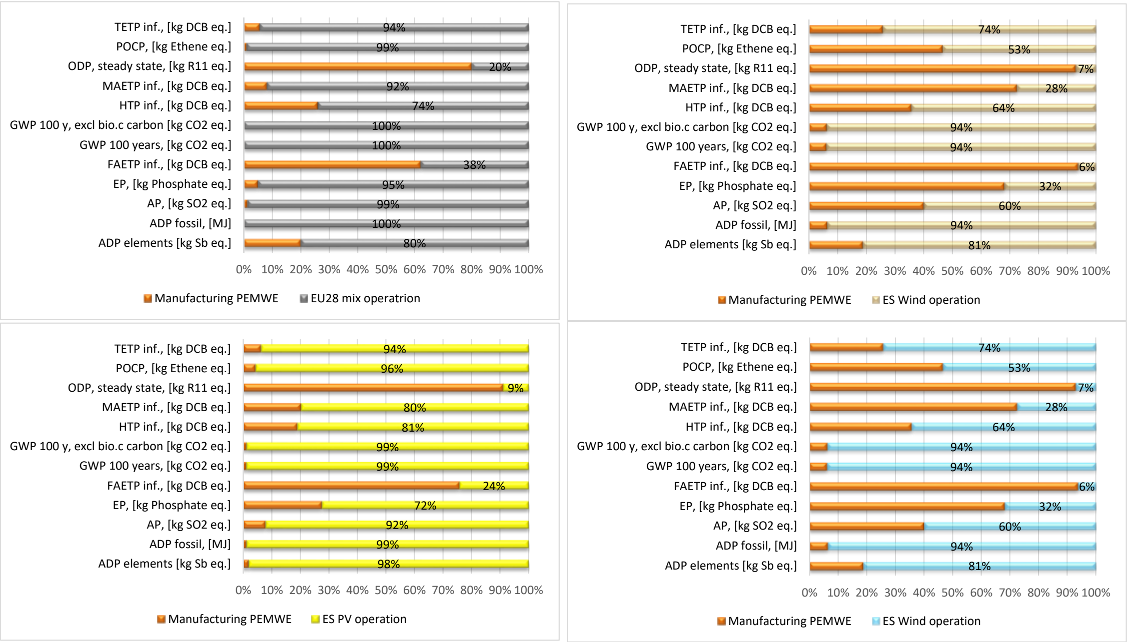


Figure 12: Comparison of manufacturing phase of PEMWE system with operation of 1 year with hydrogen production from all four observed electricity sources.

If we analyse 20 year operation the operational share is even more prevailing in total environmental impacts. The shares of operation phase in total environmental impacts of manufacturing + operational phase are:

- EU28 electricity mix: 96 %
- ES lignite electricity operation: 96 %
- ES PV electricity operation: 96 %
- ES Wind electricity operation: 90 %

Similarly than in the case of AWE, using wind electricity for hydrogen generation with PEMWE unit has in average the lowest environmental impacts.

To be able to compare results of manufacturing and operational phase to other technologies we use results from cradle to end of operation of AWE outdoor unit to produce 1 kWh of hydrogen exergy (Table 27).

Table 27: Environmental impacts from cradle to end of operation after 20 years for PEMWE outdoor unit for 1 kWh of hydrogen exergy

	20 years operation, PEMWE				
IMPACTS/1 kWh exergy H2	**EU28**	**ES PV**	**ES lignite**	**ES wind**	**NG reforming**
ADP elements [kg Sb eq.]	4.54E-07	5.71E-06	1.69E-08	4.91E-07	1.79E-08
ADP fossil, [MJ]	8.867178	1.112288	20.11574	1.94E-01	4.78
AP, [kg SO2 eq.]	0.00237	0.00039	0.009464	5.13E-05	0.000115
EP, [kg Phosphate eq.]	0.000223	3.19E-05	0.000536	6.16E-06	1.49E-05
FAETP inf., [kg DCB eq.]	0.002026	0.001139	0.00157	3.59E-04	8.62E-05
GWP 100 years, [kg CO2 eq.]	0.833774	0.097324	2.038032	1.75E-02	0.269
HTP inf., [kg DCB eq.]	0.840391	0.097324	2.038032	0.0171	0.269
MAETP inf., [kg DCB eq.]	0.047469	0.070959	0.068974	3.04E-02	0.0185
ODP, steady state, [kg R11 eq.]	100.3603	35.64801	187.7021	3.84E+00	0.219
POCP, [kg Ethene eq.]	6.36E-12	3.18E-12	2.66E-12	2.67E-12	2.07E-17
TETP inf., [kg DCB eq.]	0.000148	3.53E-05	0.000452	1.90E-06	1.75E-05

In Table 27 absolute impacts of all scenarios for operation of PEMWE system for 20 years including manufacturing phase are included. Results are calculated to 1 kWh of hydrogen exergy and compared with NG reforming from Germany. It seems that only electrolysis with PEMWE system and wind electricity is competitive with NG reforming from environmental point of view.

4.2.3 EoL results - PEMWE

To present results in EoL phase some comments have to be made in addition to data presented in chapters ***LCA approach in EoL phase*** and **EoL phase of PEMWE.** Since data are from the same manufacturer as in the case of AWE unit, the approach is the same, just materials masses and also types are different:

- To show benefits of EoL phase operational phase is not included in the analysis;
- 1st step in EoL phase is **reuse** of parts (main container that is repainted);
- Remaining equipment is ***manually dismantled***;
- After dismantling EoL processes are applied as recycling processes, landfill, incineration, etc.
- For PGM (Platinum) the recycling process from Duclos et al is used, [13];
- Secondary materials are available after recycling processes to be used in manufacturing phase.
- Energy produced (electricity, heat) in EoL processes (incineration) is used in manufacturing stage

From above comments it is clear that avoided environmental impacts in manufacturing phase come from secondary materials and extracted energy used in manufacturing phase.

In diagram in Figure 13 the effect of EoL scenario as described in previous chapters is presented. After manufacturing stage the value of indicators is set to 100 %. After applying first step of EoL (reuse of container) the environmental indicators are slightly lowered (in average 3.1 %) but after applying EoL processes and use of secondary materials instead of virgin materials in manufacturing phase the real effect of EoL phase is showed. Lowering of environmental impact indicators is in average 67.5 %.

It is very important to properly recycle all critical materials. Treating them as hazardous waste (combination of incineration/landfill) the effect of EoL phase would not be as significant as.

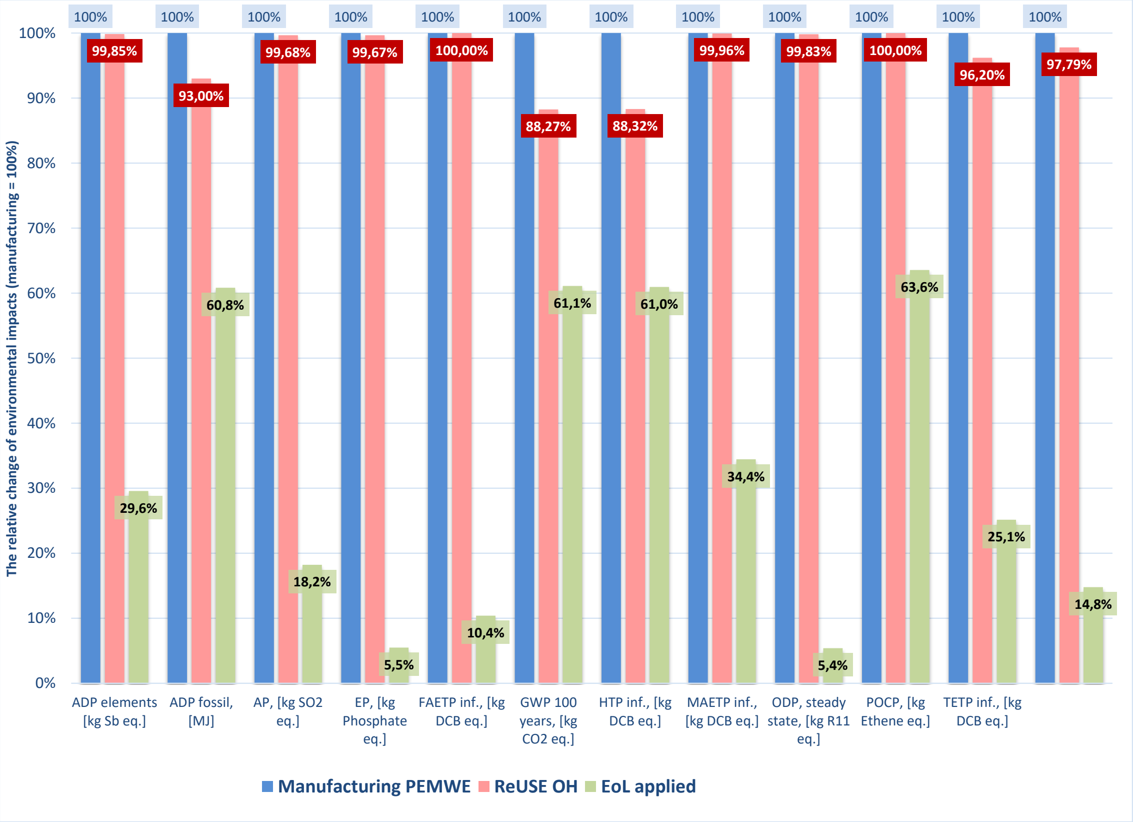


Figure 13: The effect of EoL phase on the manufacturing phase of PEMWE outdoor unit.

4.3 Polymer electrolyte membrane fuel cell – PEMFC results

4.3.1 Manufacturing phase – PEMFC results

In manufacturing phase of PEMFC we analyse environmental impacts of sub-systems of 5 kW PEMFC that serves as case study in the project. LCA model of PEMFC outdoor system consists of: BoP components, PEMFC stack, lead acid batteries, electricity needed in manufacturing phase and outdoor steel cabinet and plastic methanol/water reservoir as two separate parts.

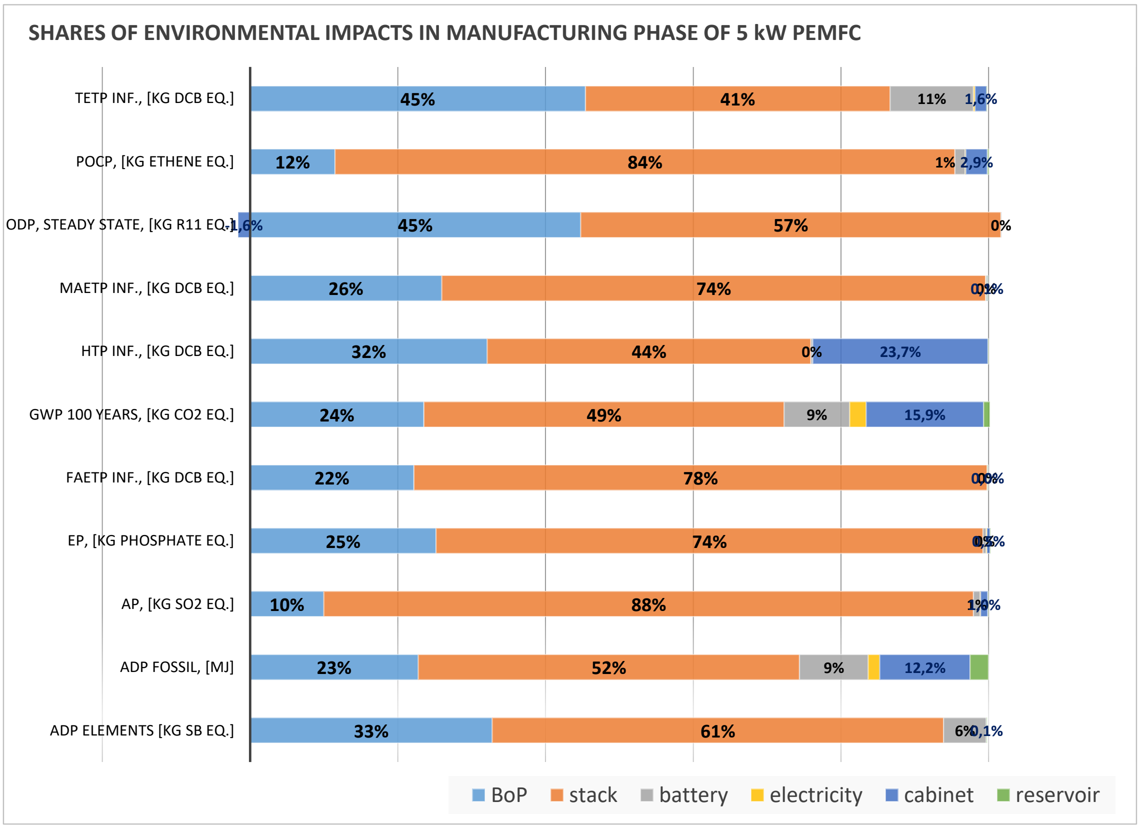


Figure 14: The share of each sub system of PEMFC in total CML2001 environmental indicators.

From results we can conclude:

- The stack in manufacturing stage represents from 41% to 88 % of total environmental impacts of the whole PEMFC unit. In average the stack represents 64 % of total environmental impacts.
    - According to masses used in the stack platinum has the share from 47.2 % in the case abiotic depletion to 99.0 % in the case of acidification.
- BoP components represent from 10 % to 45 % of total impact of the PEMFC unit manufacturing phase. In average that represents 27 % of total impacts in manufacturing stage:
    - In BoP system electronics have the share from 16.9 % to 89.5 % in total environmental impact indicators. In average that means 54.4 %.
    - Platinum as second prevalent material has in average the share of 20.7 % with aluminium as third with 11.4 %.
- Despite the fact that the battery weighs 132 kg the share of environmental impacts in manufacturing stage is only in the range of 0.03% to 11.3%.

Table 28: Absolute values of environmental indicators in manufacturing phase of PEMFC outdoor unit

	TOTAL	BOP	STACK	BATTERY	ELECTRICITY	CABINET	RESERVOIR
ADP ELEMENTS [KG SB EQ.]	0.311	0.102	0.19	0.018	2.31E-05	0.000174	3.60E-06
ADP FOSSIL, [MJ]	3.39E+04	7.72E+03	1.75E+04	3.15E+03	537	4.14E+03	839
AP, [KG SO2 EQ.]	116	11.6	102	1.06	0.0852	1.13	0.0421
EP, [KG PHOSPHATE EQ.]	18.5	4.66	13.7	0.0788	0.0139	0.0872	0.00467
FAETP INF., [KG DCB EQ.]	5.32E+03	1.18E+03	4.13E+03	2.41	0.088	1.16	0.258
GWP 100 YEARS, [KG CO2 EQ.]	2.46E+03	579	1.20E+03	218	55.2	391	20.4
HTP INF., [KG DCB EQ.]	1.13E+04	3.63E+03	4.95E+03	28.3	2.62	2.68E+03	1.86
MAETP INF., [KG DCB EQ.]	1.44E+07	3.74E+06	1.06E+07	1.31E+04	6.29E+03	2.08E+04	849
ODP, STEADY STATE, [KG R11 EQ.]	7.24E-05	3.24E-05	4.12E-05	2.31E-08	2.31E-12	-1.18E-06	5.70E-14
POCP, [KG ETHENE EQ.]	5.04	0.58	4.23	0.0691	0.00563	0.147	0.00833
TETP INF., [KG DCB EQ.]	19.4	8.81	8	2.19	0.044	0.305	0.00894

4.3.2 Operation phase – PEMFC results

In operational phase the environmental impacts of **just operational phase** is analysed with no maintenance included (data provided by technology manufacturer). As a main energy source for high temperature PEMFC is methanol – water mixture: 60 vol % methanol – 40 vol % deionised water. Methanol could be produced from different sources that results in different environmental impact of operating phase. In the case of 5 kW PEMFC system the production methods for methanol are:

- Global methanol production that is the production from natural gas (0,625 m^3 of natural gas for 1 kg of methanol)
- Methanol production from syngas from biomass (7.13 m3 of synthetic gas for 1 kg of methanol)

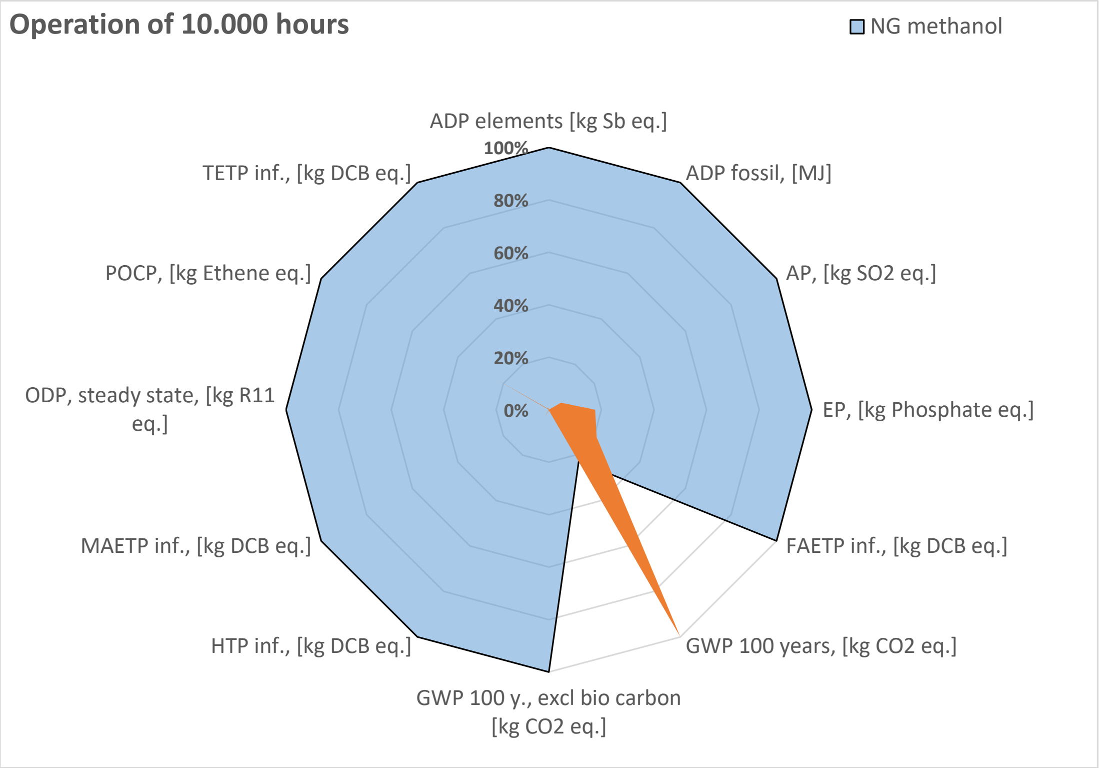


Figure 15: Comparison of operation phase of 10.000 h without maintenance and manufacturing.

In Figure 15 all CML2001 environmental indicators are presented for operation of PEMFC for 50.000 kWh electricity produced. We can see that there is a big difference in environmental impacts when operating with methanol from natural gas or methanol from syngas from biomass. GWP is the only parameter that is relatively high in the case of methanol from biomass, but when looking as GWP excluding biogenic carbon the actual reduction of GWP is 99.8 %.

In Figure 16 we can see the comparison of manufacturing phase of 5 kW PEMFC system and the operational phase of 10.000 h (mainly the methanol production).

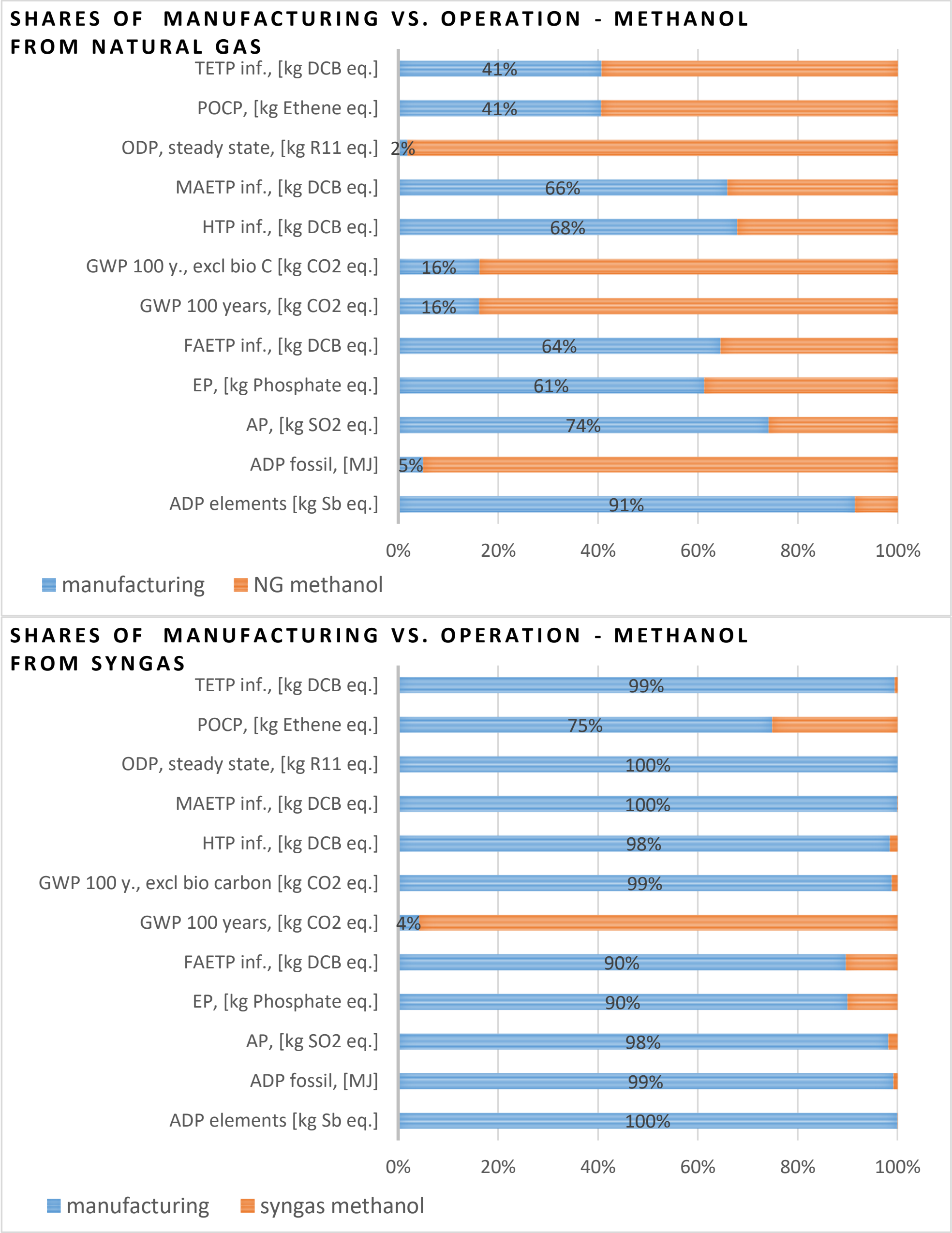


Figure 16: The share of manufacturing and operational stage in total environmental impact indicators.

From results we can see:

- The share of manufacturing stage is quite relevant in both cases.
- In the case of methanol production from natural gas the share of total environmental impacts of manufacturing stage is in average 45 % for 10.000h operation. But it spreads from 2 % in the case of ODP to 91 % in the case of ADP elements.
- In the case of methanol production from biomass syngas the share of total environmental impacts of manufacturing stage is in average 88 % % for 10.000h operation. It spreads from 4.2% in the case of GWP to 100 % in the case of MAETP and ODP.

When calculating the operational efficiency with data provided by manufacturer that are:

- 10,000 h of operation at 5 kW
- Consumption of 0.85 litre of methanol – water solution (60 vol % methanol - 40 vol % deionized water) for 1 kWh electricity generated.
- Higher heating value of 23 MJ/kg of methanol

With this data we can calculate that for 10,000 h of operation 20,196 kg of methanol (density of 0.792 kg/dm^3) and 16,969.4 kg of deionised water is needed where the system operates with efficiency of 38.74 %.

To be able to compare results of manufacturing and operational phase to other technologies we use results from cradle to end of operation of PEMFC cabinet unit to produce 1 kWh of electricity (Table 29).

Table 29: Environmental impacts from cradle to end of operation after 10 years for PEMFC cabinet unit for 1 kWh of electricity.

10,000h operation, values per 1kWhe	NG methanol	Syngas (biomass) methanol
ADP elements [kg Sb eq.]	6.80E-06	6.22E-06
ADP fossil, [MJ]	13.54	0.684
AP, [kg SO2 eq.]	0.00313	0.00236
EP, [kg Phosphate eq.]	6.04E-04	4.11E-04
FAETP inf., [kg DCB eq.]	0.165	0.1187
GWP 100 years, [kg CO2 eq.]	0.3032	1.1672
GWP 100 y., excl bio carbon [kg CO2 eq.]	0.3034	0.05
HTP inf., [kg DCB eq.]	0.333	0.230
MAETP inf., [kg DCB eq.]	437.2	288.1
ODP, steady state, [kg R11 eq.]	7.7648E-08	1.448E-09
POCP, [kg Ethene eq.]	2.48E-04	1.35E-04
TETP inf., [kg DCB eq.]	9.54E-04	3.90E-04

From results per 1 kWh of electricity for 10,000 h we can conclude:

- Operation + Manufacturing with methanol from biomass has much lower impact than operation with methanol from natural gas
- The impact of manufacturing stage is significant in both cases. That poses a big potential of the EoL phase to influence the manufacturing stage of the system. With proper EoL strategy we can therefore significantly lower environmental impacts in whole life cycle of PEMFC cabinet system.

4.3.3 EoL results – PEMFC

To present results in EoL phase some comments have to be made in addition to data presented in chapters ***LCA approach in EoL phase*** and **EoL phase of PEMFC.** The basic approach of EoL phase is:

- To show benefits of EoL phase operational phase is not included in the analysis;
- 1st step in EoL phase is **reuse** of parts (main container that is repainted);
- Remaining equipment is ***manually dismantled***;
- After dismantling EoL processes are applied as recycling processes, landfill, incineration, etc.
- For PGM (Platinum) the recycling process from Duclos et al is used, [13];
- Secondary materials are available after recycling processes to be used in manufacturing phase.
- Energy produced (electricity, heat) in EoL processes (incineration) is used in manufacturing stage

From above comments it is clear that reduced environmental impacts in manufacturing phase come from reuse of main cabinet, secondary (recycled) materials use and avoided energy used in manufacturing phase.

In the diagram in Figure 17 the effect of defined EoL scenario is presented. After manufacturing stage the value of indicators is set to 100 %. After applying first step of EoL (reuse of cabinet) the environmental indicators are lowered in average 0.6 %. The main benefit of EoL scenario comes after EoL processes application and reuse of secondary materials in manufacturing phase of PEMFC:

- In average the reduction of environmental CML2001 indicators is 48.2%
- Maximal reduction is in ODP 95.3% and minimal 27.8 % in AP.

It is very important to properly recycle all critical materials. Treating them as hazardous waste (combination of incineration/landfill) the effect of EoL phase would be not as significant or not even notable.

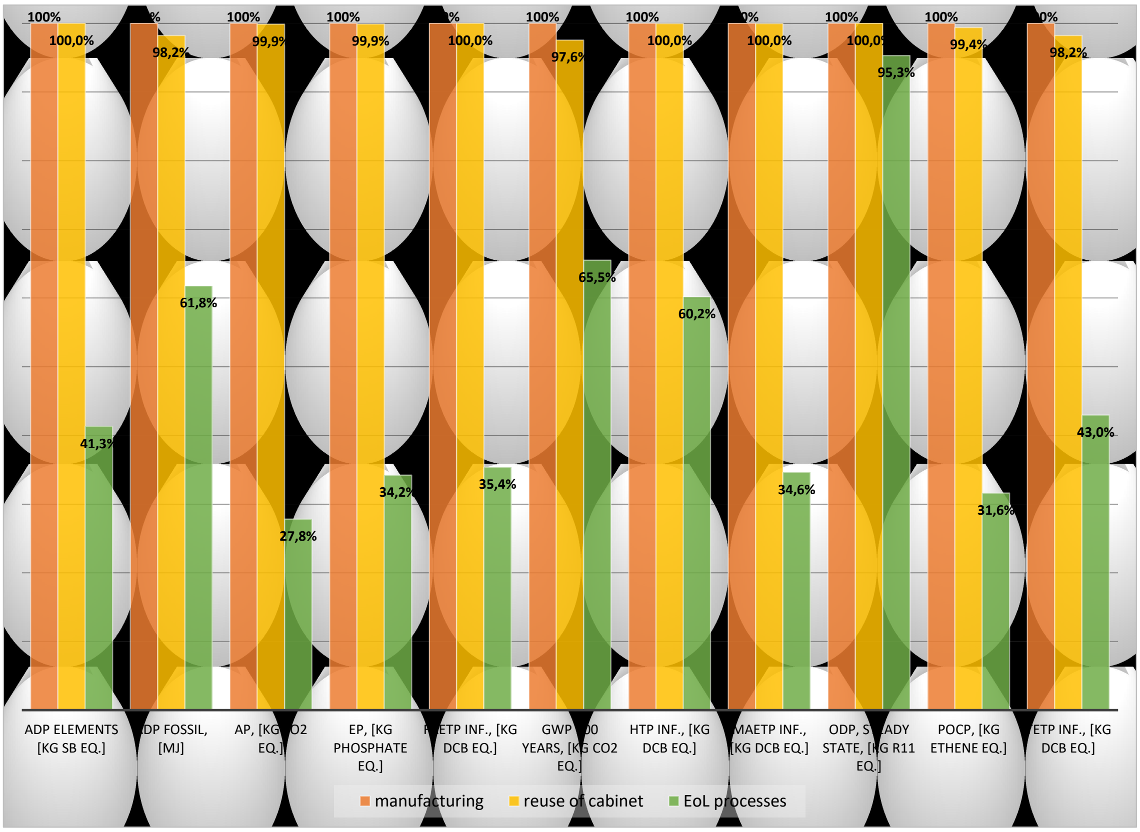


Figure 17: The effect of EoL phase on the manufacturing phase of PEMFC cabinet system.

5. Conclusions

The main objective was to make LCA case studies for all observed technologies in the project. Starting with electrolysers: AWE – alkaline water electrolyser and PEMWE – polymer exchange membrane water electrolyser and ending with fuel cells: PEMFC – polymer exchange membrane fuel cell and SOFC – solid oxide fuel cell.

LCA models were set up using Gabi ts software environment with incorporated generic databases Gabi ts and Ecoinvent. Some processes were additionally modelled on the basis of LCI from different studies and papers. The scope of the study was from cradle to grave with emphasis on manufacturing and end of life phase. These two phases are very much linked hence it is possible to substantially reduce environmental impacts with proper EoL scenarios.

The operational phase was also included, but it was modelled according to manufacturer's data. In the case of fuel cells stationary operation with no maintenance was assumed and in the case of electrolysers data were based on real operation and measured data. The functional unit was 1 kWh of exergy: electricity or chemical energy of hydrogen. For interpretation of the results the LCIA midpoint CML2001 methodology was used. The emphasis was on assessment of the impacts of critical materials, however not all materials identified as critical in previous deliverables (D2.1, [1]) are used in our specific case studies. The lists of materials are dependent on the manufacturer's data. In some cases the materials are defined on the basis of literature since no exact data (e.g. what kind of PGM) were not given from manufacturers of FCH technologies due to non-disclosure policy. Particular in the case of SOFC technology many critical and important materials in manufacturing phase are missing in generic databases, so we are very limited already in modelling of the manufacturing phase of SOFC technology. In all other technologies secondary data are more or less available. Additionally, some substitutions of materials are used and some data was created from basic chemicals.

If manufacturing and operational phases are relatively good covered with data, there is a big gap in EoL processes because there is lack of data even for conventional recycling processes from recycling industry. In cases of materials, where the industry does not have an economic interest, no market is established and thus mass and energy balances in recycling processes are missing. In some cases general recycling approaches are used for some precious metals (e.g. hydro metallurgical) or are modelled on the basis of scientific papers as in the case of platinum recycling from MEA.

The basic approach used in the case of EoL is stepwise approach in next steps: (1) manual dismantling of the system, (2) in the case of outdoor systems container is reused, (3) EoL processes are defined according to known data from recycling companies or/and literature, (4) define masses of secondary materials after EoL, (5) calculate environmental balances of EoL processes, (6) calculate avoided environmental impacts from secondary materials use (instead of virgin materials) and avoided environmental impacts from energy extracted in EoL phase, (7) post process results and combine manufacturing phase with EoL phase and present possible reduction of environmental impacts in manufacturing phase with proper EoL scenario used.

Some general comments to results:

- In the case of electrolysers AWE technology has lower environmental impacts than PEMWE technology in 20 years operation with manufacturing included. AWE outdoor unit has higher overall efficiency (64.5 %) than PEMWE (49.84 %).

  - Operational phase has much higher environmental impact than manufacturing stage. This is already visible from results in the scope of one year and much higher in 20 years.
  - When using the electricity from different sources the scenario with the lowest impact is the use of electricity from wind power to minimize the environmental impacts.
  - Hydro power was not included since hydro power is in base load of electro energetic systems and therefore probably would not be used as excess electricity for energy storage in hydrogen.

- In the case of fuel cells the PEMFC technology in this study is based on data for high temperature fuel cell with methanol as energy source. The operation is 10,000 h at maximum power with nominal methanol consumption. In SOFC technology due to lack of secondary generic data the LCA models are not completed.
  - In the case of PEMFC technology two sources of methanol production are used: from natural gas reforming and from syngas from biomass. The methanol production from biomass is environmentally sounder than from natural gas.
  - When comparing operational phase with manufacturing phase for 10,000 h working at maximum power in average the share of 45 % comes from manufacturing and 55 % from operational phase when producing methanol from natural gas.
  - When producing methanol from biomass the manufacturing phase is prevailing in the share of total environmental impacts.

Some general comments to gaps and challenges in LCA of FCH technologies:

- For manufacturing phase it is quite difficult to get real data from the industry. If they are willing to share data usually the PGM and TM groups are not exact or are entirely kept under confidentiality. In this case the masses and types of materials are defined with the help of scientific papers and literature.
- In LCI analysis large efforts were made to study various components of the systems and to identify most commonly used materials. The LCI approach in this study was to decompose all parts to basic materials and then used them in manufacturing of the technology.
- A common gap in manufacturing phase is energy required for manufacturing because companies do not have the data (or do not want to share it) about electricity consumption.
- In many cases operating regime is set to be at nominal working conditions which make the case study in operating phase to be ideal.
- Maintenance in operating phase is not included or is approximated with some general data which is usually some ideal scenario.

- EoL of FCH technologies is not yet present in recycling industry so all LCI data in EoL scenarios are based on literature review, scientific papers and approximations based on consultations with recycling industry.

- EoL phase in LCA models is linked with manufacturing phase where secondary materials could be reused instead of virgin materials. Those materials could be used also in other products but avoided impacts should be accounted to observed technology.

- In EoL there is almost no reuse according to data from manufacturers, but there are some part that can easily be reused or at least show the environmental benefits and potential in reusing.

- In the LCA EoL models recycling is set up rather optimistic with data from recycling industry or studies that shows relative high recycling ratios. That means we showed the potential of the whole system recycling.

- All secondary materials are used in manufacturing phase, therefore a large share of avoided impacts is expected in that case. In addition electricity and thermal energy is produced with incineration of some plastics and other combustible parts, hence some energy input in manufacturing phase could be avoided. This is an optimistic scenario and rather than taking results as absolutely correct, we have to interpret them as potential that is hidden in good EoL scenarios.

The study presented in this report shows the possibilities regarding the EoL of FCH technologies. The topic is very interdisciplinary and requires a broader view than just looking through environmental approach and impacts. There is a chain of manufacturer – user – recycling industry that have to decide what the strategy would be to make EoL phase of FCH technology. Also, developing a business case is important, especially in the case of critical materials that were shown to be very influential in all life cycle stages.

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