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Life cycle assessment of PEM FC applications: electric mobility and µ-CHP.

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Abstract

Polymer electrolyte membrane fuel cells (PEM FC) are seen as a suitable technology supporting the transformation towards decarbonised societies. Decision makers face the problem that there is no sound basis of the environmental performance of cutting edge technology available. We developed a comprehensive product system for two types of a high temperature (HT) PEM FC and conducted a life cycle assessment. One system utilizes functionalized multiwalled carbon nanotubes (MWCNT) as carbon support material for the platinum. The reference product applies carbon black. MWCNT render possible platinum savings of 27% simultaneously retaining equal performance parameters as for the reference FC. The inventories include all components of a FC starting with the production of the carbon support material, the catalyst powder with platinum nanoparticles, a membrane, a gas diffusion layer, bipolar flow plates up to the FC stack and FC unit including end of life treatment. Our analysis shows that platinum is the key material in HT PEM FCs and the benefits from platinum savings outweigh by far the impacts for the MWCNT production. The HT PEM FC was adjusted such that it typifies 1) a PEM FC for an electric vehicle (FCEV) allowing comparison with internal combustion engine vehicles (ICV) and battery electric vehicles (BEV) or 2) a PEM FC suitable for micro combined heat and power (µ-CHP) to be compared with a Stirling engine. We found an environmental advantage of a FCEV vis-à-vis the ICV, but only if hydrogen is produced with renewable electricity. We found similar environmental impacts for the FECV and the BEV when both vehicles are propelled with renewable energy. Both µ-CHP plants produce similar amounts of useful energy and have comparable environmental performance. Nonetheless, the PEM FC produces more electricity (less heat) than the Stirling engine. System expansion such that both systems deliver equal amounts of electricity and heat results in an advantage of nearly 20% for the PEM FC powered system. Thus, the PEM FC technology offers great potential to reduce a personal environmental (and carbon) footprint – a prerequisite on the way of a transformation to more sustainable societies.

Broader context

The prospect of changing electricity production from nuclear and fossil to predominantly renewable energy carriers as planned for example in Switzerland or Germany leads to new requirements of the electricity grid and a new electricity supply pattern. Renewable energy sources release energy congenitally intermittent over diurnal and annual cycles. The PEM FC technology can support the energy turnaround manifold. For individuals our results show that fuel cell electric vehicles provide an environmentally benign technology for individual mobility. PEM FC in combined heat and power plants are efficient devices to convert a fuel into electricity and heat for housing applications. Both fields of application provide great potential to reduce the individual environmental footprint. Decision makers planning nationwide strategy to herald the energy turnaround obtain an expedient way to store unlimited amounts of excess electricity in form of hydrogen which is efficiently converted back to electricity with a PEM FC. During periods of high power demand but low power supply the PEM FC in µ-CHP plants may produce electricity to support the electricity grid. Like that a modern electricity grid gets stabilised during phases of high electricity demand and it is protected against overload of excess electricity.

Glossary

FC	Fuel cell
PEM	Polymer electrolyte membrane
HT	High temperature
MWCNT	Multiwalled carbon nanotubes
FCEV	Fuel cell electric vehicle
BEV	Battery electric vehicle
ICV	Internal combustion vehicle
μ-CHP	Micro combined heat and power is an extension of the idea of cogeneration to the single/multi family home
LCA	Life cycle assessment
CB	Carbon black
EI99	Ecoindicator 99 is the name of an impact assessment method
IPCC	Intergovernmental Panel on Climate Change
CML	CML is the name of an impact assessment method developed at the Institute of Environmental Sciences – CML, Leiden
CED	Cumulative energy demand is the name of an impact assessment method
USEtox	USEtox is an impact assessment method characterizing human and ecotoxicological impacts of chemicals
ReCiPe	ReCiPe is the name of an impact assessment method
EC	Electrocatalyst
GDL	Gas diffusion layer
GDE	Gas diffusion electrode
MEA	Membrane electrode assembly
BoP	Balance of plant
Li-ion	Lithium ion
NEDC	New European driving cycle
PTFE	Polytetrafluoroethylene
CO	Carbon monoxide
ESI	Electronic Supplementary Information
EU	European Union
EU-mix	European electricity mix

1. Introduction

A wide variety of technologies are available to provide heating and electricity to our homes. In countries with a stable electricity grid, lighting and heating are taken for granted; but the desire for cleaner energy is highlighting how dirty grid electricity is around the world, and concerns over the future of nuclear power are adding to the debate. The current talk all over Europe about the need for an energy change emphasizes, that new concepts are required which assure higher energy efficiencies and less carbon intensity. EU leaders recently agreed on the domestic greenhouse gas reduction target of at least 40%, higher energy efficiency of at least 27 % and an increase of renewables to 27% by 2030 [1]. The fuel cell technology claims to provide a possible solution combatting climate change[2-5]. For several decades, fuel cells have been heralded for their potential as an environmentally friendly means to convert readily available chemical energy into electric energy.

Two widely used fields of application for polymer electrolyte membrane (PEM) fuel cells (FC) are on-board electricity generation for electric vehicles and as combined heat and power plants. Energy consumption for housing and individual mobility are the main contributor of the individual carbon (and generally the environmental) footprint[6-9].

The high energy density of PEM fuel cells makes them a very attractive alternative to batteries for electric mobility. Unlike batteries, they need not to be recharged, merely refuelled. These characteristics along with having no emissions during operation – at least as long as hydrogen is used as fuel - and their high efficiency make fuel cells promising for transportation and stationary power generation[10]. Fuel cell electric vehicle (FCEV) manufacturer praise such vehicles because they are supposed to combine the advantages of electric vehicles, e.g. zero emissions at tailpipe, high efficiency, silent operation, with the advantages of conventional internal combustion engine vehicles (ICV): long range and short refuelling time[11-15].

Micro-CHP (µ-CHP) is an extension of the idea of cogeneration to the single/multi family home or small office building. Local generation has a higher efficiency as it lacks the energy losses when transporting electricity or heat over long distances. PEM Fuel cells are well suited for µ-CHP plants, since the technology inherently produces both electricity and heat from a single fuel source, and the systems can run on conventional heating fuels such as natural gas. The electrical efficiency of PEM fuel cells reaches values around or even above 40%[16-21], and when the heat is used total efficiency of fuel conversion reaches 90%[16-20, 22].

Doubters argue that all the benefits mentioned above do not translate into environmental advantage, as the technology still holds severe technological problems. Drawbacks usually mentioned are the high cost due to platinum demands, hydrogen production for electric mobility, catalyst poisoning when using reformate gas or natural gas, consequentially high demands on the purity of the fuel and therefore a substantial reduction in the efficiency from fuel to power, etc. Decision makers are today in an awkward situation since there is no sound basis on the environmental impacts of the technology in comparison with reference products.

The technology developed significantly in recent years. For example, the U.S. Department of Energy shows platinum reduction from 0.35 mg/cm^2 in 2007 to 0.15 mg/cm^2 in 2013 for a 80-kW automotive PEM fuel cell system[23]. Hence, interesting studies are in fact outdated[24-26]. The well-to-tank report from the Joint Research Centre presents very low green-house gas emissions for hydrogen production depending on the hydrogen production pathway[2].

Often life cycle inventories are rather simple and do not reflect adequately the complexity of the system or the inventories are undisclosed[27-30]. Some studies focus on few environmental indicators, such as energy demand and/or climate change, but do not address the full range of environmental impacts[26-29, 31]. New technologies, in particular the nanotechnology, are suited to support the fuel cell technology in producing improved fuel cell systems[32, 33]. Higher efficiency making the technology more affordable is achieved by reductions of noble metals catalyst loading through the improvement of catalyst utilization and activity[34, 35]. Briefly, there is no environmental performance analysis of a cutting-edge PEM fuel cell technology available with high resolution life cycle inventories, addressing a wide range of environmental indicator, and comparing reference products for electric mobility and µ-CHP.

The aim of this article is to present comprehensive life cycle inventories and then credibly analyse the environmental impacts for two types of high temperature (HT) PEM fuel cells using comparative life cycle assessment (LCA). As substrate for the catalytic active platinum nanoparticles one fuel cell uses multiwalled carbon nanotubes (MWCNT) while the reference product utilises carbon black (CB). The substitution of CB by MWCNT allows for 27% of platinum savings when using reformate gas without a decrease in FC life or FC performance[36], such as the specific cell power, fuel conversion efficiency, , etc. The research question is whether the effort for the production of MWCNT (over-) compensates the benefits achieved by the platinum savings.

Subsequently, we compare the environmental performance of heat and electricity production for two types of CHP plants: a HT PEM fuel cell with MWCNT as carbon support for platinum with a Stirling engine. Finally, the components of the HT PEM fuel cell are modified such that the model depicts an automotive (low temperature) PEM FC and the same platinum savings are envisioned. The environmental achievement of FCEV is opposed to an internal combustion engine vehicle (ICV) and a battery electric vehicle (BEV). The results of this study are discussed considering the options this technology offers to individuals and societies on their way of handling the energy turnaround, phase out of nuclear power plants or combat against climate change[9].

2. Methods

2.1 Life cycle assessment

LCA is an established but evolving tool primarily designed for accounting and assessing the potential environmental impacts caused by products, processes or activities. It aspires to identify and quantify the energy and materials used in all stages of a products lifetime and the associated wastes flows and emissions released to the environment. The life cycle approach goes far beyond a single individual unit operation (e.g. manufacturing). It encompasses a whole cradle-to-grave-system and considers a functional unit perspective[37]. Both criteria are especially important when competing products are analysed to allow for a comparative assertion.

LCA includes compiling inventories of all relevant flows for materials, energy, wastes and emissions for the production, use phase and end of life of products and processes. The study encompasses a cradle-to-grave system without predefined cut-off limits. Materials and processes are only neglected when their contribution to the potential environmental burdens is considered negligible based on a combination of mass, energy demand, and expected burdens per mass or energy unit. The LCA methodology for this study follows the ISO standards[37, 38].

The life cycle impact assessment was carried out with the LCA software SimaPro[39]. A life cycle impact assessment method, e.g. ReCiPe[40], quantifies the life cycle environmental burdens based on the inventory data. ReCiPe is a damage oriented life cycle impact assessment which provides the three endpoint indicators damage to human health, to ecosystems quality and to resources availability. The endpoint indicators are split in total 17 midpoint indicators, which provide a comprehensive overview to most environmental problems discussed in LCA today. We present environmental burdens as ReCiPe midpoint indicator, as endpoint indicator and as single score indicator. In order to test the robustness of the impact assessment results we compared the results derived with ReCiPe with those from Impact 2002+[41], Eco-indicator 99[42] (EI99), IPCC[43], CML[44] and USEtox[45]. The energy efficiency for conventional and electric mobility is expressed with the Cumulated Energy Demand[46] (CED).

2.2 Product system for a HT PEM fuel cell

The product system encompasses all components of a HT PEM fuel cell beginning with the production of the carbon substrate material for the catalytic active platinum to the fuel cell unit and the disposal of the HT PEM fuel cell. Life cycle inventory data for the PEM fuel cell are compiled specifically for this study (Figure 1), while LCI data for the materials and processes in the background system are taken from the ecoinvent database version 2.2[47]. It is important to state that neither of the products (PEM fuel cells, vehicles, µ-CHP plants) was meant to represent specific products but rather technically sensible options. The functional unit is chosen as a 10 kW HT PEM fuel cell unit with MWCNT as carbon substrate (CB for the reference product) for the platinum. The corresponding reference flow is 1 unit.

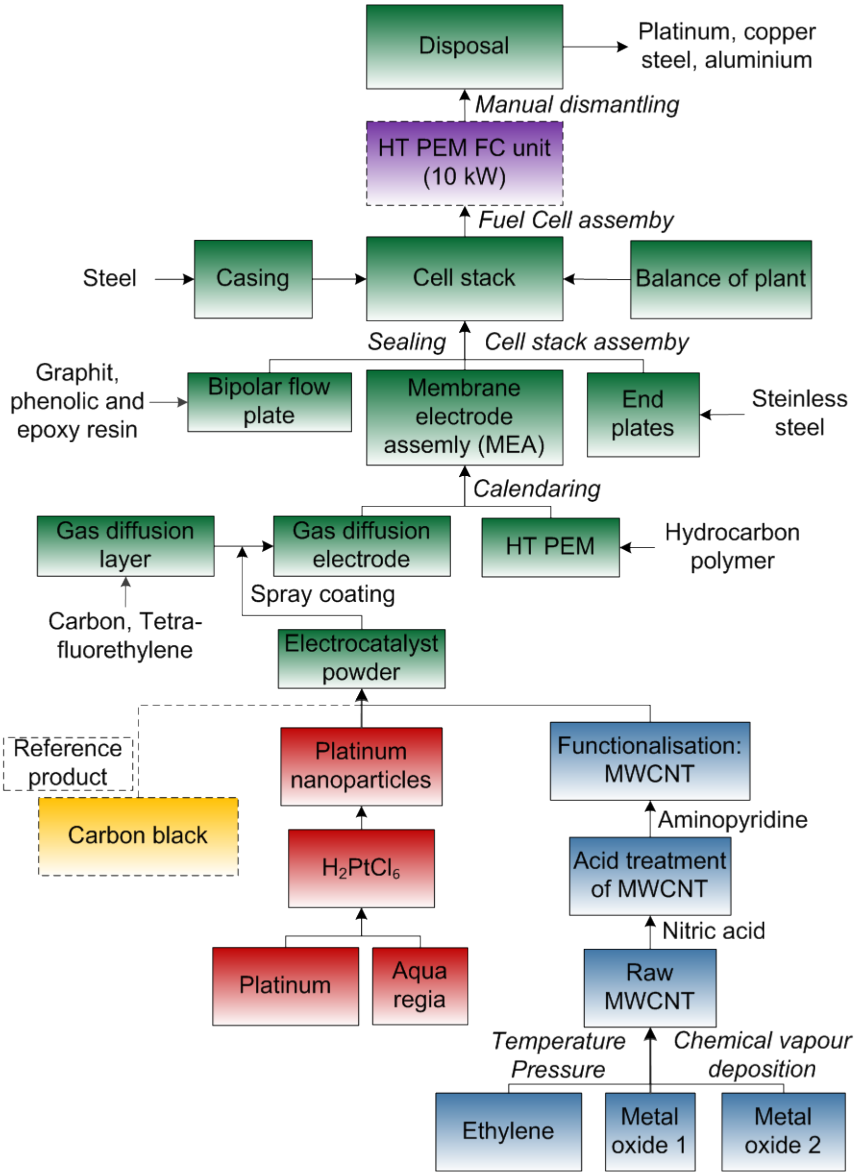


Figure 1. Simplified product system of a high temperature (HT) polymer electrolyte membrane (PEM) fuel cell (FC). The present study considers all relevant processes for the production and disposal of a 10 kW fuel cell. Yellow (carbon black) and blue boxes (multiwalled carbon nanotubes (MWCNT)) refer to the carbon substrate for the platinum nanoparticles (red boxes). Green boxes refer to the major components of a PEM fuel cell and. The purple box depicts the functional unit.

It is important to stress that for both types of HT PEM fuel cells all components and all performance parameters are exactly the same. The only difference between the two types of fuel cells is the type and amount of carbon substrate and the amount of platinum (Table 1).

Description of Unit Processes

MWCNT are attractive candidates for a carbon support in PEM fuel cell applications due to the high specific surface area, the high corrosion resistance and unique electrical, mechanical and thermal properties[48]. In addition, CNTs have shown to be more corrosion resistant than carbon black under simulated fuel cell operation conditions. A better distribution of platinum particles on the MWCNT surface and an optimised deposition[35], as well as the formation of a more extended and stable electrochemical interface allows reducing the platinum content in the electrocatalyst powder by 27% without a loss of the fuel cell performance when reformate gas is used as fuel[36].

Nanothinx S.A[49] provided detailed inventory data for the production of MWCNT. The process applied for the MWCNT is chemical vapour deposition. In their lab scale batch process the carbon feedstock ethylene is fed into a quartz tube. Inside the tube gaseous nitrogen assures an inert atmosphere and a mixture of two metal oxide catalysts is added. At specific pressure and temperature conditions there is spontaneous growth of MWCNT on the metal oxide powder. The MWCNT used in this case study appears as a black powder. It is a bulk material that forms agglomerates from 1mm to 1 cm on average. The MWCNT form 10 to 20 tubes and have a diameter of 15-35 nm and a length bigger than 10 µm. The MWCNT are highly pure (97% MWCNT). The residual 3% of the product represent the catalyst. There is almost no amorphous carbon present in the product [50]. Subsequently the raw MWCNT are treated with nitric acid in order to attach carboxyl acid groups onto the sidewalls of the MWCNT.

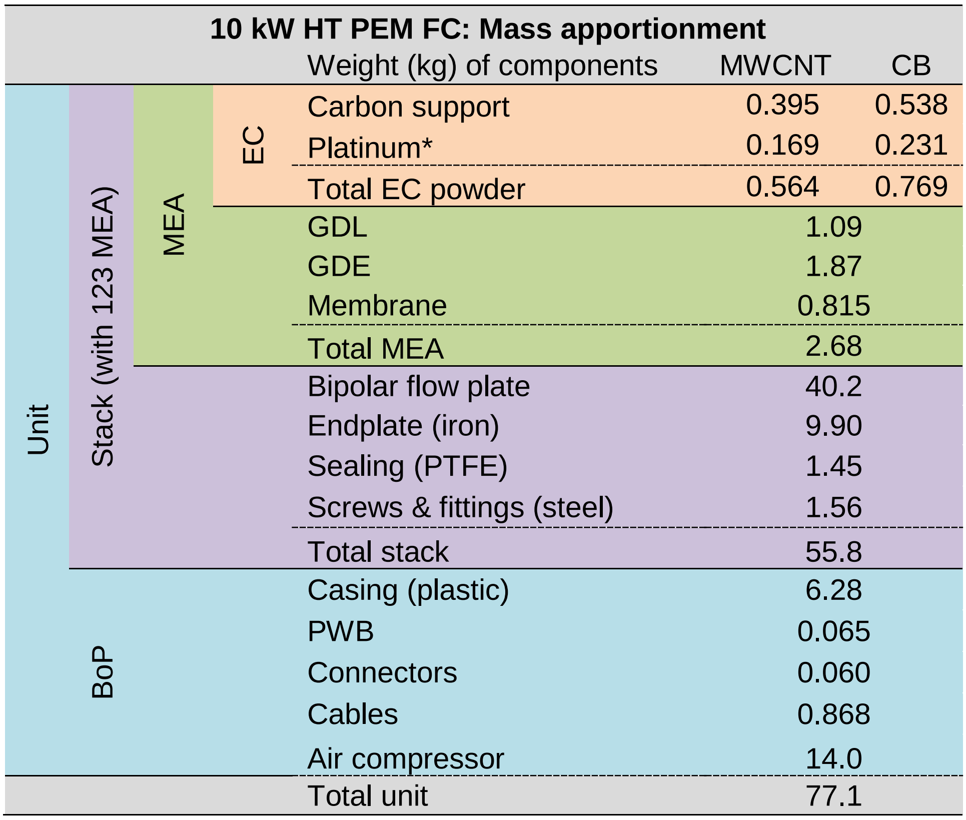
To deposit platinum and prepare the aforementioned electrocatalyst, the functionalised MWCNT or CB is dispersed in ethylene glycol. Then the platinum precursor (H_2PtCl_6) is added such that the final platinum weight reached 30%. The outcome of this mixture after drying is the electrocatalyst (EC) powder with platinum nanoparticles. In order to prepare the gas diffusion electrodes (GDE), the electrocatalyst powder is formulated into an ink, which is sprayed on a gas diffusion layer (GDL). The GDL is a porous layer based on carbon (85%) and polytetrafluoroethylene (15%). The amount of electrocatalyst deposited on the GDL is determined such that the platinum content reaches 3 mg of platinum per cm^2 of electrode using CB as carbon support and 2.2 mg/cm^2 when using MWCNT. The GDL is then calendared on to the PEM which consists mainly of aromatic hydrocarbon type polymers doped with phosphoric acid[51]. The PEM and the GDL which is coated with the electrocatalyst powder form the membrane electrode assembly (MEA).

The primary function of bipolar flow plates is the efficient and homogeneous supply of reactant gases to the GDE via the flow channels. The effectiveness of reactant transport depends partially on the art of the flow-field design[52]. In addition, flow plates must provide electrical connections between the individual cells, they must be relatively impermeable to gases, sufficiently strong to withstand stack assembly and easily mass-produced[53]. Production of the carbon-polymer composites involves the hot moulding of carbon or graphite filler in a thermosetting matrix (epoxy resin, phenolic resins).

The cell stack assembly is a process where numerous MEAs are stacked, each one separated by a bipolar flow plate. The number of single MEA included in the cell stack determines the peak power of the fuel cell. Each bipolar flow plate is sealed against the next one with polytetrafluoroethylene preventing a bypass of reactants (fuel and air) to the wrong side of the electrode. The cell stack is sandwiched between endplates and fixed with screws with moderate pressure so that electric conductivity is assured.

The PEM fuel cell stack is placed in a steel box and equipped with the balance of plant (BoP). The BoP is the infrastructure of a fuel cell, not including the single cells. Electrical and mechanical infrastructure is required, such as cables, printed wiring boards, clamp connector and connectors for electronic devices or a gas compressor which produces the required pressure on the fuel to be fed efficiently through the flow plates to the single cells.

Table 1. Mass apportionment for a HT PEM FC. MEA: membrane electrode assembly; MWCNT: Multiwalled carbon nanotubes; CB: Carbon black; EC: Electrocatalyst; GDL: Gas diffusion layer; GDE: Gas diffusion electrode; PTFE: Polytetrafluoroethylene; PWB: Printed wiring board; BoP: Balance of plant. * calculated platinum consumption using reformate gas (platinum loading 2.2 mg/cm^2, cell power: 0.13 W/cm^2)



10 kW HT PEM FC: Mass apportionment

				Weight (kg) of components	MWCNT	CB
Unit	Stack (with 123 MEA)	MEA	EC	Carbon support	0.395	0.538
				Platinum*	0.169	0.231
				Total EC powder	0.564	0.769
				GDL	1.09	
				GDE	1.87	
				Membrane	0.815	
				Total MEA	2.68	
				Bipolar flow plate	40.2	
				Endplate (iron)	9.90	
				Sealing (PTFE)	1.45	
				Screws & fittings (steel)	1.56	
				Total stack	55.8	
	BoP			Casing (plastic)	6.28	
				PWB	0.065	
				Connectors	0.060	
				Cables	0.868	
				Air compressor	14.0	
				Total unit	77.1	

Most components of a PEM fuel cell have considerable value so that it is worth to recycle the materials. The benefit of recycling is accounted for using an avoided burden model[54]. This benefit is calculated as the difference between the environmental burdens of the recycling process and those of the disposal and standard production of the corresponding good. The MEA of the PEM fuel cell is sent to a pyrolysis process to recycle platinum. The process requires high temperatures so that the carbon substrate and the GDE incinerates. Platinum is recycled with a recycling rate of 95%[55]. The bipolar flow plates, and the sealing are sent to incineration, endplates and the casing is treated as iron scrap.

Detailed input−output tables for inventory models, refined process flow schemes and the assumptions for transport distances, infrastructure, and electricity mixes are provided in the Electronic Supplementary Information (ESI; Table S1 –Table S18 and Figures S1 – Figure S5).

2.3 Product system for µ-CHP

Typical µ-CHP plants for domestic application have electric power output of about 1 kW$_{peak}$. PEM fuel cell based systems have an electric efficiency of about 40% and heat efficiency of about 50% which leads to 90% overall efficiency[16-22]. The life cycle inventory data from the 10 kW HT PEM fuel cell has been adjusted to a fuel cell with peak electricity output of 1 kW (Mass disclosure of major components ESI Table S19).

The reference system is a µ-CHP plant powered by a Stirling engine. The Stirling engine has the same peak electric output as the PEM fuel cell, but a slightly higher overall efficiency. The electric efficiency is considerably lower vis-à-vis the HT PEM fuel cell powered µ-CHP plant, in return, the heat production is substantially higher for the Stirling engine powered µ-CHP plant (Table 2).

Table 2. System characteristics for a PEM fuel cell and Stirling engine with heat and electricity added for system expansion.

	HT PEM FC	Stirling engine
Peak power output	1 kW	1 kW
Fuel	natural gas	natural gas
Output per 1 MJ natural gas		
Overall efficiency; output	90%; 0.9 MJ	96%; 0.96MJ
Electric efficiency; output	40%; 0.4 MJ	15%; 0.15 MJ
Heat efficiency; output	50%; 0.5 MJ	81%; 0.81 MJ
System expansion (MJ)		
EU electricity mix	0	0.25
Heat, natural gas	0.31	0
Total electricity	0.4	0.4
Total heat	0.81	0.81

The functional unit is chosen as the power and heat produced when burning 1 MJ of natural gas in a HT PEM fuel cell and the corresponding reference flow is 1 MJ. The output of µ-CHP plants are heat and electricity – two products with different value. The two types of µ-CHP plants have similar total energy output but the amounts of heat and electricity distinguish substantially. For that reason a comparison of the environmental impacts is not valid. ISO standards[38] suggest to expand the system, rather than allocating impacts to the products. System expansion here means that in addition to the environmental impacts for the production of 0.15 MJ electricity by the Stirling engine, environmental impacts for another 0.25 MJ electricity produced with a European electricity mix is added so that the total electricity output of the system with the Stirling engine sums up to 0.4 MJ – the same amount as produced with the HT PEM fuel cell. Vice versa, Stirling engines produce more heat. For that reason the impacts for the production of 0.31 MJ heat from natural gas combustion is added to the PEM fuel cell system so that the total output of heat is 0.81 MJ.

2.4 Product system for mobility

Adjustments of the PEM FC for automotive purpose

The requirements to performance, components and the design of an automotive PEM fuel cell differs from those of a HT PEM fuel cell[53]. The working temperature is below 100°C. Highly pure hydrogen serves as fuel[13-15]. There is limited space for a PEM fuel cell in a car what leads to volume savings using alternative materials. Bipolar flow plates, for example, can be designed thinner when using stainless steel compared to graphite composite material[56, 57]. The platinum loading is much lower (0.15 mg/cm^2 [58]) and highly pure hydrogen is used as fuel. As for the HT PEM FC, we consider 27% platinum savings if we replace CB with MWCNT as carbon substrate. This reduction is an unproven assumption deducted from the proven savings in the lab for the HT PEM FC. The most important changes for the automotive FC vis-à-vis the HT PEM FC are shown in Table 3.

Table 3: Comparison between PEMF FC for automotive and micro combined heat and power (μ-CHP) application. Pt: platinum; CO: Carbon monoxide; MEA: membrane electrode assembly

	μ-CHP	**Automotive**
Electricity output	1 kW	90 kW
Weight	19.6 kg	68.7 kg
Pt loading per cm^2 of MEA	2.2 mg/cm^2	0.11 mg/cm^2
Cell power	0.13 W/cm^2	0.7 W/cm^2
Flow plates	Graphite-resin composite	Stainless steel
Fuel	Natural gas	Hydrogen
CO-tolerance	<5%	<10-20 ppm
Temperature	160-200 °C	60-80 °C
Membrane	Hydrocarbon polymer	Nafion
Fuel to power efficiency	η_{el}=40%; η_{th}=50%; η_{tot}=90%[22]	$\eta_{el.}$=~60%
Water management	None	Complex

The change from a HT PEM FC to an automotive FC requires adaptations of the life cycle inventory data. The mass disclosure of major components of the 90 kW PEM FC is provided in the ESI (Table S20).

The functional unit is chosen as one average kilometre driven with a FCEV on the European road network. The corresponding reference flow is one vehicle-kilometre.

Comparison ICV, BEV and FCEV

Both reference vehicles are taken unaltered from Notter et al.[59]. To assure a fair comparison between the three types of vehicles we took all components of the BEV from Notter et al. and replaced the lithium ion (Li-ion) battery with the PEM fuel cell and a small Li-ion battery. All other components remained unchanged.

FCEV

There is very low data available about the fuel efficiency of FCEVs. Two studies indicate hydrogen consumption of 0.8 kg H_2 per 100 km during NEDC (New European Driving Cycle)[60, 61]. The energy content of 0.8 kg hydrogen is 26.6 kWh. Similar to the BEV the overall efficiency of the electric drivetrain is 87% (DC/AC controller: 97%; electric motor 92%; mechanical powertrain: 98%)[62] and the energy demand at the wheel is 14.1 kWh in the NEDC. Thus, the fuel to power efficiency of the PEM FC results in 60% - a value which is supported from recent literature[23, 63].

$$\eta_{Fuel\ cell} = \frac{energy\ demand\ at\ the\ wheel_{per\ 100\ km}}{\eta_{drivetrain} * H_{2\,\text{per 100 km}} * H_{2\,\text{energy density}}} = \frac{14.1\ kWh}{0.87 * 0.8\ kg * 33.3 kWh/kg} = 0.6$$

Auxiliary energy consumption of 0.5 kWh/100 km accounts for air conditioning and 0.5 kWh/100km for other electricity consumer (light, windshield wiper, ventilation, radio, navigation, etc.)[59]. In contrast to a BEV, no electricity is required for heating purpose since waste heat from the PEM FC (~80°C) can be used. The total electricity consumption therefore sums up to 15.1 kWh/100 km and translates into 0.85 kg H_2/100 km with the fuel to power efficiency of 59%.

To conform to the ICV and BEV reference vehicles the FCEV is assumed to have a life time driving distance of 150`000 km. It is assumed that contemporary fuel cell stacks don`t have to be replaced during the life time driving distance[58, 64].

The FCEV today stores about 5 kg of hydrogen which is enough to travel more than 500 km. In addition, the FCEV is equipped with a small Li-ion battery of 20 kg (2.3 kWh battery capacity) allowing for regenerative braking.

Table 4: Comparison of technical data between three different types of vehicle. [a)] energy consumption for the New European Driving Cycle as well as auxiliary demand (heating, cooling, electronic devices, etc.).

	ICV	**BEV**	**FCEV**
Fuel	petrol	electricity	Hydrogen
Fuel consumption[a]	6.1 l/100 km	17 kWh/100 km	0.85 kg H_2/100km
Fuel on board	50 litre	34 kWh (300 kg Li-ion battery)	5 kg (@70 MPa) + 2.3 kWh (20 kg Li-ion battery)
Driving autonomy	820 km	200 km	600 km
Motor power output	55 kW	55 kW	55 kW
Fuel cell: peak power			90 kW
EU emission standard	Euro 5		

Hydrogen infrastructure and production

Beside a road net and a car with an electric drivetrain, transport with a FCEV requires a hydrogen production and refuelling infrastructure (Figure 2).

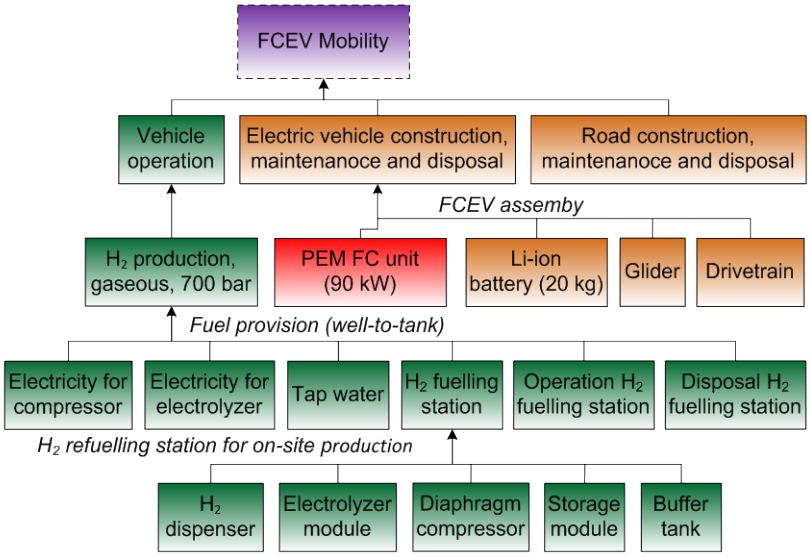


Figure 2. Simplified product system for mobility with a fuel cell electric vehicle (FCEV). Green boxes refer to the operation of the vehicle and mainly contain the fuel provision. Brown boxes represent most important components of an electric car including a small lithium ion (Li-ion) battery and the road net, both is taken from Notter et al. 2010[59]. The fuel cell is red highlighted. The purple box represents the functional unit (transport of 1 km with an FCEV).

For this work we assume decentralised hydrogen production by electrolysis of water[60]. A report from Maack[65] contains comprehensive description of the total infrastructure for decentralised hydrogen production including life cycle inventory data. Today different technologies exist for water electrolysis, and energy consumption for water splitting depends on the technology applied. Technologies working at room temperature like alkaline electrolysers and proton exchange membrane electrolyser require around 4 kWh/Nm^3 H_2[66-69] production. Electrolysis at higher temperature with solid oxide electrolyser cells reach values well below 4 kWh/Nm^3 [69, 70] . For this study we used 4.1 kWh/Nm^3 H_2, a value found from a plant available on the market[67].

According to the DOE theoretical energy to compress hydrogen isothermally from 20 bar to 700 bar is 1.36 kWh/kg H_2. If H_2 is available at ambient conditions, an additional theoretical minimum of 1.02 kWh/kg H_2 would be required. The DOE reports an actual electricity consumption of 2.67 kWh/kg H_2 for compression and in addition 0.18 kWh/kg H_2 for precooling from 30°C to -20°C. We assume therefore 2.85 kWh/kg H_2 for the refuelling process at 700 bar[71, 72] pressure.

3. Environmental analysis of a HT PEM Fuel cell

Figure 3 (and Table S21 with numerical values) shows that the mass share of the MWCNT and the catalytic active platinum is below 1 %. Similarly, the GDE and the membrane reach mass shares around 1 %. The MEAs, consisting of membranes, GDL, the MWCNTs and platinum have a total mass of 3.5%. The bipolar flow plates contribute significantly (52.2%) to the total mass of a HT PEM fuel cell unit. Other components with high mass contributions are the endplates (12.8%) and the BoP (27.6%) with its major mass components air compressor (18.2 %) and the casing (8.2 %).

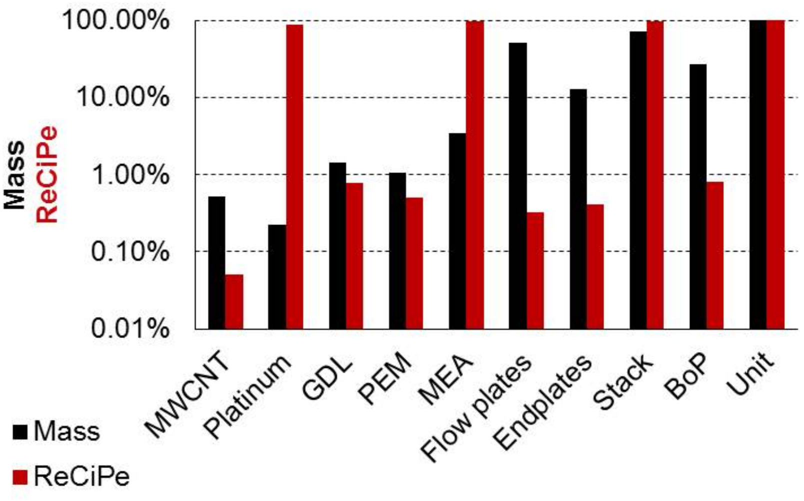


Figure 3. Mass (%; black bars) versus environmental impacts in ReCiPe (%; red bars) for the basic components of a PEM FC on a log scale. MWCNT: multiwalled carbon nanotubes; GDL: Gas diffusion layer; PEM: polymer electrolyte membrane; MEA: membrane electrode assembly; BoP: balance of plant.

The most remarkable result with respect to the environmental impacts is that the very small mass of platinum causes 89.4% of all environmental burdens. In addition the spraying process of the electro-catalytic powder on the GDE generates 4.2% due to high amount of organic solvent (isopropanol). The solvent evaporates during the drying process of the coated MEA and the organic vapour is released as emission to ambient air. About 6% of the impacts are shared over a myriad of processes and materials such as the casing, the printed wiring board, cables, endplates, membranes, sealing of the single cells, etc. The impact of MWCNT is negligible (0.03%).

One could argue that effects of nanoparticle release are not yet included in LCA[73]. Thus, a slumbering potential could occur from exposure to MWCNT and consequentially severe damage to human health similar to damage from asbestos fibres. Two reasons clearly rule out this scenario. First, studies of Nanothinx' MWCNTs employed in biomedical applications show high biocompatibility (or low toxicity)[74]. Second, the MWCNTs appear as bulk material of 1 mm to 1 cm diameter on average. Single MWCNT which potentially could be inhaled and penetrate into the respiratory system do not occur during the production process. Therefore there is no release to ambient air and accordingly human exposure via ambient air is implausible. Likewise, release of MWCNT is unlikely during the use phase and end of life. During the use phase, the MWCNT are encased between sealed flow plates. For end of life treatment of a PEM FC the MEAs are manually dismantled and sent to platinum recycling via a pyrometallurgical process. It is assumed that the MWCNT are degraded in this process (which requires temperatures well above 1000 degree Celsius[75] and are higher than the combustion temperature of MWCNT[76, 77]) or eliminated by the emission control system (e.g. particle filter). Figure 4 illustrates endpoint and midpoint indicators of production, end of life and overall environmental performance for both types of HT PEM FC. With respect to production, the total impact of the endpoint indicator damage to human health amounts to 36.3%, whereas this impact is mainly apportioned by the midpoint indicators climate change (5.0%), human toxicity (9.8%) and particulate matter formation (21.3%). The total damage to ecosystem is much smaller (4.0%) and almost all impacts arise out of the indicator climate change (3.2%). The endpoint indicator damage to resources covers 59.8% and is split into the midpoint indicator metal depletion (53.3%) and fossil depletion (6.5%).

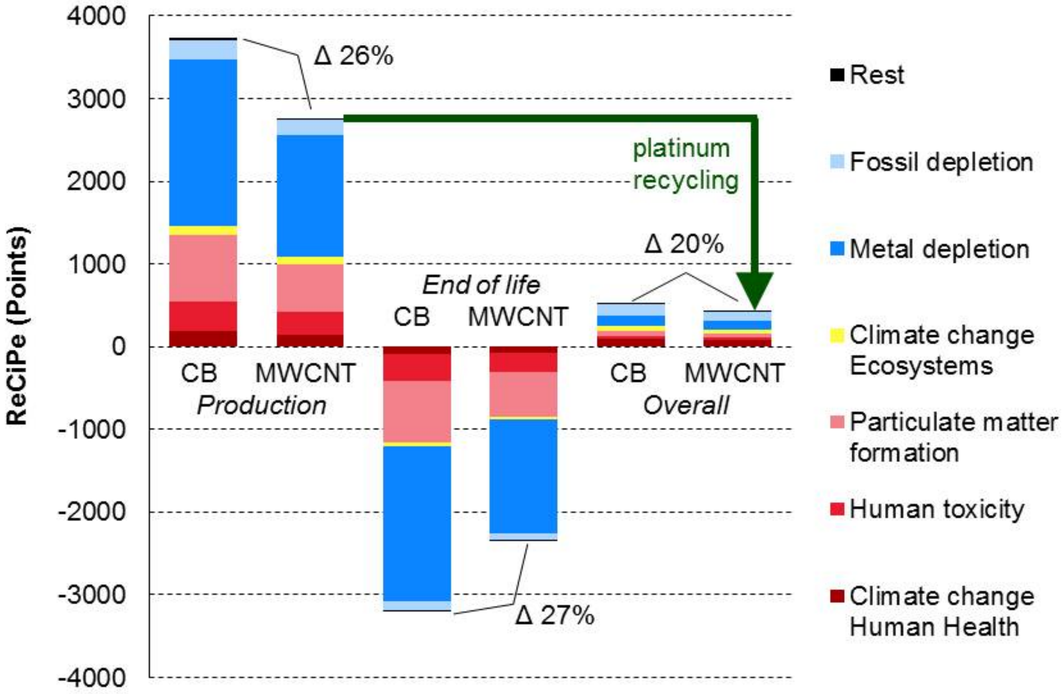


Figure 4. Production, end of life and overall environmental performance for both types of HT PEM fuel cells in ReCiPe point split into the three endpoints (reddish colours: damage to human health; yellow: damage to ecosystem; blueish colours: damage to resource depletion) and 6 midpoint indicators. “Rest” represents the remaining 11 midpoint indicators all together. CB: PEM FC with carbon black as carbon substrate; MWCNT: PEM FC with multi-walled carbon nanotubes as carbon substrate.

From the 17 midpoint indicators of the ReCiPe method 6 indicators contribute with more than 1 % each to the final score of the production process. The residual indicators contribute with 1.1% all together and are not further discussed (numerical values to all 17 midpoint indicators in ESI Table S22). Climate change is induced by energy intensive platinum mining and refining processes and a myriad of other processes throughout the production processes of a PEM fuel cell which demand energy (all together 80%), such as industrial heat or transport steps. Other contributors to climate change impacts are the spraying process (10%) of the electrocatalyst on the gas diffusion layer and the sealing of the flow plates (9%), which requires tetrafluoroethylene. Fossil depletion is closely related to climate change. Therefore the same processes which induced climate change are also responsible for fossil depletion. Platinum extraction from ground is responsible for 98% of the midpoint indicator metal depletion. Particulate matter formation is generated predominantly by the platinum mining and refining process (94%) and by a myriad of fossils used in industrial processes and transport steps. Finally, human toxicity is almost entirely determined by the disposal of sulfidic tailings from platinum mining (85.5%) and by disposal of spoils from lignite mining (13.0%).

Recycling of PEM FC illustrates the dominant influence of the platinum in PEM FCs. The recycling share of platinum is assumed to be 95%. Because of platinum recycling, a benefit is given for the yield of recycled platinum which substitutes virgin platinum. The benefit outweighs 84.7% of the environmental impacts of production. The environmental burdens of the recycling process (0.5%) are negligible compared to the benefit. Recycling reduced the overall impacts to 15.3%. All other components together contribute less than 1% for either recycling/disposal of the components or the benefits given for substitution of virgin material.

Considering the dominant influence of platinum and the negligible impact from the carbon support material MWCNT or CB, it is not surprising that the PEM fuel cell with MWCNT achieves remarkable advantages over the reference fuel cell with CB. The 27% platinum savings during PEM fuel cell production translates into 26% less environmental burdens. Vice versa, the lower platinum consumption during production leads to fewer benefits during recycling and therefore the benefit for the PEM FC with MWCNT is smaller compared to the benefit for the PEM FC with CB. However, in relative terms an environmental advantage of about 20% results for the PEM FC with MWCNT because of lower platinum consumption during production and less impacts caused by the recycling process of platinum.

We tested the robustness of the results assessed with ReCiPe single score, end and midpoint indicators by comparing the environmental performance for production of both PEM FCs. Figure 4 shows the environmental advantage in % for the PEM FC relying on MWCNT. Each indicator which had an overall influence of at least 1% was tested against corresponding indicators of at least two other methods.

Table 5. Robustness of ReCiPe results from PEM FC production when compared with five different impact assessment methods. N.A.: Comparison not applicable because the indicator in the corresponding method does not exist.

Type	Name/Method	ReCiPe	EI99	Impact 2002+	CML	USEtox	IPCC
single score		25.9%	25.9%	26.0%	N.A.	N.A.	N.A.
endpoint	Human health	25.7%	26.2%	26.3%	N.A.	N.A.	N.A.
endpoint	Ecosystem	22.6%	25.0%	24.6%	N.A.	N.A.	N.A.
endpoint	Resource	26.3%	24.6%	25.2%	N.A.	N.A.	N.A.
midpoint	Human toxicity	25.9%	26.1%	24.9%	24.2%	24.5%	N.A.
midpoint	Particulate matter	26.4%	26.3%	26.4%	N.A.	N.A.	N.A.
midpoint	Resource depletion	26.3%	24.6%	25.2%	25.7%	N.A.	N.A.
midpoint	Climate Change	22.1%	22.1%	23.6%	22.1%	N.A.	22.3%

The robustness check confirmed the environmental advantage of the PEM FC with MWCNT. The difference between the impacts assessed within each type of indicators from all methods is not more than 2.4% (ecosystem: ReCiPe 22.6% and EI99 25.0%). Across all methods and indicators the environmental advantage for the HT PEM FC with MWCNT varies not more than 4.3% (ReCiPe midpoint particulate matter: 26.4%, EI99 midpoint climate change: 22.1%). This finding only can be explained by the fact that the inventories for both types of PEM FC are almost identical. The only contrast between both products is the platinum content and the carbon substrate. The environmental impacts of MWCNT and CB, however, can be ignored. For that reason virtually all differences stem from one material – from platinum.

4. Environmental performance of a FCEV

Figure 5 (numerical values: ESI Table S24) shows the results of the environmental assessment of transport with an ICV, a BEV and a FCEV passenger car. The environmental burdens, expressed as percentage, are assessed with ReCiPe points (panel A) and climate change impacts (panel B). The ICV is used as benchmark (=100%). Our analysis confirms the results from other LCA studies for the BEV and ICV[78-81]. The assessment with ReCiPe points illustrates that there are no differences between the three types of cars when looking at the road use (infrastructure, maintenance, and disposal; 5%) and the glider (16.3%). A contrast of no importance is related to the drivetrain (ICV=6.7%; BEV and FCEV=8.5%) and maintenance and disposal of the car (ICV=4.2%; BEV and FCEV=4.1%). Both types of electric vehicles cause substantial environmental burdens for the production, maintenance and disposal of the PEM FC and the Li-ion battery. The effort for the 300 kg Li-ion battery (19.3%) in the BEV is slightly higher than the effort for PEM FC (11.7%) and the small battery (1.3%) for the FCEV. From all three vehicles the ICV generates least environmental burdens if we consider the passenger car infrastructure only.

As shown in Table 3 the material composition of an automotive PEM FC is very different in contrast to the HT PEM FC. For that reason the distribution of environmental impacts over the various components varies significantly from that of the HT PEM FC. In particular the platinum consumption receives much less relevance by reason of its twentyfold lower loading (36.1% of all impacts of the automotive PEM FC). As a consequence, the benefits of platinum recycling have much lower influence on the overall performance of an automotive PEM FC (ESI Figure S7). In contrast to the HT PEM FC, many other components substantially contribute to the impacts in the automotive PEM FC. Worth mentioning is the high impact of the bipolar flow plates (40.5%) for which the mass fraction decreased, but a change of raw materials from graphite resin composite material to stainless steel increases environmental impacts. Detailed disclosure of mass and environmental impacts of the automotive PEM FC is provided in the ESI (Figure S6, Table S20 and S23). The lower demand of virgin platinum in automotive PEM FC reduces to total environmental impacts for the production of an automotive PEM FC compared to a HT PEM FC and vice versa the benefits from recycling.

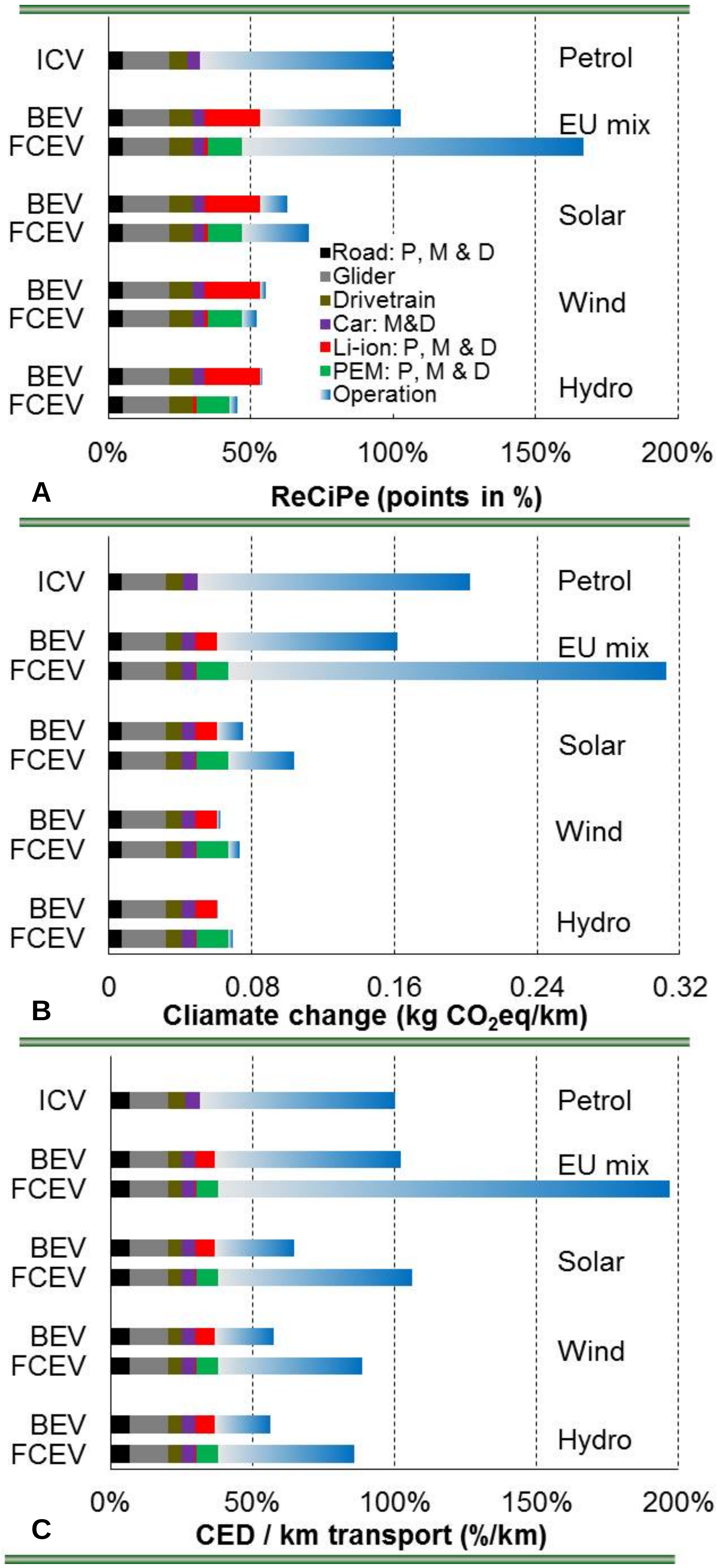


Figure 5. Environmental burdens expressed as ReCiPe points (panel A) and climate change impacts (panel B) and energetic efficiency expressed as cumulated energy demand (CED; panel C) for a transport service of 1 km trav-

elled by an ICV (internal combustion engine vehicle), a BEV (battery electric vehicle) and a FCEV (fuel cell electric vehicle). P: production; M: maintenance: D: disposal; Li-ion: lithium ion battery; PEM: polymer electrolyte membrane fuel cell; EU-mix: European electricity mix

Anyway, all these impacts from infrastructure are significantly lower than those from operation of the car, at least as long as the cars are not fuelled with renewable energy. The FCEV fuelled with a European electricity mix from 2007[82] causes by far more environmental burdens during operation (120.2%) than the BEV (49.7%) or the petrol fuelled ICV (67.6%).

Switching from fossil to renewable electricity to propel the BEV or FCEV reduces the environmental impacts from operation substantially. In this case the ICV achieves always the worst result.

The difference between the BEV and FCEV fades away when using solar power, is evened out for wind power and yet turns into a slight advantage for the FCEV when using hydropower. This is an effect of the lower impacts from infrastructure accounting for the PEM FC vis-à-vis the battery – in economic terms this represents a difference referred to as “fixed costs”. On the other hand, irrespective of the energy source, the FCEV has always higher efforts for operation of the car (“current costs”) because of the inherent inefficiency of hydrogen production via electrolysis of water followed by converting hydrogen directly back to electricity within the PEM FC. Figure 5 panel C shows the CED for all vehicle types and energy sources assessed for fuel provision. Independent of the energy source, the FCEV is never competitive with a BEV. This drawback of being less energy efficient is illustrated by the CED of operation. Regardless of the energy source the CED for the BEV reaches about 40% compared to the CED of the PEM FC. The much higher energy efficiency is explained by the losses from electrolysis (efficiency ~70%) and electricity generation in the PEM FC (efficiency ~60%).

However, if the environmental effects of these energy losses do not translate into environmental impacts – for example if hydrogen production is based on hydropower or wind – then the “current (environmental) costs” for operation are negligible and overall a small net environmental advantage for the FCEV results. Similar results were found earlier from a well-to-tank analysis for hydrogen production[2]. If we pick the midpoint indicator climate change the FCEV is not superior to the BEV anymore irrespective of the energy source for operation. The reason for this is that there is no advantage for the PEM FC versus the Li-ion battery for climate change impacts. This drawback together with the worse energy efficiency during operation leads to the fact that the FCEV will never achieve favourable results considering climate change impacts. However, for all other midpoint indicators which contribute at least 1% to the final score, the PEM FC is superior to the Li-ion battery (particulate matter, human toxicity, metal depletion).

In contrast to an earlier publication from our lab the BEV powered with European electricity mix does not show environmental advantages compared to the ICV anymore when we reassess the same ICV and BEV[59, 83]. The difference disappeared because of new inventory data which are related to disposal of tailings from metal mining (metals used for the battery and electric drivetrain) and disposal of spoils from fossil mining (lignite used for power production in the European electricity mix). Table 6 shows results from break-even analysis considering the fuel consumption of the ICV with the BEV and the FCEV. The break-even point is the point at which total environmental impacts are equal: there is no net advantage for either vehicle. The point is reached when the sum of impacts over total infrastructure (car and road production, maintenance and disposal) and operation of two vehicles is even. The break-even point for the ICV is higher than its real consumption when the BEV or FCEV is fuelled with European electricy mix. However, when fuelled with renewable electricity the ICV would have to consume between 3.4 and 1.5 litre petrol per 100 km.

Table 6. Break-even analysis for the petrol consumption (in litre/100 km) of the internal combustion engine vehicle (ICV) compared with the battery electric vehicle (BEV) and the fuel cell electric vehicle (FCEV) when using the ReCiPe method. EU-mix: European electricity mix.

	Petrol	EU-mix	Solar	Wind	Hydro
Fuel consumption ICEV	6.1				
Break-even with BEV		6.4	2.8	2.1	2.0
Break-even with FCEV		12.1	3.4	1.8	1.5

5. Environmental performance of µ-CHP

In Figure 6 (numerical values for midpoint, endpoint and single score indicator: ESI Table S25) we compare the environmental impacts (panel A) and the corresponding energy production (panel B) of µ-CHP plants run either with the HT PEM FC or a Stirling engine. In addition to the energy produced with both devices (blue bars) the amount of heat for HT PEM FC and electricity for the Stirling engine (monochrome pattern) is added resulting in similar amounts of heat and electricity output for both µ-CHP plants. The environmental burdens for both µ-CHP plants are similar (coloured bars in panel A). A very small advantage for the Stirling engine results for production of the device. This advantage is partly compensated by cleaner operation of the PEM FC. As similar as the environmental achievement is the total energy output for both devices. The crucial difference between the two µ-CHP plants is the much higher electricity gain of the HT PEM FC (dark blue). A supplement of 0.25 MJ from European electricity mix for the Stirling powered device entails 40% of all impacts (grid pattern). Vice versa, the 0.31 MJ heat supplement for the HT PEM FC system causes only about 20% additional impacts (diagonal stripe line pattern).

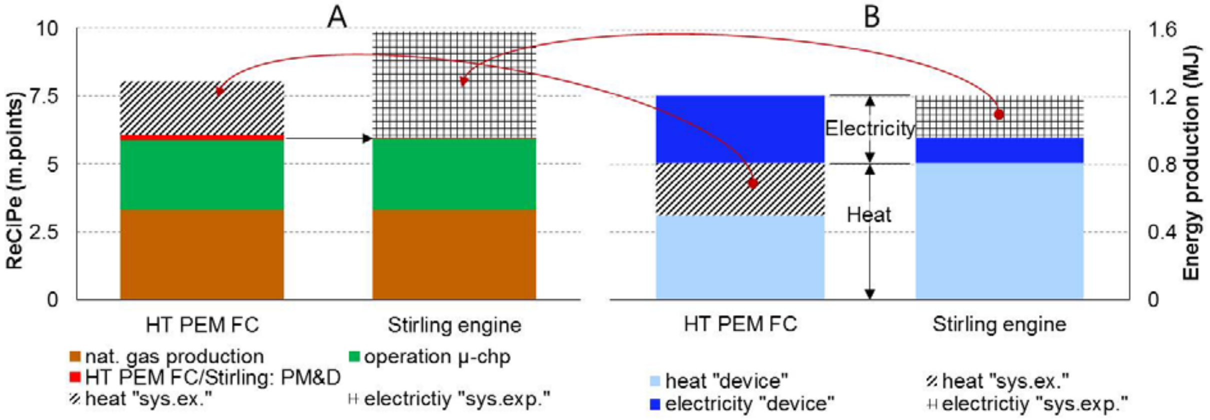


Figure 6. Environmental performance (Panel A) in ReCiPe millipoints (m.points) and energy output (Panel B) of micro combined heat and power plant (µ-CHP). "sys.ex.": system expansion; PM&D: production, maintenance and disposal; "device" refers specifically to the high temperature polymer electrolyte membrane (HT PEM FC) or the Stirling engine.

Hence, the contrast between the two µ-CHP plants is neither related to the infrastructure involved nor to the total energy output, but to the quality of the energy produced. A supplement with the missing amount of heat for the HT PEM FC or electricity supplement for the Stirling engine results in an environmental advantage for the HT PEM FC powered µ-CHP system of 18.5%.

Without any analysis we dare to argue that the HT PEM FC reaches also favourable environmental results than most other technologies among µ-CHP plants, e.g. a µ-CHP plant with an internal combustion engine. Our reasoning is that the infrastructure of µ-CHP plant with HT PEM FC most probably generates slightly more impacts than gas burning technologies, but infrastructure plays a minor role in the case of µ-CHP. The key factor, however, is the very high electricity output of PEM fuel cells. Gas burning technologies for µ-CHP may have similar or even slightly higher total energy output – but significantly lower electricity production[84, 85]. In addition, the process of reforming the fuel at low temperatures in the absence of air, rather than combusting it, results in lower emissions of harmful air pollutants, including nitrogen oxides, carbon monoxide (CO) and particulate matter[84-86]. According to Dodds et al.[86] emissions from fuel cells are around 1 order of magnitude smaller compared to other gas-burning technologies.

6. Discussion

One of the key findings of this study is the dominant share of platinum in the LCA results for a HT PEM fuel cell. Although the mass share of platinum is below 1% the noble metal causes about 90% of the environmental burdens. All other components with more than 99% of the total mass play a minor role. A reduction of platinum consumption in a PEM fuel cell is highly wishful not only for environmental, but also for economic reasons. Platinum is the major cost driver in this technology and frequently believed to be the major reason stopping the technology from successful market penetration. Using MWCNT allows for a substantial reduction of platinum and at the same time the effects of MWCNT production on the environmental performance is negligible. Substitution of CB with MWCNT results in a 20% environmental advantage for the HT PEM FC with MWCNT applied as carbon support material, even after rigorous recycling of platinum.

The comprehensive scope of LCA is useful in order to avoid problem-shifting, for example, from one phase of the life-cycle to another, from one region to another, or from one environmental problem to another. In our analysis we found problem shifting between different phases of the life cycle of a product, namely from the use phase (ICV) to the infrastructure (BEV and FCEV). This shift affects also the environmental compartments. The new technologies discussed here show substantial potential reducing impacts from operation what leads to mitigation of climate change. This reduction, however, is partly at cost of increased demands for the infrastructure which translates into a rise of impacts for particulate matter formation, human toxicity and metal depletion.

6.1 Uncertainties and limitations

For two reasons we consider the environmental advantage for the HT PEM FC with MWCNTs compared to the reference product as a reliable result. First, the robustness tests with a set of indicators shows high consensus. Similar results are found across impact assessment methods and across various indicators (single score, endpoint and midpoint). Hence, the result is independent on the impact assessment and the indicators. Second, the contrast between the two types of HT PEM FC is not subject to uncertainties from the life cycle inventories. We justify this claim by the fact that the only difference between the inventories refers to the carbon support material and amount of platinum. From all other data compiled for this study and the data used in the background there is no uncertainty which explains a contrast. All uncertainties which arise in the life cycle inventory for the processes we developed, e.g. in terms parameters choice, materials used, energy consumption, waste and emission flows, are identical for both types of HT PEM FC and fail to explain any difference. The entire advantage from the HT PEM FC with MWCNT stems from the lower platinum consumption since we know that the MWCNTs don`t influence the results. The lower platinum consumption together with MWCNT has been approved to result in the same PEM fuel cell performance as for the PEM fuel cell with CB. The platinum consumption is a prerequisite of the study and is not subject to uncertainty.

In contrast to a comparison of two similar PEM FCs, a comparison of two different devices, such as a PEM FC and a Li-ion battery, ends up with much higher uncertainties from life cycle inventories and from life cycle impact assessment. The inventory of a Li-ion battery is very different from that of an automotive PEM fuel cell. For either device each parameter assumed, each material chosen and each process modelled includes uncertainties. But the uncertainties deviate for the two devices and this deviation propagates into impacts. For example it is the author`s choice whether to balance 240 kg Li-ion battery instead of 300 km Li-ion battery for a BEV. The impact for the battery would be reduced for 20%. Contrary, the automotive PEM FC could be designed for 80 kW instead of 90 kW peak power. Such uncertainties from the inventories directly transmit into the impact assessment. A second example refers to the BEV assessed in Notter et al.[59] and the reassessment in this study. A couple of years ago we found an advantage for the BEV over the ICV. It is lost today due to improvements of disposal datasets referring to the disposal of tailings from metal and spoil from coal mining. This effect entirely depends on changes in the background database and does not even refer to the foreground model.

The error propagation from the inventory into the impact assessment is manifold. First of all, it refers to all material, energy, waste and emissions flows from the inventories and all of them contain uncertainties which transmit into impacts. In addition, uncertainties which arise from similar products (similar inventory flows) are fed to similar extent into the same impact assessment models. Else, inventory flows from a comparison of different products (PEM FC versus Li-ion battery) affect different parts in an impact assessment model. The impact assessment models contain as well high uncertainties[73]. Hence, the impact assessment amplifies the uncertainty in results when two different products are compared. Furthermore, uncertainties arise from potential impacts which are not assessed as a result of limitation in impact assessment models. For example, current impact assessment methods often do not provide characterisation factors for resource depletion of lithium. Hence, while platinum in PEM fuel cells, with a mass share of below 1%, causes more than 50% of all impacts by reason of depleting platinum resources, we do not know the impacts from depleting lithium resources. In analogy to changes in the inventory background database, impact assessment models also develop and in the future characterisation factors for lithium depletion may be developed, or new midpoint indicator may be introduced, e.g. for noise[87] or indoor pollution[88] or others.

In this study we found small differences when comparing the automotive PEM FC and the Li-ion battery. For a correct interpretation of this result we have to be aware of the uncertainties as discussed above. Therefore we conclude that the advantage for the PEM FC may not be big enough to claim that we found a true difference.

6.2 FCEV

The environmental performance of the BEV and the FCEV depends on the electricity chosen for fuel provision. Transport with electric vehicles makes sense only if the vehicles are powered with renewable electricity. Using a European electricity mix for fuel provision doesn`t result in an overall environmental advantage. However, the BEV induces less greenhouse gas emissions than the ICV and for some decision makers this is the crucial point. In contrast, the FCEV powered with a European electricity mix is definitely a clear no-go strategy. Nevertheless, the technology provides substantial potential for a future low carbon society. All over the world there is a debate about energy change, abandon nuclear power and switching from fossil to renewable energy systems. In a society with a high share of renewable electricity production the FCEV becomes competitive from the environmental point of view, even compared to a BEV, which is much more energy efficient. The advantage of a FCEV is the slightly lower impacts related to the infrastructure. Even though we consider the environmental advantage as negligible the FCEV has the advantage of higher driving autonomy and very short refuelling time.

The amount of platinum in an automotive PEM FC substantially reduced recently[23]. In our model of a 90 kW automotive PEM FC the platinum content is not more than 14.3 gram. And the platinum recycling rate is above 95%. The platinum content (or platinum group metal content) in the three-way-catalyst of an ICV depends on the size of the ICV and is in the same dimension (about 4-9 g[89, 90]) as the platinum content in our automotive PEM FC[89-92]. In contrast to the platinum in PEM fuel cells the platinum group metals in three-way catalysts of ICV are – although in very small fractions – emitted during vehicle operation and lost for recycling purposes[93-95].

6.3 Implications of renewable power supply

The prospect of changing electricity production from nuclear and fossil to predominantly renewable energy carriers as it is planned for example in Germany[96] and Switzerland[97] leads to new requirements of the electricity grid and new electricity supply pattern.

Because renewable energy sources release energy inherently intermittent over diurnal and annual cycles and are not aligned with patterns of human energy demand, great value is placed on renewable energy technologies capable of providing forms of energy that are easily stored and a flexible electricity grid. Since 2009 excess amounts of available German wind power entailed several times negative prices on the energy markets[11]. Pump storage hydro power station is the only viable option today to act as buffer for such extreme events. However, the technology provides limited energy storage because of the low energy density and it does not fit to all countries since regular rainfall events and enough elevation difference is prerequisite. By the way, Switzerland has many pump storage hydropower plants today. Despite its favourable geographical conditions Switzerland hesitates to extend its share of this technology, mainly by reasons of landscape preservation in the alpine region (increase of the height of dam, high voltage transmission lines, etc.)[98]. Batteries also do not provide a suitable option due to the comparatively low energy density. Even large fleets of smart-grid capable BEVs[99] are not able to store a reasonable amount of excess energy[11, 100].

Hydrogen possesses the required energy density to store huge amounts of excess energy in a small volume and a modernised electric grid facilitate decentralised handling of electricity supply. Power-to hydrogen may attenuate the problem of excess energy supply by converting electricity into chemically stored energy in form of hydrogen and thereby prevent the grid from electricity overload. Vice versa, µ-CHP plants may supply electricity during shortfalls and at the same time provide heat for households. The PEM FC technology could serve as device to convert hydrogen efficiently back to electricity.

6.4 Potential pitfalls and perils of the energy turnaround

No doubt, the fight against climate change is on top of the agenda. But what are the perils of a change to renewable energies? Our results show a substantial reduction of the environmental burdens for operation of a BEV or FCEV when they are powered with electricity from renewable energy. Just as clear are the impacts that stem from the additional infrastructure – the PEM FC or the Li-ion battery. The break-even point for the ICV with the BEV when it is propelled with hydropower is at about 2.2 litres. If we consider the impacts from operation negligible so that they can be ignored, the remaining difference between the two cars is reflected by the battery. Thus, the break-even point says that the battery infrastructure consumes as much as 2.2 litres per 100 km. Analogical thinking for the FCEV and the µ-CHP approves that we have gains in terms of environmental performance for the operation phase, but these gains are partly on cost of additional infrastructure required. The crux here is that all these emerging technologies (BEV, FCEV, wind or solar power) rely on critical raw materials in a way that fossil-fuelled energy infrastructure, based mostly on concrete and steel, does not[101]. Critical raw materials in this context is defined as raw materials which have a high economic importance combined with a high risk associated with their supply[102, 103]. Decision maker face two different problems. First, as earlier discussed already, the environmental impacts of many new technologies are not assessable yet because of shortcomings in impact assessment methods. These shortcomings mainly address emerging technologies, because of missing characterisation factors for resource depletion of lithium or many other geochemically scarce metals[104, 105], including rare earth elements. In addition, models to assess specific impacts from the nanotechnology [73] are not implemented in LCA today. Therefore the results shown in our analysis do not illustrate the full picture of the environmental impacts.

Second, there is growing concern of a supply shortfall for precisely these scarce metals[106, 107]. The concern of a supply risk is driven by the monopolistic position of China presently producing more than 90% of the global rare earth elements and the countries increasingly tight export quota. Roelich et al., for example, demonstrated that the supply disruption potential of neodymium will decrease for about 30% by 2050. In a scenario where the roll out of wind turbines is expedited, the risk for a shortage of low carbon electricity production increases ninefold over this period as a result of increasing exposure to neodymium-reliant technologies. It is further mentioned that not just the overall trend is of concern, but the steep increases in criticality over short periods of time[101].

In addition to a potential supply bottleneck, there are no established recycling systems available yet for many scarce metals and therefore closed materials flows cannot be expected. Lithium, for example, is hardly recycled since its recovery is economically not viable[78, 108]. In total, less than 1% of the rare earth elements currently enter the recycling loop[107-109]. To what extent recycling contributes to mitigate potential supply risks is uncertain today.

A supply shortage of essential resources for transition to renewable energy production may entail a shortage of electricity supply leading to increased dependency from electricity imports. A slower adaptation to less carbon intensive energy production by reasons of supply disruption may endanger the meeting of challenging targets set by international and national bodies. What is then a suitable answer to the predicament? A potential solution is to enlarge the diversity of products and thereby reducing reliance of single technology, component or set of materials. That way the vulnerability to material supply issues reduces and system resilience increases. With respect to power supply this implies diversification of available energy carriers: wind, solar, hydro, biomass, geothermal and - above all - a rigorous exploitation of wastes. Further diversification is achieved when new technologies use established energy source, as for example kite power[110] also uses wind energy, new forms of solar power[111], new forms of tidal power plants[112], new forms of generating hydrogen[113, 114] and other fuels[115]. Likewise, a successful strategy does not rely on BEVs alone. A future passenger car fleet may comprise also FCEVs, hybrid cars, cars propelled with natural gas, biofuels, etc. Similarly, heating and cooling systems for households may use μ-CHP plants, but also other technologies such as heat pumps, solar heating, etc. The choice of power generation technology, the passenger cars portfolio, or the preferred portfolio of heating systems should be assimilated to local geographical conditions and the feature of the landscape.

A diversification strategy for power supply does not only minimize the supply disruption risk for essential materials required for new technologies, it also balances intermittent energy availability over diurnal and annual cycles.

7. Conclusions

To recap, our analysis strove to assess the environmental performance of two types of HT PEM FCs. In a PEM fuel cell with MWCNT as carbon support the platinum share can be reduced by 27% without any losses considering performance parameters compared to a HT PEM FC using CB as carbon support material. The production of MWCNT generates almost tenfold higher environmental impact than the production of CB. Anyway, in terms of mass and in terms of environmental impact the carbon support material is irrelevant. The key determinant for the environmental achievement of a HT PEM FC is the platinum consumption. The platinum savings overcompensates by far the impacts caused by the production of MWCNT. Even after recycling of 95% of the platinum, the noble metal remains the dominant contributor considering environmental burdens and the 27% platinum savings transform in a 20% overall advantage of the HT PEM FC with MWCNT. In this application the nanotechnology provides an efficient way to reduce environmental burdens and production costs. For that reason it can take over a key role for the competitiveness of PEM FC technology and may substantially accelerate successful market penetration.

We compared two up-to-date applications with PEM FC technology which can take over key function in upcoming technology transition from the petroleum age to the age of renewable energy. First, HT PEM FC in μ-CHP plants has by far higher electric efficiency compared to the Stirling engine in μ-CHP plants, but the overall efficiency of the Stirling engine is slightly higher. The environmental performance of the HT PEM FC powered μ-CHP plant has an advantage of nearly 20% over the Stirling engine device. The favourable balance is based on the high electric efficiency of the HT PEM fuel cell.

A transition to hydrogen fuel cell drivetrains in passenger vehicles is not automatically a more environmentally benign solution to using conventional fossil fuelled ICV. Far from it, the FCEV is only competitive when hydrogen is produced with renewable electricity. The reason for this is the adverse energetic efficiency. Electrolysis of water and backwards transformation with the PEM FC to electricity consumes 2.4 times more energy than propelling the BEV directly. In case renewable energy is used for hydrogen production, the impacts from operation fade away. As soon as the impacts from operation become small enough the FCEV is a competitive to a BEV or even a tad better. The environmental advantage of the FCEV versus the BEV originates from the lower impacts related to the PEM FC in comparison to the battery.

Both applications of PEM FC technology, the µ-CHP plant and the FCEV, offer great potential to willing individuals to reduce their personal environmental (and carbon) footprint and provides a solution for more sustainable societies, as long as fuel is produced from renewables energies[9] ENREF 8.

A comprehensive transition of the energy system away from fossil and nuclear power to renewable power supply implies renovation of the electricity grid. The smart grid permits many feed-in points from decentralised supply and can handle bidirectional energy flows. Both features are inevitable for electricity production of renewables sources which is supplied decentralised and include diurnal and annual cycles. The PEM FC technology suits to support a smart grid in different ways. Excess electricity can be transformed into hydrogen which can easily be stored in unlimited amounts. That’s a strong argument in favour of the FCEV which efficiently converts hydrogen back to electricity. During periods of high power demand the PEM FC in µ-CHP plants may produce electricity and additionally supply heat. Both technologies support a renovated electricity grid by stabilising power supply. Like that the electricity grid is automatically supported during high electricity demands, it is protected from overload and excess electricity does not have to be destroyed.

The crucial point here is that all these emerging technologies (BEV, FCEV, wind or solar power) rely on critical materials. A poorly diversified product portfolio involves the risk of a supply disruption of scarce materials. A national strategy to decarbonise a society could be configured by an energy production system as diversified as possible, considering the local economic, social and ecological circumstances and embedded in the feature of the landscape. That way the vulnerability to material supply issues reduces and system resilience increases, thus empowering legal bodies meeting environmental targets more likely.

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Text - 1 sentence:

This work presents a life cycle assessment of a cutting edge PEM FC for transportation and stationary applications.