Article

Life Cycle Assessment of the Domestic Micro Heat and Power Generation Proton Exchange Membrane Fuel Cell in Comparison with the Gas Condensing Boiler Plus Electricity from the Grid

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Content:

A) Methods and Scenarios settings

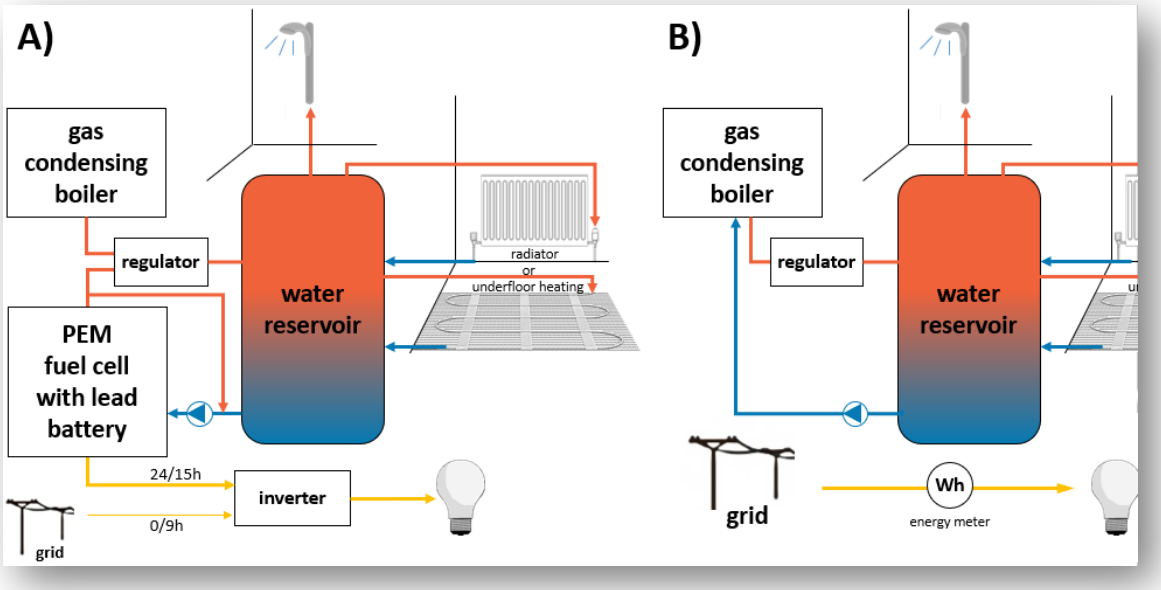


Figure S1. A) Investigated innovative energy supply system consisting of the proton-exchange-membrane fuel cell (PEMFC), gas condensing boiler, water reservoir, under floor heating (alternatively radiators), inverter (full load operation of the PEMFC in the basis and old building scenario and part load operation (15 h/day) in the new building scenario); B) Investigated conventional energy supply system consisting of stand-alone gas condensing boiler, water reservoir, under floor heating (alternatively radiators).

B) Life cycle inventory of the PEMFC system

Table S1. Life cycle inventory of the PEMFC system

PEMFC		
Stack		
Material	**Value**	**GaBi Dataset**
Polybenzimidazole	0.270 kg	DE Glass fibres agg Sphera 01.03.2022 DE Pelletizing and compounding e-ep Sphera 01.03.2022 GLO Plastic injection moulding (parameterized) e-ep Sphera 01.03.2022
Phosphoric acid	0.075 kg	EU-28 Phosphoric acid (H3PO4. 54% P2O5) agg 01.03.2022
Carbon fiber	0.090 kg	
Ammonia	0.0111 kg	EU-28 Ammonia (NH3) production mix. without CO2 recovery (carbon dioxide emissions to air) agg Sphera 01.03.2022
Propylene	0.0283 kg	EU-28 Propylene agg PlasticsEurope 01.03.2022 production mix. at plant
Acrylonitrile	0.0232 kg	RER Acrylonitrile (AN) agg PlasticsEurope 01.03.2022 technology mix
Methyl methacrylate	0.00117 kg	RER Methyl methacrylate (MMA) agg PlasticsEurope 01.03.2022 technology mix
Polyacrylonitrile Fibres	0.0244 kg	EU-28 Polyacrylonitrile Fibres (PAN) agg Sphera 01.03.2022 Polymerization. dissolving. spinning
Natural gas	0.00177 kg	EU-28 Natural gas mix agg Sphera 01.03.2022 technology mix
Electricity	0.9 MJ	EU-28 Electricity grid mix (production mix) Mfg Sphera 01.03.2022
Platinum	0.0075 kg	GLO Platinum mix agg Sphera 01.03.2022 primary production
Carbon black	0.075 kg	DE Carbon black (furnace black; general purpose) (economic allocation) agg Sphera 01.03.2022

Synthetic graphite	1.8 kg	DE Carbon black (furnace black; general purpose) (economic allocation) agg Sphera 01.03.2022 Graphitization e-ep 18.10.2021 DE Electricity grid mix agg Sphera 01.03.2022 AC. technology mix
Polytetrafluoroethylene	0.0225 kg	EU-28 Polyethylene. HDPE. granulate agg PlasticsEurope 01.03.2022 production mix. at plant
Aluminium ingot	0.210 kg	DE Aluminium ingot mix agg Sphera 01.03.2022 primary production
Gold (primary)	0.00027 kg	GLO Gold (primary) agg Sphera 01.03.2022 primary route
Stainless Steel	0.060 kg	DE Stainless Steel slab (X6CrNi17) t-agg Sphera 01.03.2022 EAF route
Total	**2.610 kg**	
BoP Components		
Aluminium ingot	20.4 kg	DE Aluminium ingot mix agg Sphera 01.03.2022 primary production
Stanless steel	6.5 kg	DE Stainless Steel slab (X6CrNi17) t-agg Sphera 01.03.2022 EAF route
Cast iron	0.6 kg	DE Cast iron component (EN15804 A1-A3) t-agg Sphera 01.03.2022 EAF route
Copper	0.1 kg	GLO Copper mix (99.999% from electrolysis) agg Sphera 01.03.2022 from electrolysis
Reformer Catalyst – TMs based	2.5 kg	
Nickel oxide	0.060 kg	GLO Nickel (Class 1. >99.8% Nickel) agg Nickel Institute 01.03.2022 technology mix DE Oxygen (liquid) agg Sphera 01.03.2022 via cryogenic air separation
Bauxite	5.260 kg	EU-28 Bauxite agg Sphera 01.03.2022 technology mix
Quicklime	0.0738 kg	EU-27 Quicklime agg EuLa 01.03.2022 Quicklime. granular or powder. free CaO from 89.5% to 97.5%. stored in silos. ready to be shipped
Electricity	0.749 MJ	DE Electricity grid mix agg Sphera 01.03.2022 AC. technology mix
Sodium hydroxide	0.116 kg	DE Sodium hydroxide (caustic soda) mix (100%) agg Sphera 01.03.2022 technology mix
Thermal energy from heavy fuel oil	0.0772 MJ	DE Thermal energy from heavy fuel oil (HFO) agg Sphera 01.03.2022 technology mix regarding firing and flue gas cleaning
Thermal energy from light fuel oil	0.00497 MJ	DE Thermal energy from light fuel oil (LFO) agg Sphera 01.03.2022 technology mix regarding firing and flue gas cleaning
Thermal energy from natural gas	18.1 MJ	DE Thermal energy from natural gas agg Sphera 01.03.2022 technology mix regarding firing and flue gas cleaning
Process steam from natural gas	0.102 MJ	DE Process steam from natural gas 90% agg Sphera 01.03.2022 technology mix regarding firing and flue gas cleaning
Heating control unit	1 piece	
Liquid Crystal Display	0.0105 sqm	GLO Liquid Crystal Display (LCD). Panel Assembly LED TFT. mixed TN-IPS technology (mobile phone). in sqm agg Sphera 01.03.2022
Printed wiring board with signal electronics	0.056 sqm	GLO Average Printed Wiring Board with Signal Electronics (DfX-compatible) agg Sphera 01.03.2022 Production of signal electronics on base of FR4 substrate
Polyamide 6	0.6 kg	EU-28 Polyamide 6 (PA6) agg PlasticsEurope 01.03.2022 1 kg of primary PA6 “at gate” (production site output) representing a European industry production average. in pellet form
Steel plate	7.6 kg	EU Steel plate agg worldsteel 01.07.2022 blast furnace route and electric arc furnace route

Cable 3 wire	1.75 kg	EU-28 Cable 3 wire (EN15804 A1-A3) agg Sphera 01.03.2022 technology mix
Expanded Polystyrene	1.1 kg	EU-28 Expanded Polystyrene (EPS) Foam (25 kg/m3. EN15804 A1-A3) agg Sphera 01.03.2022 styrene polymerization. foaming
Glass ceramic	0.17 kg	EU-28 Glass ceramic production agg Sphera 01.03.2022 Mixing. melting minerals and forming glass
Platinum	0.01 kg	GLO Platinum mix agg Sphera 01.03.2022 primary production
Triethylene glycol	2.5 kg	EU-28 Triethylene glycol agg PlasticsEurope 01.03.2022 production mix. at plant
Steel plate	150.0 kg	EU Steel plate agg worldsteel 01.07.2022 blast furnace route and electric arc furnace route
Polyethylene	12.0 kg	EU-28 Polyethylene. LDPE. granulate agg PlasticsEurope 01.03.2022 production mix. at plant GLO Plastic injection moulding (parameterized) e-ep Sphera 01.03.2022 injection moulding
Gold	0.003 kg	GLO Gold (primary) agg Sphera 01.03.2022 primary route. underground mining. underground mining and leaching
Total weight	**206 kg**	
Lead Battery Pack		
Lead	80.4 kg	DE Lead (99.995%) agg Sphera 01.03.2022 primary production
Acrylonitrile butadiene styrene	0.871 kg	EU-28 Acrylonitrile butadiene styrene (ABS) agg PlasticsEurope 01.03.2022
Brass	0.201 kg	EU-28 Brass (CuZn39Pb3) t-agg Sphera 01.03.2022
Glass ceramic	0.1 kg	EU-28 Glass ceramic production agg Sphera 01.03.2022 Mixing. melting minerals and forming glass
Polypropylene Ethylene	0.062 kg	DE Polypropylene / Ethylene Propylene Diene Elastomer Granulate (PP/EPDM. TPO. TPE-O) Mix agg Sphera 01.03.2022
Polyester resin	0.699 kg	DE Polyester Resin (unsaturated) (UP) agg Sphera 01.03.2022 esterification and polymerization. from propylene glycol. phthalic anhydride and styrene
Polypropylene	0.489 kg	DE Polypropylene GMT part agg Sphera 01.03.2022 hot rolling. from polypropylene and glass fibres
Polyurethane	0.034 kg	RER Polyurethane rigid foam (PU) agg PlasticsEurope 01.03.2022 technology mix
Polyvinylchloride	1.3 kg	RER Polyvinylchloride injection moulding part (PVC) agg PlasticsEurope 01.03.2022 technology mix
Sulphuric acid	39.3 kg	EU-28 Sulphuric acid (96%) agg Sphera 01.03.2022 concentrated. sulphur dioxide route
Styrene acrylonitrile	8.61 kg	EU-28 Styrene acrylonitrile (SAN). a-Methyl styrene acrylonitrile (AMSAN) agg PlasticsEurope 01.03.2022
Total weight	**132 kg**	
Water Reservoir		
Stainless steel	95.4 kg	EU-28 Stainless steel sheet (EN15804 A1-A3) t-agg Sphera 01.03.2022 EAF route - stainless steel production GLO Steel sheet stamping and bending (5% loss) e-ep Sphera 01.03.2022 technology mix
Copper pipe	21 kg	EU-28 Copper pipe mix. bare (A1-A3) agg Sphera 01.03.2022 technology mix
Expanded Polystyrene foam	1.61 kg	EU-28 Expanded Polystyrene (EPS) Foam (25 kg/m3. EN15804 A1-A3) agg Sphera 01.03.2022 styrene polymerization. foaming
Total weight	**118 kg**	
Inverter (0.5 pieces) *		
AlSi12(Cu)	12.8 kg	DE Aluminium ingot mix agg Sphera 01.03.2022 primary production CN Magnesium agg Sphera 01.03.2022 technology mix, primary production

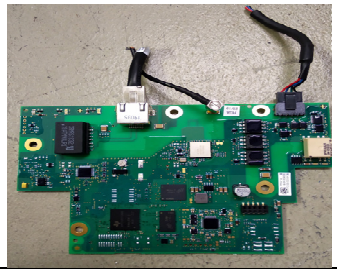
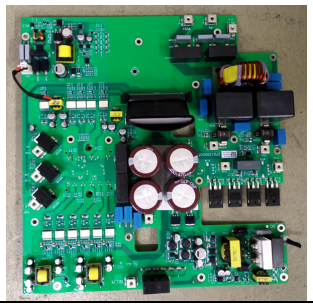
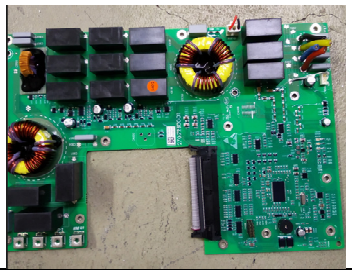
		GLO Silicon mix (99%) agg Sphera 01.03.2022 purified, electric arc furnace process, from quartz sand GLO Ferro-manganese, refined (Ref. FeMn), 80 to 85 wt. % Mn, less than 1.5 wt % carbon agg Sphera 01.03.2022 primary production GLO Copper (99.99%; cathode)agg ICA 01.03.2022 from pyrometallurgical (including secondary) and hydrometallurgical production DE Aluminium cast machining e-ep Sphera 01.03.2022 technology mix
Stainless steel	0.266 kg	EU-28 Stainless steel sheet (EN15804 A1-A3) t-agg Sphera 01.03.2022 EAF route - stainless steel production GLO Steel sheet stamping and bending (5% loss) e-ep Sphera 01.03.2022 technology mix
Polyamide (PA 6)	0.588 kg	EU-28 Polyamide 6 (PA6) agg PlasticsEurope 01.03.2022 1 kg of primary PA6 “at gate” (production site output) representing a European industry production average, in pellet form {c3a53e26-b87f-4d41-bffa-785fc0ca4935} GLO Plastic injection moulding (parameterized) e-ep Sphera 01.03.2022 injection moulding
Copper	0.0252 kg	GLO Copper mix (99,999% from electrolysis) agg Sphera 01.03.2022 from electrolysis
Screws	0.281 kg	EU-28 Fixing material screws stainless steel (EN15804 A1-A3) agg Sphera 01.03.2022 technology mix
Signal electronics	0.186 sqm	GLO Average Printed Wiring Board with Signal Electronics (DfX-compatible) agg Sphera 01.03.2022 Production of signal electronics on base of FR4 substrate
Signal-power electronics	0.156 sqm	GLO Average Printed Wiring Board with Signal Electronics (DfX-compatible) agg Sphera 01.03.2022 Production of signal electronics on base of FR4 substrate GLO Average Printed Wiring Board with Power Electronics (DfX-compatible) agg Sphera 01.03.2022 production of power electronics on base of FR4 substrate
Cable	0.475 kg	EU-28 Cable CAT 7 (EN15804 A1-A3) agg Sphera 01.03.2022 technology mix
Plug (PA6)	1 piece	EU-28 Plug (PA6) (EN15804 A1-A3) agg Sphera 01.03.2022 technology mix
Glue	0.346 kg	EU-28 Glue for gypsum boards (EN15804 A1-A3) agg Sphera 01.03.2022 technology mix
Ring core coils	4 pieces	DE Lead (99,995%) agg Sphera 01.03.2022 primary production DE Ferro chrome high carbon, consumption mix agg Sphera 01.03.2022 primary production DE Aluminium ingot mix agg Sphera 01.03.2022 primary production DE Polycarbonate Granulate (PC) agg Sphera 01.03.2022 durable material, posgenation of Bisphenol A DE Polyamide 6.6 Granulate (PA 6.6) Mix agg Sphera 01.03.2022 technology mix DE Polyethylene High Density Granulate (HDPE/PE-HD) Mix agg Sphera 01.03.2022 technology mix GLO Plastic injection moulding (parameterized) e-ep Sphera 01.03.2022 injection moulding EU-28 Copper Wire Mix (Europe 2015) agg DKI/ECI 01.03.2022 technology mix
Checkbox Fronius	1.2 kg	
AlSi12(Cu)	0.988 kg	DE Aluminium ingot mix agg Sphera 01.03.2022 primary production CN Magnesium agg Sphera 01.03.2022 technology mix, primary production GLO Silicon mix (99%) agg Sphera 01.03.2022 purified, electric arc furnace process, from quartz sand

		GLO Ferro-manganese, refined (Ref. FeMn), 80 to 85 wt. % Mn, less than 1.5 wt % carbon agg Sphera 01.03.2022 primary production GLO Copper (99.99%; cathode)agg ICA 01.03.2022 from pyrometallurgical (including secondary) and hydrometallurgical production DE Aluminium cast machining e-ep Sphera 01.03.2022 technology mix
Screws	0.0233 kg	EU-28 Fixing material screws stainless steel (EN15804 A1-A3) agg Sphera 01.03.2022 technology mix
Signal-power electronics	0.0244 sqm	GLO Average Printed Wiring Board with Signal Electronics (DfX-compatible) agg Sphera 01.03.2022 Production of signal electronics on base of FR4 substrate GLO Average Printed Wiring Board with Power Electronics (DfX-compatible) agg Sphera 01.03.2022 production of power electronics on base of FR4 substrate
Smart meter	0.268 kg	
Polyamide (PA 6)	0.0743 kg	DE Polyamide 6.6 Granulate (PA 6.6) Mix agg Sphera 01.03.2022 technology mix GLO Plastic injection moulding (parameterized) e-ep Sphera 01.03.2022 injection moulding
Signal electronics	0.00598 sqm	GLO Average Printed Wiring Board with Signal Electronics (DfX-compatible) agg Sphera 01.03.2022 Production of signal electronics on base of FR4 substrate
Power electronics	0.00553 sqm	GLO Average Printed Wiring Board with Power Electronics (DfX-compatible) agg Sphera 01.03.2022 production of power electronics on base of FR4 substrate
Liquid crystal display	0.0027 sqm	GLO Liquid Crystal Display (LCD), Panel Assembly LED TFT, mixed TN-IPS technology (mobile phone), in sqm agg Sphera 01.03.2022 TN-IPS technology, without LCD controller, without glass overlay
Total weight	**18.5 kg**	
Other parts of the system		
Gas condensing boiler < 20 kW (0.5 pieces) **	66.5 kg	EU-28 Gas condensing boiler < 20 kW (upright unit) (EN15804 A1-A3) t-agg Sphera 01.03.2022 technology mix
Underfloor heating system copper (UHS) ***	40.9 sqm	EU-28 Underfloor heating system copper (200 mm distance) (EN15804 A1-A3) agg Sphera 01.03.2022 technology mix
Underfloor heating system PP (UHS) ****	40.9 sqm	EU-28 Underfloor heating system pp (200 mm distance) (EN15804 A1-A3) agg Sphera 01.03.2022 technology mix
Underfloor heating system PEX (UHS) ****	40.9 sqm	EU-28 Underfloor heating system pex (200 mm distance) (EN15804 A1-A3) agg Sphera 01.03.2022 technology mix
Steel Radiator ****	5 pieces	EU Steel organic coated agg worldsteel 01.07.2022 blast furnace route GLO Steel turning e-ep Sphera 01.03.2022 technology mix EU-28 Electricity grid mix agg Sphera 01.03.2022 AC. technology mix EU-28 Solvent paint white (EN15804 A1-A3) agg Sphera 01.03.2022 technology mix

*** The scaling factor 0.5 due to the lifetime of the GCB of 20 years (lifetime of PEMFC 10 years)**
**** The weight according to the scaling factor 0.5 due to the lifetime of the GCB of 20 years (lifetime of PEMFC 10 years)**
***** Basis scenario UHS**
****** Sensitivity scenario UHS/Radiators**

Life cycle inventory of the inverter (primary data)

Table S2. Life cycle inventory of the SMA Inverter, which was manually dismantled and analyzed for the material composition.

SMA Inverter				
	Material component	**Weight, g**	**Material**	
1	housing	2783	aluminium-silicon	
2	fastening part	228	aluminium-silicon	
3	core part	266.2	steel sheet	
4	Fan	84 (58.8/25.2)	plastics/copper	
5	signal electronics (dimension 11 x 16.9 cm)	92.6	printed circuit board (epoxy resins, semiconductor metals and metalloids, other metals)	
6	signal-power-electronics (dimension 30 x 31.3 cm)	1361	printed circuit board (epoxy resins, semiconductor metals and metalloids, copper, plastics, ferro chrome, lead, other metals	
7	signal-power-electronics (dimension 20 x 31.2 cm)	963.2	printed circuit board (epoxy resins, semiconductor metals and metalloids, copper, plastics, ferro chrome, lead, other metals	
8	screws	281.1	stainless steel	
9	cable with connector	535.2	Plastics, copper	

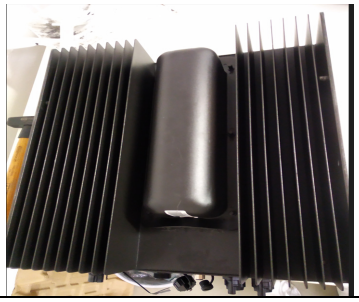
10	housing. ring core coils. glue	10406.1	9740.5 aluminium-silicon 320 coils 345.6 glue	
	total weight	**17000**		

Table S3. Life cycle inventory of the checkbox Fronius, which was manually dismantled and analyzed for the material composition.

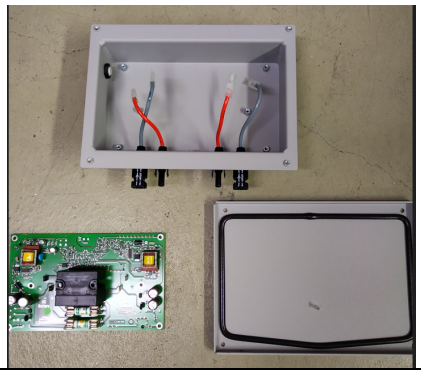
Checkbox Fronius				
Material component		**Weight, g**	**Material**	
1	signal-power electronics (dimension 20 x 12.2 cm)	187.6	printed circuit board (epoxy resins, semiconductor metals and metalloids, copper. Plastics, ferro chrome, lead, other metals	
2	housing	987.5	aluminium-silicon	
3	screws	23.3	stainless steel	
	total weight	**1198.4**		

Table S4. Life cycle inventory of the smart meter, which was manually dismantled and analyzed for the material composition.

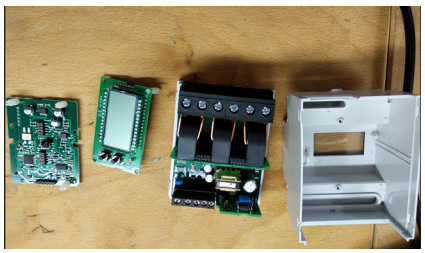
Smart meter				
1	housing	74.25	plastic (PA)	
2	power-electronics (dimension 8.5 x 6.5 cm)	161	printed circuit board (epoxy resins. Copper, plastics, ferro chrome, lead other metals)	
3	signal-electronics (dimension 6.5 x 4 cm and 6.5 x 5.2 cm)	33	printed circuit board (epoxy resins, semiconductor metals and metalloids, other metals)	
	total weight	**268.25**		

Table S5: Technical performance of the fuel cell heating unit Vitovalor PT 2 [1]

Vitovalor PT 2	**Type**	**F11T**
Nominal heat output	kW th	0.9 - 11.4
Electrical power	W el	750
Thermal performance	kW th	1.1
Sound power	dB (A)	48
Electrical efficiency	%	38 (Hi)
Overall efficiency	%	Up to 92 (Hi)

Standard efficiency Peak load boiler	%	Up to 98 (Hs)
Fuel		Natural gas

Table S6: Assumptions for the durability and degradation of the PEMFC based on the reviewed literature [2-5]

Parameter	Value	Source	Comments
Degradation (minimal), µV/h	1	Wu et al._2008	According to Wu et al., 2008, normal degradation targets require less than 10% loss in the efficiency of the fuel cell system at the end of life, and a degradation rate of 2–10µV/h is commonly accepted for most applications.
Operating hours, h_scenario 1	83038	Viesmann; Dodds, P.E., et al_2015 (80000)	Vitovalor PT2 produces electricity for up to 45.5 hours without interruption. The fuel cell then regenerates for 2.5 hours (Viessmann).
Operating hours, h_scenario 2	41519	S-Y. Ahn_2002; Wu et al._2008 (40000)	According to Wu et al., 2008, for different applications, the requirements for fuel cell lifetime vary significantly, ranging from 5000 h for cars to 20,000 h for buses and 40,000 h of continuous operation for stationary applications.
Cell voltage, V	0.7	Wong et al_2015	According to Wong et al_2015 Cell voltage is further reduced to 0.7 V, representing a more practical fuel cell operating voltage.
Degradation_scenario 1, %	12%	calculated	According to Dodds, P.E., et al, 2015: the degradation of PEMFC amounts to 1% per year, whereas 1% degradation in electricity production is compensated by 1% increase in heat generation.
Degradation_scenario 2, %	6%	calculated	
Scenario 1: th. Energy yield [kWh/a] (83038 h)	10779	calculated	x1 pieces PEMFC (Lifetime of the considered system - 10 years)
Scenario 1: el. Energy yield [kWh/a] (83038 h)	5791	calculated	x1 pieces PEMFC (Lifetime of the considered system - 10 years)
Scenario 1: gas consumption [kWh/a] (83038 h)	18011	calculated	x1 pieces PEMFC (Lifetime of the considered system - 10 years); According to Dodds, P.E., et al, 2015: The efficiency of the PEMFC is 92%.
Scenario 2: th. Energy yield[kWh/a] (41519 h)	10208	calculated	x2 pieces PEMFC (Lifetime of the considered system - 10 years)
Scenario 2: el. Energy yield [kWh/a] (41519 h)	6180	calculated	x2 pieces PEMFC (Lifetime of the considered system - 10 years)
Scenario 2: gas consumption [kWh/a] (41519 h)	17813	calculated	x2 pieces PEMFC (Lifetime of the considered system - 10 years); According to Dodds, P.E., et al, 2015: The efficiency of the PEMFC is 92%.

C) Parameterized GaBi-model of the manufacturing phase of the energy supply system

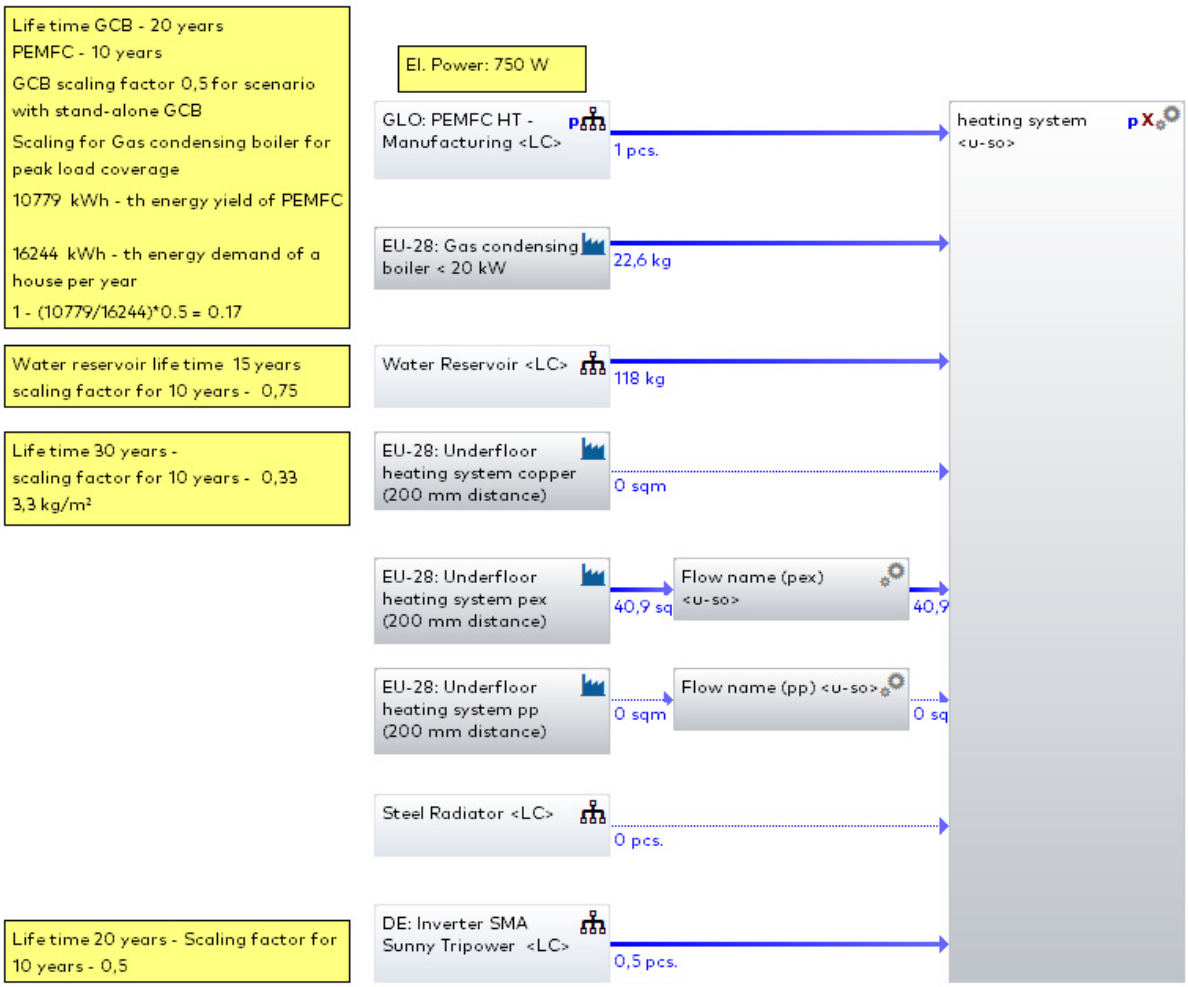


Figure S2. Flow chart of the parameterized GaBi-model of the manufacturing phase of the entire energy supply system.

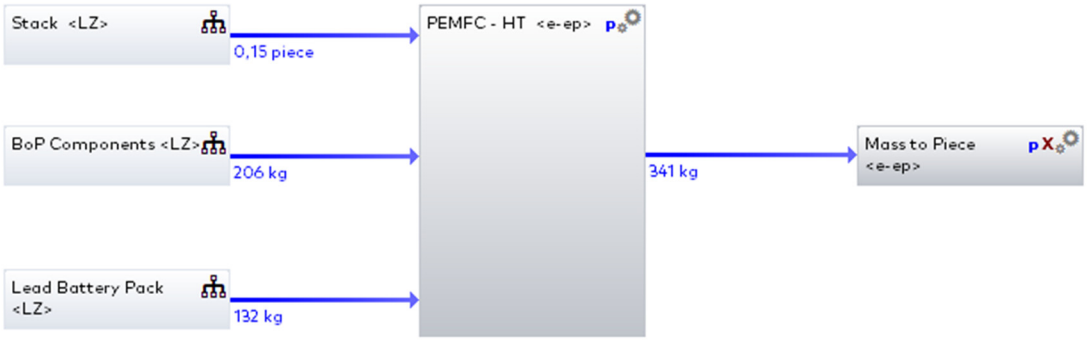


Figure S3. Flow chart of the parameterized GaBi-model: manufacturing phase of the PEMFC

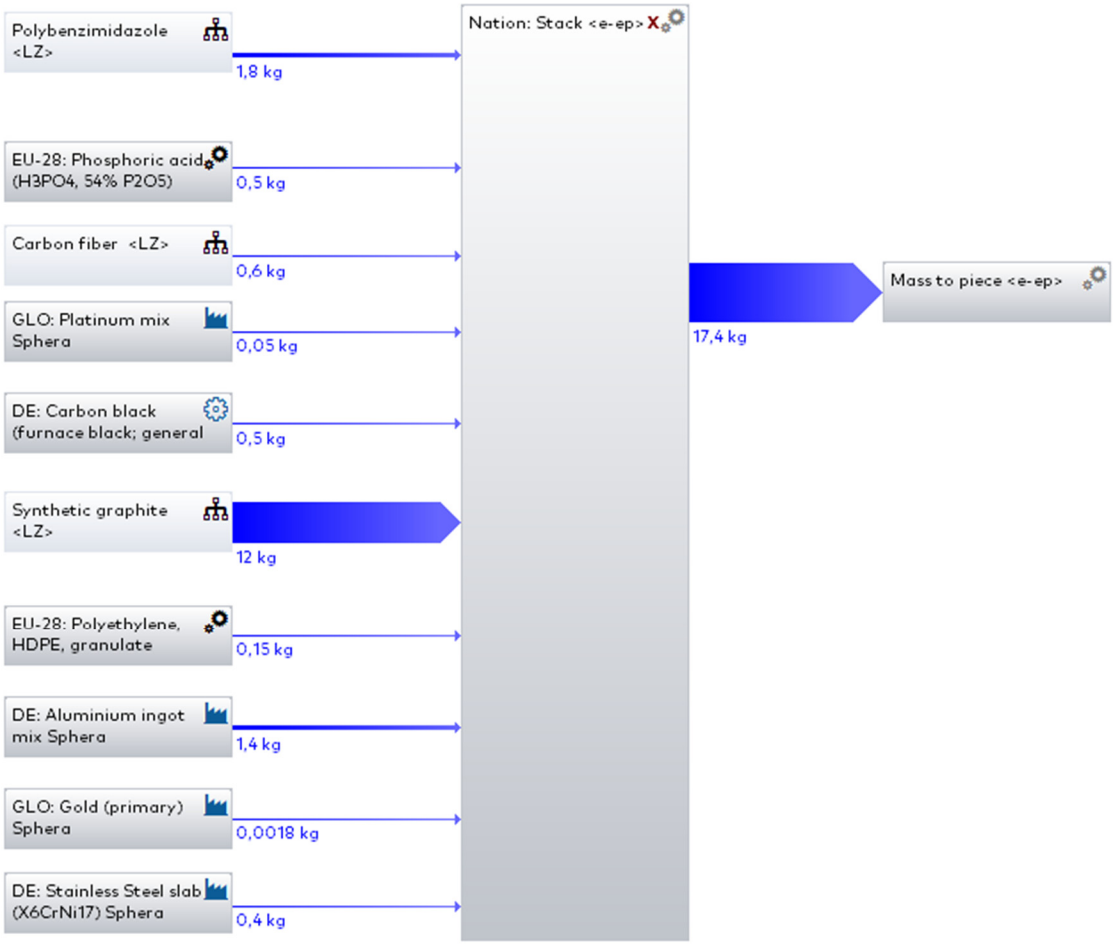


Figure S4. Flow chart of the GaBi-model: manufacturing phase of the stack module of the PEMFC

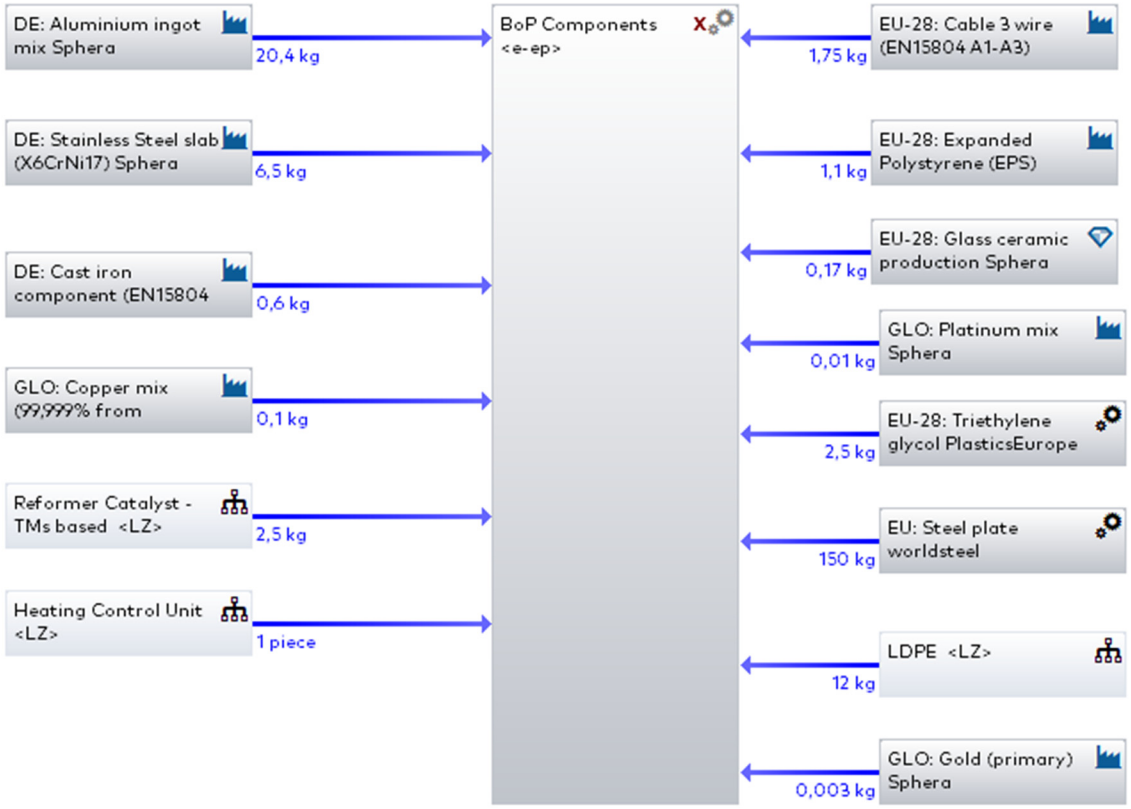


Figure S5. Flow chart of the GaBi-model: manufacturing phase of the Balance-of-Plant module of the PEMFC

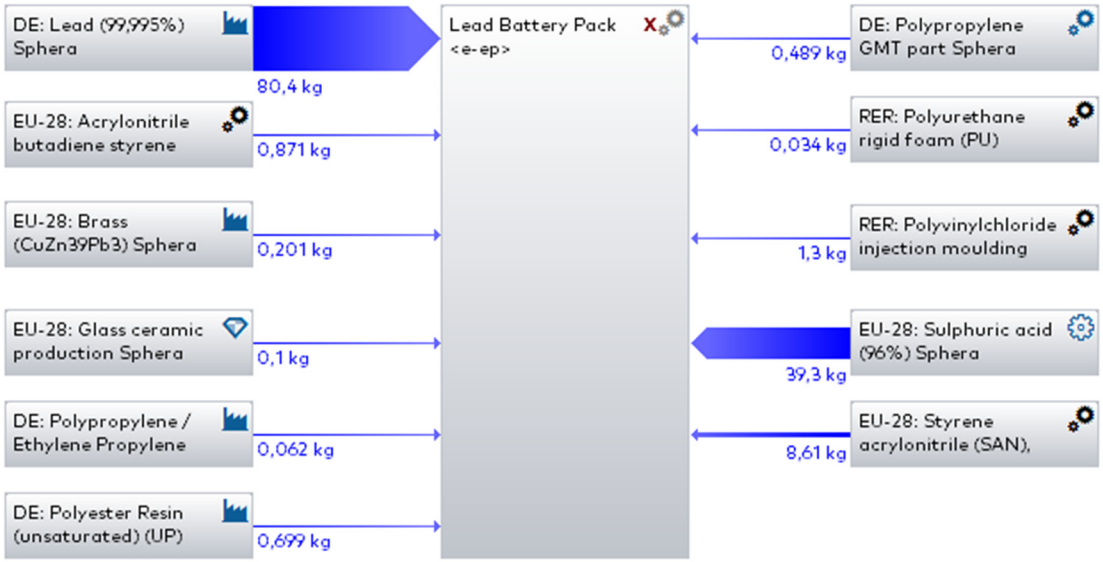


Figure S6. Flow chart of the GaBi-model: manufacturing phase of the lead battery pack module of the PEMFC

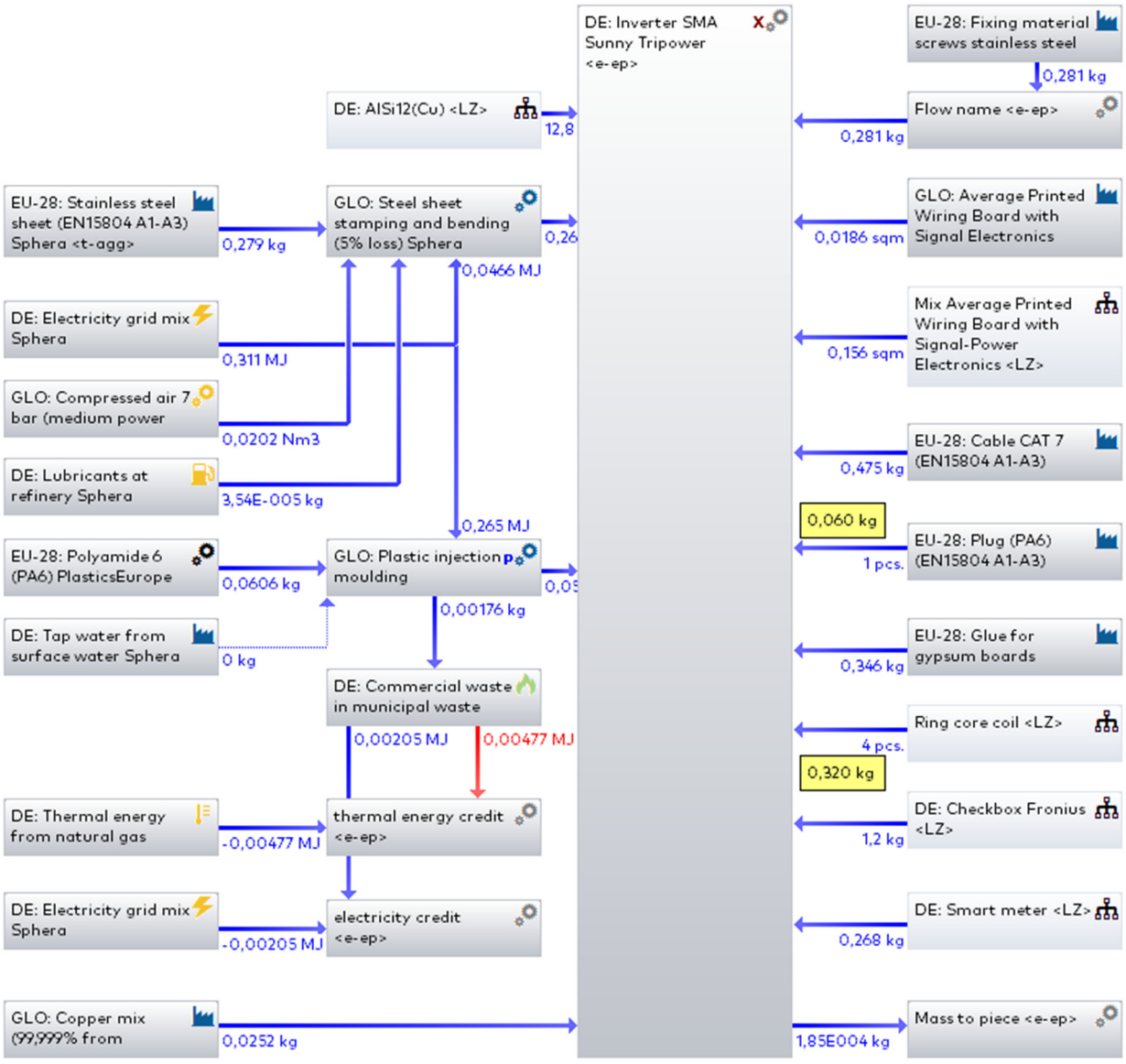


Figure S7. Flow chart of the GaBi-model: manufacturing phase of the SMA Inverter

D) Parameterized GaBi-model of the use phase of the energy supply system

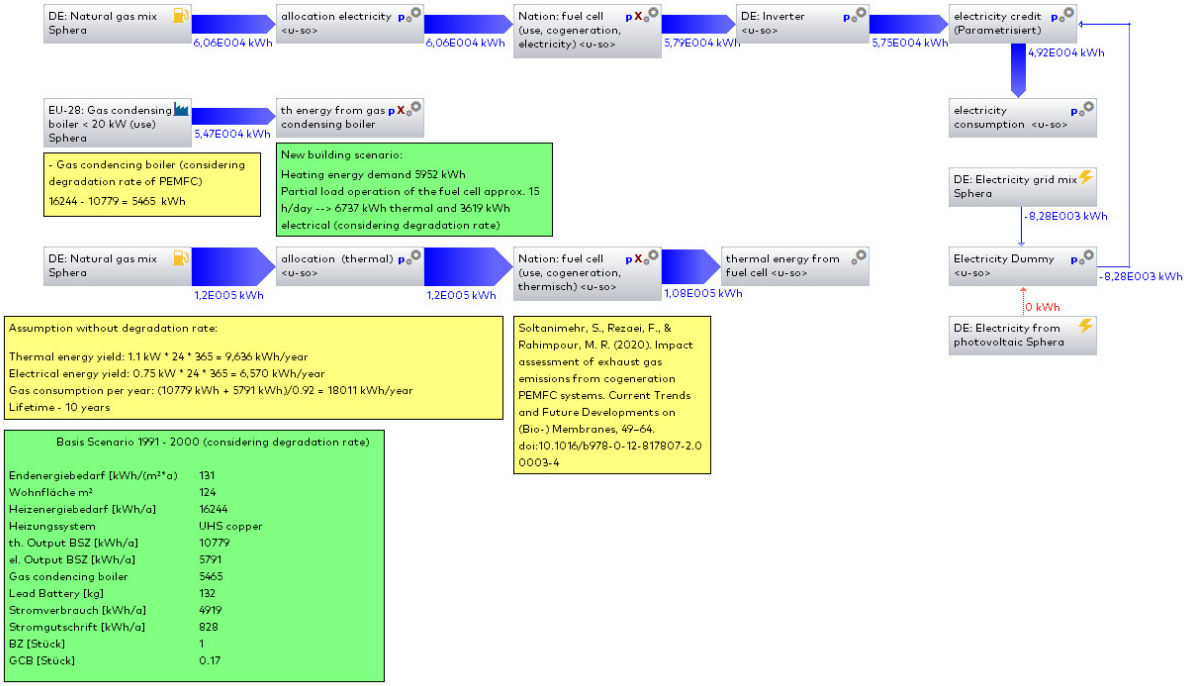


Figure S8. Flow chart of the GaBi-model: use phase of the PEMFC system (basis scenario)

Table S7. GaBi Parameters for the use phase (basis scenario)

Parameter	Formula	Value	Comments
Allocation_el	1-Allocation_th	0.336	
Allocation_th	BZ_th_out/heating_demand	0.664	
BZ_el_out		5791	kWh/a electrical energy output from fuel cell
BZ_th_out		10779	kWh/a thermal energy output from fuel cell
el_consumption		4919	kWh/a electrical energy demand of one single-family hous per year
heating_demand		16244	kWh/a thermal energy demand of one single-family hous per year
Inverter_in_out		1	choice wether Inverter is applicable or not
Lifetime		10	[a] Lifetime of the system
NG_input	(BZ_el_out+BZ_th_out)/0.92 *3.6/47.5	1365.03	kg/a total natural gas consumption by PEMFC
NG_input_el	NG_input*Allocation_el	459.24	kg consumption of the natural gas for electricity production in the PEMFC
NG_input_th	NG_input*Allocation_th	905.79	kg consumption of the natural gas for thermal energy production in the PEMFC

E) Parameterized GaBi-model of the EoL phase of the energy supply system

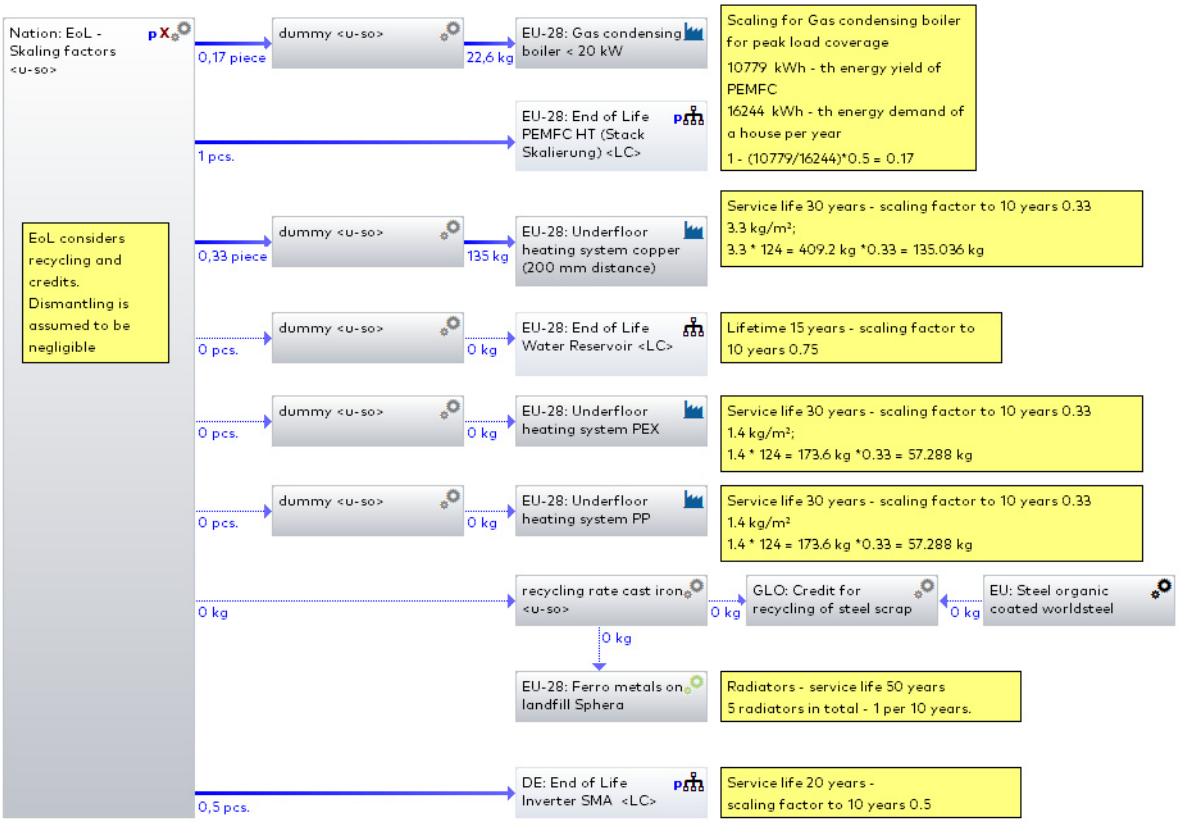


Figure S9. Flow chart of the GaBi-model - EoL phase of the entire energy supply system

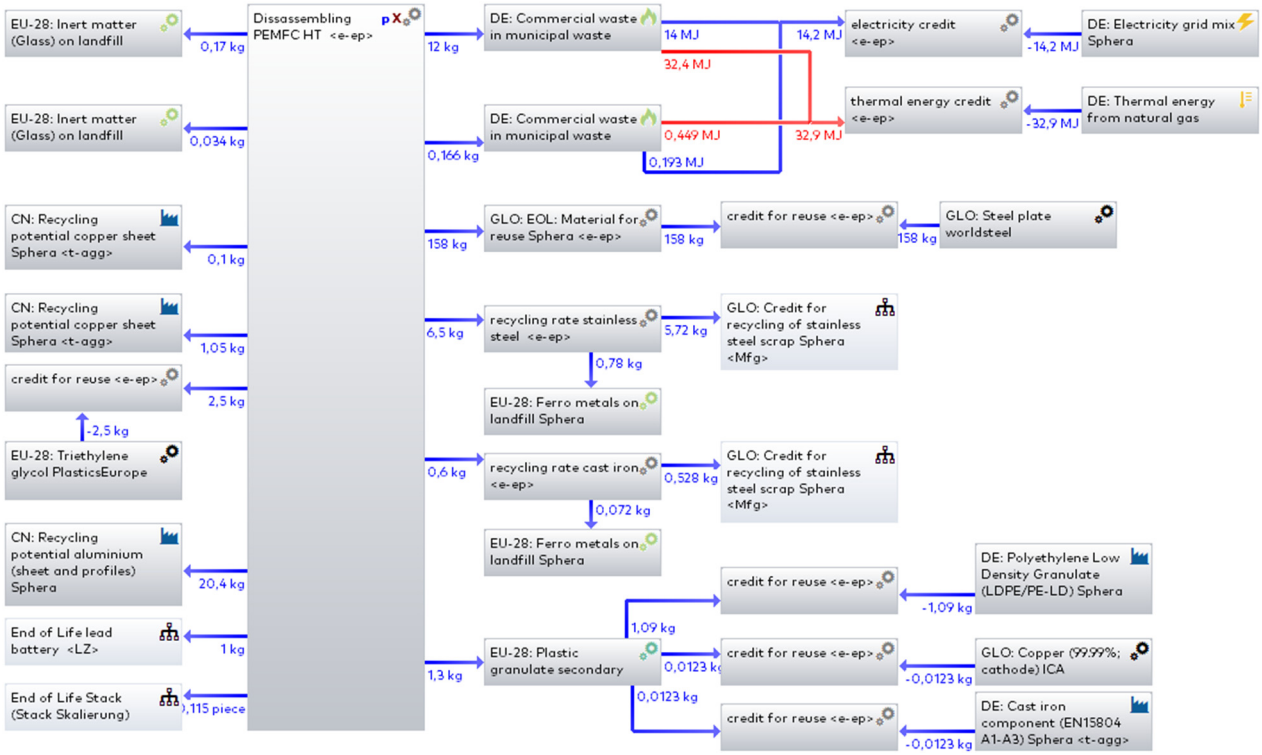


Figure S10. Flow chart of the GaBi-model - EoL phase: disassembling of the PEMFC

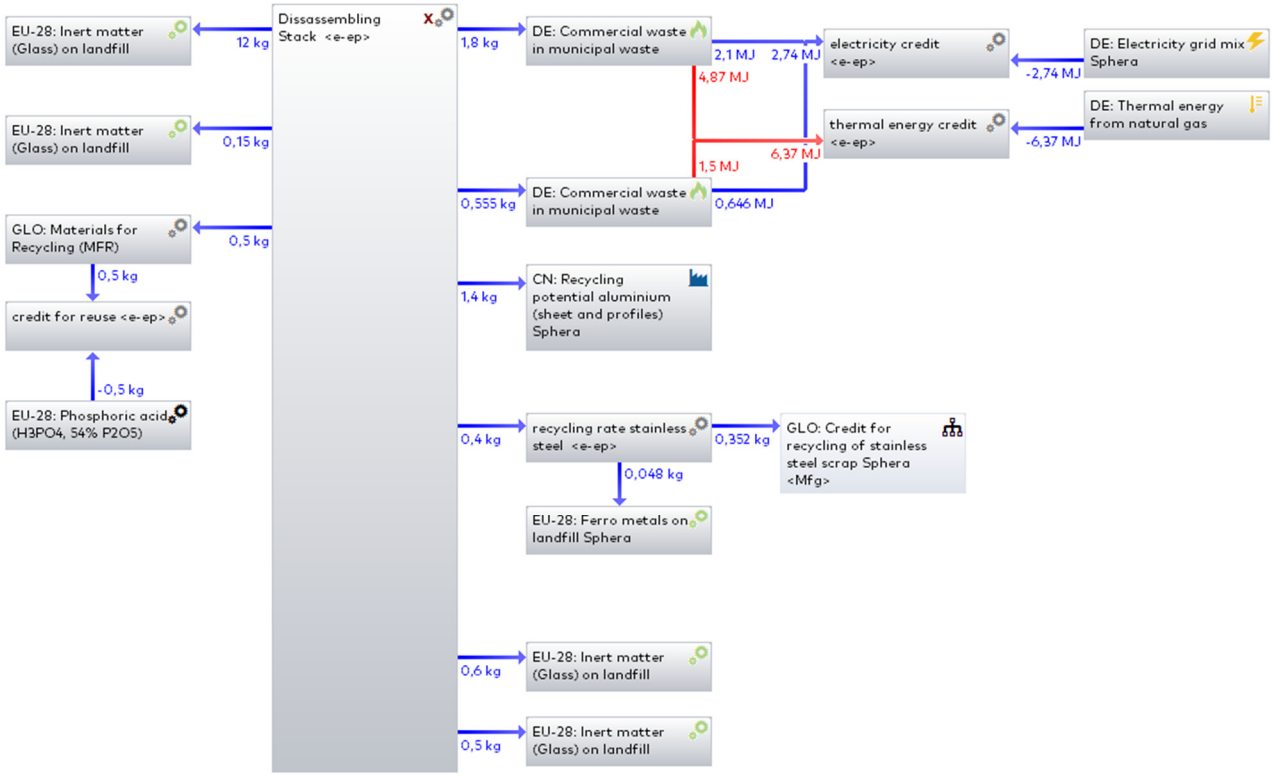


Figure S11. Flow chart of the GaBi-model - EoL phase: disassembling of the Stack

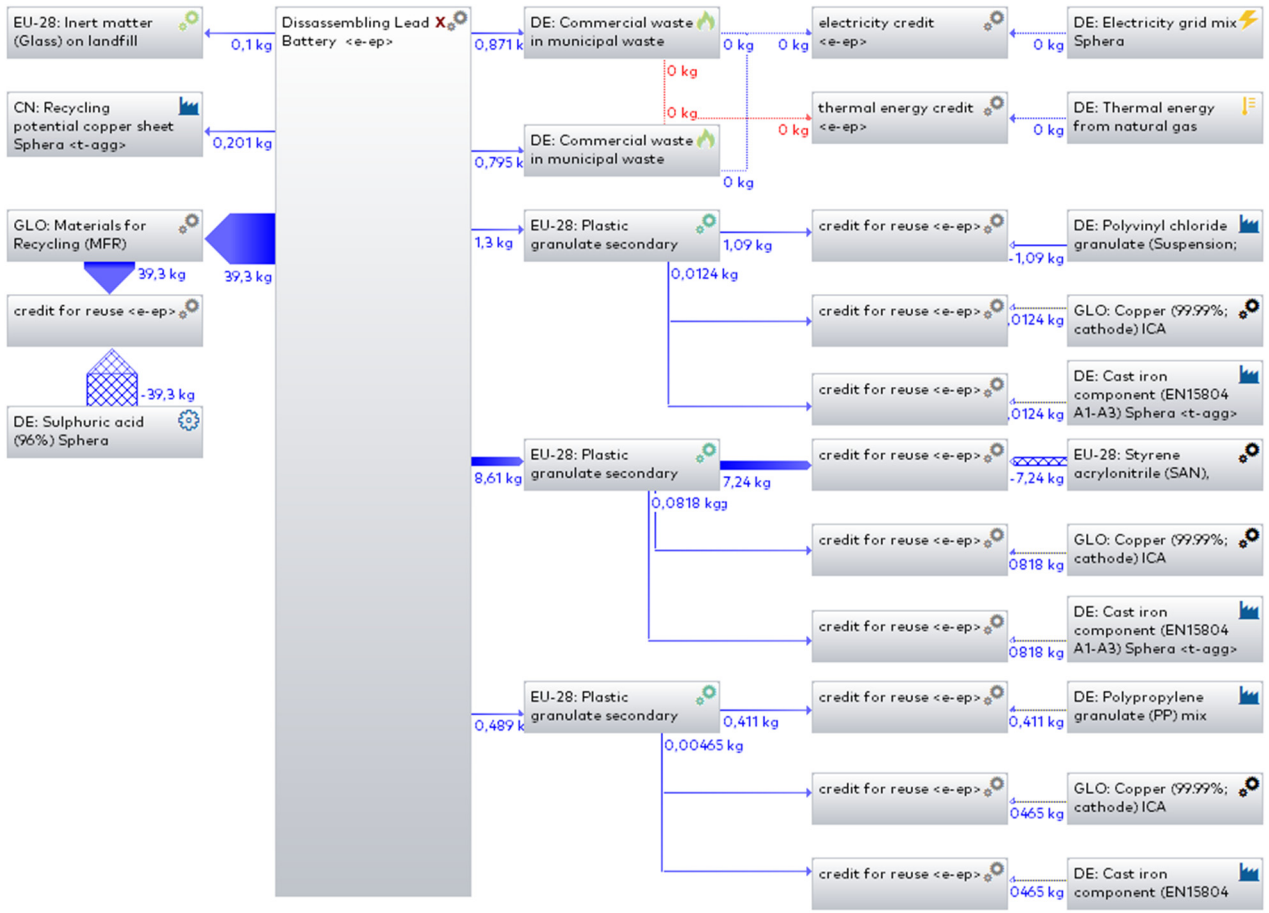


Figure S12. Flow chart of the GaBi-model - EoL phase: disassembling of the Lead Battery

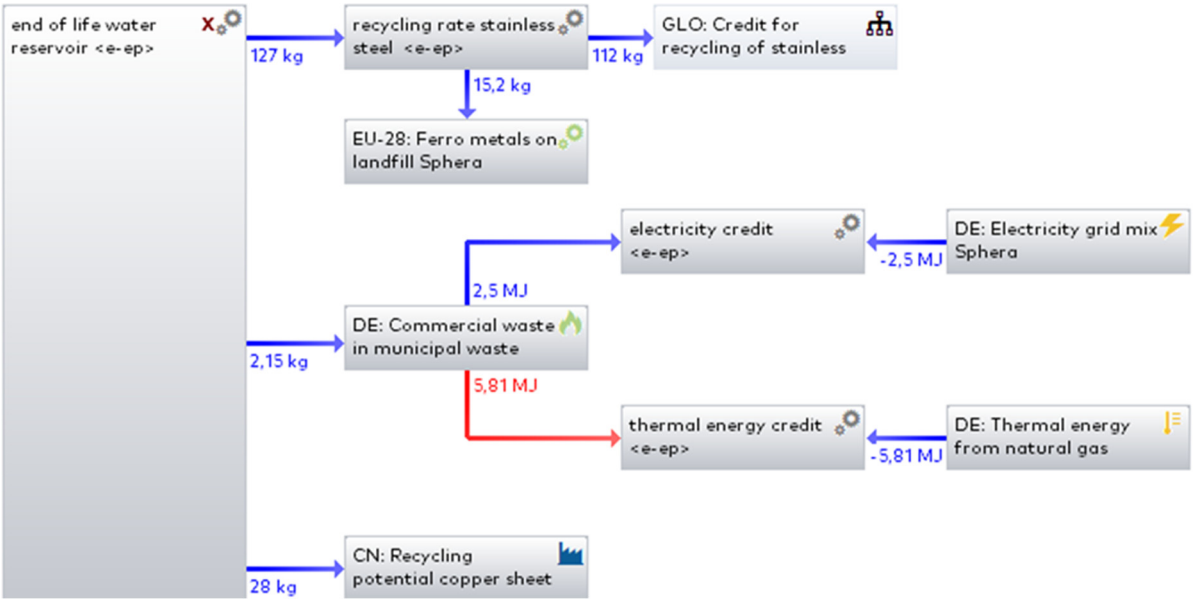


Figure S13. Flow chart of the GaBi-model - EoL phase: water reservoir

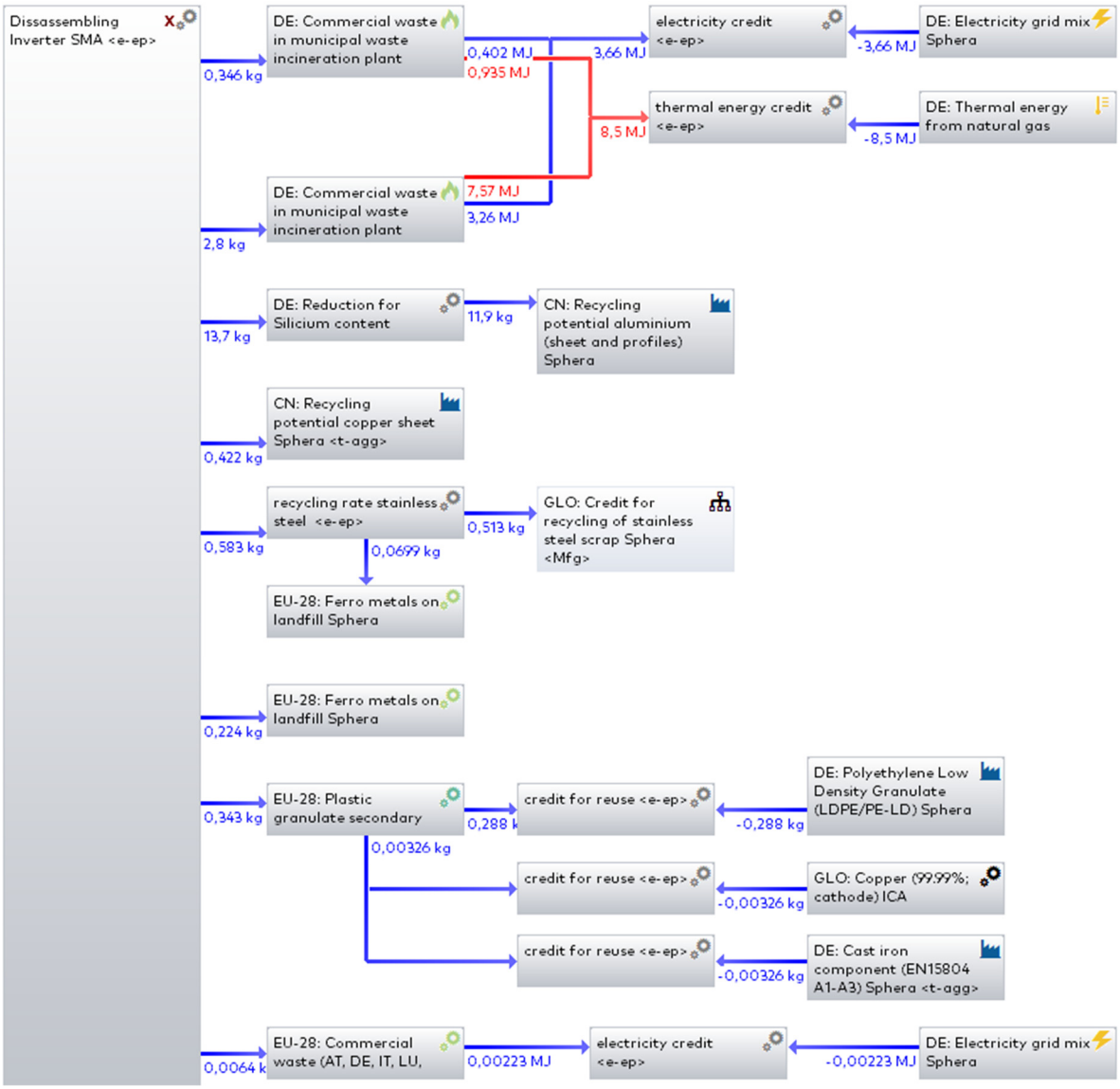


Figure S14. Flow chart of the GaBi-model - EoL phase: SMA Inverter

F) Key parameters for the description of the energy supply system of a single-family house in Germany

Table S8. Description of energy supply system of a single-family house (basis scenario). [2-4, 6-8]

Parameter	Value
end energy demand [kWh/(m²*a)]	131
living space m²	124
heating energy demand [kWh/a]	16244
electricity consumption [kWh/a]	4919
PEMFC* operation [h/a]	8303.8
thermal energy yield from PEMFC [kWh/a]	10779
electrical energy yield from PEMFC [kWh/a]	5791
gas consumption by PEMFC [kWh/a]	18011
thermal energy from Gas condensing boiler [kWh/a]	5465

* Proton exchange membrane fuel cell.

G) Assumptions for the use phase basis scenario and sensitivity scenarios (old and new building types)

Table S9. Sensitivity analysis (building type): key figures for the use phase basis scenario and sensitivity scenarios (old and new building types) [7]

Parameters	Basis Scenario 1991 - 2000	Old Building (unrefurbished) 1949 - 1978	New Building from 2009*
End energy demand [kWh/(m²*a)]	131	236	48
Heating energy demand [kWh/a]	124	124	124
Heating system	16244	29264	5952
Thermal energy yield PEMFC [kWh/a]	UHS copper	UHS copper	UHS copper
Electrical energy yield PEMFC [kWh/a]	10779	10779	6737
Fuel cell operation [h/a]	5791	5791	3619
Gas consumption (GCB) [kWh/a]	5465	18485	-785
Electricity consumption (household) [kWh/a]	4919	4919	4919
Electricity credit * [kWh/a]	828	828	-1327
FC [pieces]	1	1	0.66
GCB [pieces]	0.17	0.32	0
Lifetime of the system [years]	10	10	10

*Surplus fed into grid/shortage covered from grid

Table S10. Sensitivity analysis (PEMFC durability): Key figures for the life cycle model for the PEMFC-based energy supply system for a single-family house: basis scenario (83038 operating hours) and sensitivity scenario (41519 operating hours) [7]

	Basis Scenario 1991 - 2000 (83038 h)	Basis Scenario 1991 - 2000 (41519 h)
End energy demand [kWh/(m²*a)]	131	236
Heating energy demand [kWh/a]	124	124
Heating system	16244	16244
Thermal energy yield PEMFC [kWh/a]	UHS copper	UHS copper
Electrical energy yield PEMFC [kWh/a]	10779	10208
Fuel cell operation [h/a]	5791	6180
Gas consumption (GCB) [kWh/a]	5465	6036

Electricity consumption (household) [kWh/a]	4919	4919
Electricity credit * [kWh/a]	828	1261
FC [pieces]	1	2
GCB [pieces]	0.17	0.19
Lifetime of the system [years]	10	10

*Surplus fed into grid/shortage covered from grid

H) Life cycle assessment (LCA) results

Table S11. Absolute values for the results from comparative LCA of the energy supply system for a single-family house. Gas condensing boiler and electricity from grid mix was used as reference scenario and compared to the alternative system with a proton exchange membrane fuel cell (PEMFC).

Gas condensing boiler (GCB) & electricity from grid mix					
Impact category[1]	**Manufacturing phase**	**Use phase**	**End-of-life phase**	**Total**	**Environmental performance (100% = reference)**
GWP [kg CO2 eq.]	1.24E+03	6.46E+04	-2.33E+02	6.56E+04	100%
AP [kg SO2 eq.]	1.11E+01	4.44E+01	-2.15E+00	5.34E+01	100%
EP [kg Phosphate eq.]	1.03E+00	8.05E+00	-7.03E-02	9.01E+00	100%
ODP [kg R11 eq.]	1.58E-08	6.63E-07	-7.63E-10	6.78E-07	100%
POCP [kg Ethene eq.]	1.15E+00	4.18E+00	-1.12E-01	5.22E+00	100%
ADP fossil [MJ]	1.61E+04	8.91E+05	-2.40E+03	9.05E+05	100%
ADP elements [kg Sb eq.]	3.92E-01	1.46E-02	-9.28E-02	3.14E-01	100%
FAETP [kg DCB eq.]	3.62E+01	5.10E+01	-4.69E+00	8.25E+01	100%
HTP [kg DCB eq.]	1.04E+04	1.29E+03	-4.49E+02	1.12E+04	100%
MAETP [kg DCB eq.]	5.31E+05	3.13E+06	-1.26E+05	3.54E+06	100%
TETP [kg DCB eq.]	1.04E+01	7.15E+01	-1.48E+00	8.04E+01	100%
PED net cal. value [MJ]	2.18E+04	1.33E+06	-3.33E+03	1.35E+06	100%
PEMFC mini-CHP					
Impact category[1]	**Manufacturing phase**	**Use phase**	**End-of-life phase**	**Total**	**Environmental performance (100% = reference)**
GWP [kg CO2 eq.]	2.92E+03	1.41E+04	-1.51E+03	1.55E+04	39%
AP [kg SO2 eq.]	3.07E+01	5.47E+00	-1.62E+01	2.00E+01	232%
EP [kg Phosphate eq.]	1.72E+00	9.98E-01	-5.57E-01	2.16E+00	83%
ODP [kg R11 eq.]	3.10E-07	-9.59E-08	-2.33E-09	2.12E-07	367%
POCP [kg Ethene eq.]	2.17E+00	1.61E+00	-9.53E-01	2.83E+00	134%
ADP fossil [MJ]	3.66E+04	8.57E+05	-1.70E+04	8.77E+05	109%
ADP elements [kg Sb eq.]	8.15E-01	1.17E-03	-1.36E-01	6.80E-01	291%
FAETP [kg DCB eq.]	7.77E+01	8.96E+00	-1.36E+01	7.31E+01	681%
HTP [kg DCB eq.]	1.11E+04	5.12E+02	-7.83E+02	1.08E+04	110%
MAETP [kg DCB eq.]	1.13E+06	-5.61E+04	-7.23E+05	3.51E+05	37%
TETP [kg DCB eq.]	2.16E+01	6.71E+01	-6.27E+00	8.24E+01	168%
PED net cal. value [MJ]	4.87E+04	9.09E+05	-1.99E+04	9.38E+05	78%

[1] Global Warming Potential (GWP 100 years) [kg CO2 eq.]; Acidification Potential (AP) [kg SO2 eq.]; Eutrophication Potential (EP) [kg Phosphate eq.]; Ozone Layer Depletion Potential (ODP. steady state) [kg R11 eq.]; Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]; Abiotic Depletion (ADP fossil) [MJ]; Abiotic Depletion (ADP elements) [kg Sb eq.]; Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]; Human Toxicity Potential

(HTP inf.) [kg DCB eq.]; Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]; Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]; Primary energy demand from ren. and non ren. resources (net cal. value) (PED) [MJ]

Table S12. Absolute values for the LCA results for the manufacturing phase of the PEMFC energy supply system for a single-family house in Germany.

Impact category[1]	PEMFC (0.75 kW)	Inverter	Water Reservoir	Gas condensing boiler < 20 kW	UHS copper (200 mm distance)	Total
GWP [kg CO2 eq.]	1.50E+03	3.86E+02	4.31E+02	1.06E+02	4.99E+02	2.92E+03
AP [kg SO2 eq.]	1.90E+01	1.72E+00	3.43E+00	5.86E-01	5.94E+00	3.07E+01
EP [kg Phosphate eq.]	6.29E-01	1.30E-01	2.36E-01	3.52E-02	6.90E-01	1.72E+00
ODP [kg R11 eq.]	2.56E-07	4.61E-08	1.69E-09	4.10E-09	2.02E-09	3.10E-07
POCP [kg Ethene eq.]	9.72E-01	1.27E-01	1.90E-01	3.80E-02	8.45E-01	2.17E+00
ADP fossil [MJ]	1.85E+04	4.44E+03	5.15E+03	1.26E+03	7.28E+03	3.66E+04
ADP elements [kg Sb eq.]	4.12E-01	3.26E-02	7.23E-02	1.10E-02	2.87E-01	8.15E-01
FAETP [kg DCB eq.]	3.88E+01	4.65E+00	2.08E+01	1.03E+00	1.24E+01	7.77E+01
HTP [kg DCB eq.]	1.02E+03	3.52E+02	8.71E+03	3.67E+02	6.23E+02	1.11E+04
MAETP [kg DCB eq.]	4.71E+05	1.85E+05	1.84E+05	3.07E+04	2.56E+05	1.13E+06
TETP [kg DCB eq.]	3.80E+00	8.08E+00	4.03E+00	3.66E-01	5.34E+00	2.16E+01
PED net cal. value [MJ]	2.25E+04	6.42E+03	6.78E+03	1.63E+03	8.98E+03	4.63E+04

[1] Global Warming Potential (GWP 100 years) [kg CO2 eq.]; Acidification Potential (AP) [kg SO2 eq.]; Eutrophication Potential (EP) [kg Phosphate eq.]; Ozone Layer Depletion Potential (ODP. steady state) [kg R11 eq.]; Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]; Abiotic Depletion (ADP fossil) [MJ]; Abiotic Depletion (ADP elements) [kg Sb eq.]; Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]; Human Toxicity Potential (HTP inf.) [kg DCB eq.]; Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]; Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]; Primary energy demand from ren. and non ren. resources (net cal. value) (PED) [MJ]

Table S13. Absolute values for the comparative life cycle assessment results for the use phase of the energy supply system for a single-family house in the German climatic conditions: gas condensing boiler and electricity from grid mix vs. the PEM fuel cell.

Gas condensing boiler (GCB) & electricity from grid mix						
Impact category[1]	**Electricity from grid mix**	**Natural gas for fuel cell**	**Gas condensing boiler**	**PEMFC**	**Total**	**Environmental performance (100% = reference)**
GWP [kg CO2 eq.]	2.49E+04	3.97E+04	-	-	6.46E+04	100%
AP [kg SO2 eq.]	3.20E+01	1.24E+01	-	-	4.44E+01	100%
EP [kg Phosphate eq.]	6.02E+00	2.03E+00	-	-	8.05E+00	100%
ODP [kg R11 eq.]	6.38E-07	2.50E-08	-	-	6.63E-07	100%
POCP [kg Ethene eq.]	2.22E+00	1.96E+00	-	-	4.18E+00	100%
ADP fossil [MJ]	2.45E+05	6.46E+05	-	-	8.91E+05	100%
ADP elements [kg Sb eq.]	1.23E-02	2.37E-03	-	-	1.47E-02	100%
FAETP [kg DCB eq.]	3.84E+01	1.26E+01	-	-	5.10E+01	100%
HTP [kg DCB eq.]	8.36E+02	4.51E+02	-	-	1.29E+03	100%
MAETP [kg DCB eq.]	2.73E+06	3.96E+05	-	-	3.13E+06	100%
TETP [kg DCB eq.]	2.81E+01	4.35E+01	-	-	7.16E+01	100%
PED net cal. value [MJ]	5.66E+05	6.72E+05	-	-	1.24E+06	100%
PEMFC mini-CHP						
Impact category[1]	**Electricity credit**	**Natural Gas for Fuel cell**	**Gas condensing boiler**	**Fuel cell**	**Total**	**Environmental performance (100% = reference)**

GWP [kg CO2 eq.]	-4.19E+03	4.94E+03	1.34E+04		1.42E+04	22%
AP [kg SO2 eq.]	-5.39E+00	6.68E+00	4.18E+00	5.62E-05	5.47E+00	12%
EP [kg Phosphate eq.]	-1.01E+00	1.33E+00	6.83E-01	1.46E-05	1.00E+00	12%
ODP [kg R11 eq.]	-1.07E-07	3.01E-09	8.41E-09		-9.56E-08	-14%
POCP [kg Ethene eq.]	-3.74E-01	1.32E+00	6.59E-01	1.07E-05	1.61E+00	38%
ADP fossil [MJ]	-4.13E+04	6.81E+05	2.17E+05		8.57E+05	96%
ADP elements [kg Sb eq.]	-2.07E-03	2.44E-03	7.99E-04		1.17E-03	8%
FAETP [kg DCB eq.]	-6.46E+00	1.12E+01	4.25E+00		8.96E+00	18%
HTP [kg DCB eq.]	-1.41E+02	5.01E+02	1.52E+02	1.35E-04	5.12E+02	40%
MAETP [kg DCB eq.]	-4.60E+05	2.71E+05	1.33E+05		-5.60E+04	-2%
TETP [kg DCB eq.]	-4.73E+00	5.72E+01	1.46E+01		6.71E+01	94%
PED net cal. value [MJ]	-9.53E+04	7.59E+05	2.26E+05		8.90E+05	72%

[1] Global Warming Potential (GWP 100 years) [kg CO2 eq.]; Acidification Potential (AP) [kg SO2 eq.]; Eutrophication Potential (EP) [kg Phosphate eq.]; Ozone Layer Depletion Potential (ODP. steady state) [kg R11 eq.]; Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]; Abiotic Depletion (ADP fossil) [MJ]; Abiotic Depletion (ADP elements) [kg Sb eq.]; Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]; Human Toxicity Potential (HTP inf.) [kg DCB eq.]; Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]; Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]; Primary energy demand from ren. and non ren. resources (net cal. value) (PED) [MJ]

I) Life cycle assessment (LCA) results - sensitivity scenarios

Table S14. Absolute values for the sensitivity scenario LCA of the PEM fuel cell energy supply system: comparison of basis scenario building type from 1991 – 2000 with the old building type from 1949 – 1978 and new building type from 2009

Impact category[1]	**Basis scenario 1991 - 2000**	**Old building 1949-1978**	**New building - from 2009**
GWP [kg CO2 eq.]	2.74E+03	5.92E+03	1.98E+03
AP [kg SO2 eq.]	2.24E+01	2.34E+01	2.19E+01
EP [kg Phosphate eq.]	1.31E+00	1.48E+00	1.40E+00
ODP [kg R11 eq.]	2.97E-07	2.99E-07	3.17E-07
POCP [kg Ethene eq.]	1.68E+00	1.83E+00	1.58E+00
ADP fossil [MJ]	1.06E+05	1.57E+05	6.35E+04
ADP elements [kg Sb eq.]	6.67E-01	6.67E-01	6.39E-01
FAETP [kg DCB eq.]	3.68E+01	3.78E+01	3.60E+01
HTP [kg DCB eq.]	1.00E+04	1.00E+04	9.21E+03
MAETP [kg DCB eq.]	1.62E+05	1.94E+05	2.32E+05
TETP [kg DCB eq.]	1.71E+01	2.06E+01	1.40E+01
PED net cal. value [MJ]	1.04E+05	1.58E+05	7.62E+04

[1] Global Warming Potential (GWP 100 years) [kg CO2 eq.]; Acidification Potential (AP) [kg SO2 eq.]; Eutrophication Potential (EP) [kg Phosphate eq.]; Ozone Layer Depletion Potential (ODP. steady state) [kg R11 eq.]; Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]; Abiotic Depletion (ADP fossil) [MJ]; Abiotic Depletion (ADP elements) [kg Sb eq.]; Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]; Human Toxicity Potential (HTP inf.) [kg DCB eq.]; Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]; Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]; Primary energy demand from ren. and non ren. resources (net cal. value) (PED) [MJ]

Table S15. Absolute values for the sensitivity scenario LCA of the PEM fuel cell energy supply system: comparison of basis scenario 83038 h (durability of the PEMFC 10 years) and the 41519 h (durability of the PEMFC 5 years). The GCB and electricity from grid mix system is presented as a reference system and is set as 100%.

Impact category[1]	**Reference System: GCB & Grid mix**	**Basis Scenario 1991 - 2000 (83038 h)**	**Basis Scenario 1991 - 2000 (41519 h)**
GWP [kg CO2 eq.]	6.56E+04	1.55E+04	1.52E+04
AP [kg SO2 eq.]	5.34E+01	2.00E+01	2.32E+01
EP [kg Phosphate eq.]	9.01E+00	2.16E+00	1.91E+00
ODP [kg R11 eq.]	6.78E-07	2.12E-07	4.18E-07
POCP [kg Ethene eq.]	5.21E+00	2.83E+00	2.87E+00
ADP fossil [MJ]	9.05E+05	8.77E+05	8.77E+05
ADP elements [kg Sb eq.]	3.14E-01	6.81E-01	1.05E+00
FAETP [kg DCB eq.]	8.26E+01	7.31E+01	1.01E+02
HTP [kg DCB eq.]	1.13E+04	1.08E+04	1.14E+04
MAETP [kg DCB eq.]	3.53E+06	3.47E+05	1.11E+05
TETP [kg DCB eq.]	8.05E+01	8.25E+01	8.07E+01
PED net cal. value [MJ]	1.26E+06	8.43E+05	8.21E+05

[1] Global Warming Potential (GWP 100 years) [kg CO2 eq.]; Acidification Potential (AP) [kg SO2 eq.]; Eutrophication Potential (EP) [kg Phosphate eq.]; Ozone Layer Depletion Potential (ODP. steady state) [kg R11 eq.]; Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]; Abiotic Depletion (ADP fossil) [MJ]; Abiotic Depletion (ADP elements) [kg Sb eq.]; Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]; Human Toxicity Potential (HTP inf.) [kg DCB eq.]; Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]; Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]; Primary energy demand from ren. and non ren. resources (net cal. value) (PED) [MJ]

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