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PP	Restricted to other programme participants (including the Commission Services)	☐
CO	Confidential, only for members of the consortium (including the Commission Services)	☐

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Glossary

Table 1: Glossary

Sunfire	Sunfire GmbH
ICI	ICI Caldaie
PNO	PNO Consultants
µCHP	Micro Combined Heat and Power
SOFC	Solid Oxide Fuel Cell
PEMFC	Proton-Exchange Membrane Fuel Cells
LT-PEM	Low-Temperature Proton-Exchange Membrane
HT-PEM	High-Temperature Proton-Exchange Membrane
MCFC	Molten-Carbonate Fuel Cells
LCOE	Levelized Cost of Energy
CAPH	Cathode Air Pre-Heater
LCA	Life Cycle Analysis
BoP	Balance of Plant
OEM	Original Equipment Manufacturer

1 Objective

The goal of the HEATSTACK project is to develop production techniques that allow a cost reduction of µCHP fuel cell systems in order to develop the market for such systems.

A detailed techno-economic investigation was performed in order to assess the best business cases for the proposed SOFC µCHP. As part of this work, ICI evaluated the next technical and commercial steps required in order to develop opportunities for the heat exchangers design evaluated with their PEMFC system. An assessment of the techno-economic impacts of the HEATSTACK project includes:

- The potential for job creation across the supply chain and economic development at manufacturing locations (Dresden/Neubrandenburg/Olomouc).
- An analysis of the projected levelized costs of energy based on component and overall system cost saving potential as a result of HEATSTACK and gains in system efficiency and performance.
- Life Cycle Analysis - As fuel cell CHP technologies are commercialised, they will be required to meet environmental standards and minimise impact, and part of this will be the ability to recycle and dismantle products at the end-of-life.
- A summary of the benefits, including availability of supply (raw materials, tooling, components, equipment), emissions reductions and potential cost savings from an end-use perspective, and an evaluation of the impact on the industrialisation of fuel cell mCHP systems and development of the FCH sector in Europe.

2 Next steps in the evaluation of m-CHP based on PEMFC

The study of micro-cogeneration based on fuel cells started several years ago and traditionally was based on LT-PEM cells powered directly by hydrogen.

The choice was dictated by the fact that, compared to other types of cells such as HT-PEM, MCFC and SOFC, the LT-PEM type cells were those with the highest level of technological maturity (thanks also to the boost received by the automotive industry).

Unlike others fuel cells, to operate LT-PEM cells requires pure hydrogen, or at least a syngas with a CO concentration of the order of a few ppm. However, the use of direct H2 cylinder is too expensive to be applicable on a large scale and is competitive only in a limited number of niche applications.

In order to be competitive on the micro-cogeneration market, a system based on LT-PEM must therefore be able to work directly with available natural gas. The use of a fuel processor that transforms natural gas into syngas compatible with PEM type cells is therefore essential.

The efficiency of the m-CHP system (both electrical and total) must therefore consider not only the efficiency of the fuel cell but also the efficiency of the reactors for the on-site hydrogen production.

The energy requirement of an apartment depends on its size, the number of tenants, their lifestyle, the period of the year and the geographical area. On average, however, it can be considered that the energy requirement can be divided into 80% heat (space heating and domestic hot water) and 20% electricity.

In this context, it is clear that not only the electrical efficiency of a CHP system but also and above all its total efficiency (thermal and electrical) becomes of fundamental importance.

The use of specific heat exchangers that manage to capture and reintroduce heat into the system by capturing it from the exhaust fumes (such as that developed in the HEATSTACK project) allows users to reduce the amount of fuel needed to keep the reactors at the correct operating temperature, thus favouring the increase in electrical and total efficiency of the system

The continuous decrease in the cost of LT-PEM thanks also to the required volumes for the automotive (DOE projections speak of 40 $ / kWe for a production of 500k pieces / year), the reduction in the cost of specific components (such as heat exchangers developed in the project) and the increase in efficiency that results from its use, make micro-cogeneration based on LT-PEM cells one of the main players in the sector.

3 Potential job creation across the supply chain

Based on the projections of the HEATSTACK Business Plan and Exploitation Strategy (see Deliverable D8.7), the job creation potential numbers shown in Table 2 (below) were identified in the supply chain when considering production and development staff. The forecast covers Sunfire's staff for the fuel cell production in Dresden and for the µCHP system in Neubrandenburg. Furthermore, production staff is covered for Senior Flexonics in Olomouc whilst all other supply chain jobs are included in "Other EU". A continuous increase of produced units per year, a rising share of automated production steps and a shift of production from Sunfire to suppliers is combined in the forecast.

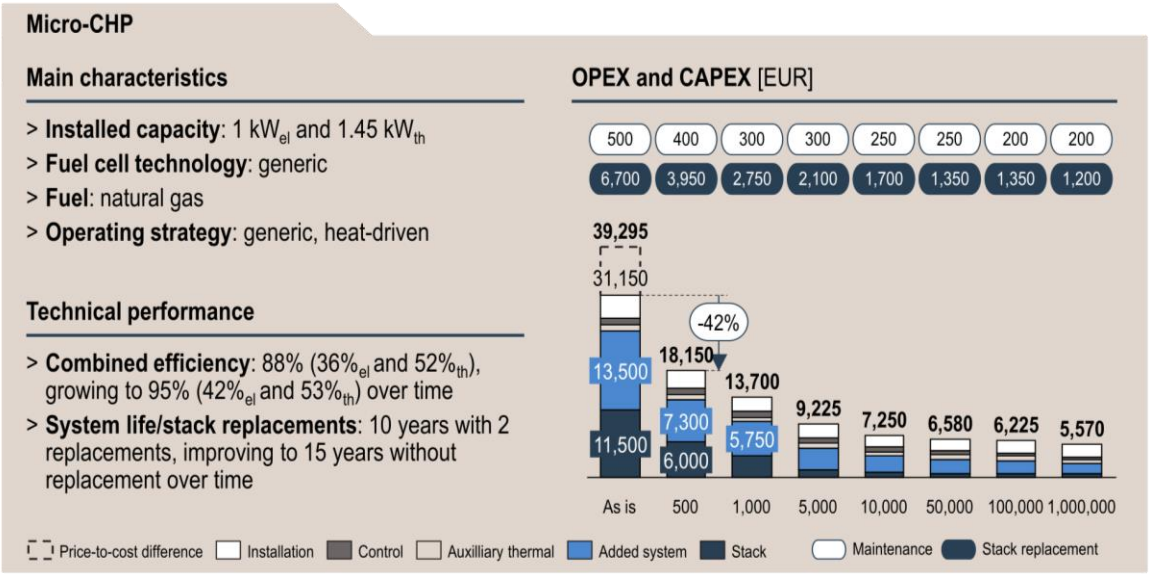
Table 2: Potential job creation across the supply chain of Sunfire-Home 750

Place / Year	**2020**	**2021**	**2022**	**2023**
Dresden	6	7	8	9
Neubrandenburg	16	19	22	23
Olomouc	2	2	4	6
Other EU	5	10	15	25
Total EU	29	38	49	63

4 Projected Levelized Costs of Energy (LCOE)

An exact cost reduction cannot be pointed out, due to the change of system manufacturers during the project period. Both the initial costs and the production costs after the project cannot be made public, mainly because of antitrust issues.

A comprehensive cost analysis of the µCHP fuel cell application was done by Roland Berger (Ammermann 2015) together with 30 independent stakeholders from different parts of the industry. One of the key outcomes was a consolidated cost break down and projection of the application. This was compiled as the result of a survey of several industrial partners. So, it reflects the vision of the industry. Figure 1 shows the projected cost breakdown potential of the µCHP fuel cell technology:



Micro-CHP

Main characteristics

- > **Installed capacity**: 1 kW_{el} and 1.45 kW_{th}
- > **Fuel cell technology**: generic
- > **Fuel**: natural gas
- > **Operating strategy**: generic, heat-driven

Technical performance

- > **Combined efficiency**: 88% (36%$_{el}$ and 52%$_{th}$), growing to 95% (42%$_{el}$ and 53%$_{th}$) over time
- > **System life/stack replacements**: 10 years with 2 replacements, improving to 15 years without replacement over time

Figure 1: Summary of Roland Berger Study (Ammermann 2015) showing cost breakdown potential of the µCHP fuel cell technology

We see that the identified cost reduction potential is 42% in the first step towards 500 units per manufacturer. Assuming that the CAPH is one of the most expensive components of the "added system", one can estimate that it covers about 15%[1] of the added system costs. If this does not change over time, the cost of the CAPH has to drop as much as every other component. This is a conservative approach, because actually, the cost break-down potential of the CAPH should be higher than for the other components. Nevertheless, the cost projection of the CAPH is shown in Figure 2, assuming the above-mentioned percentage being constant.

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[1] This is not the actual percentage of costs in the Vaillant or Sunfire µCHP system. But it can be used as an indicator.

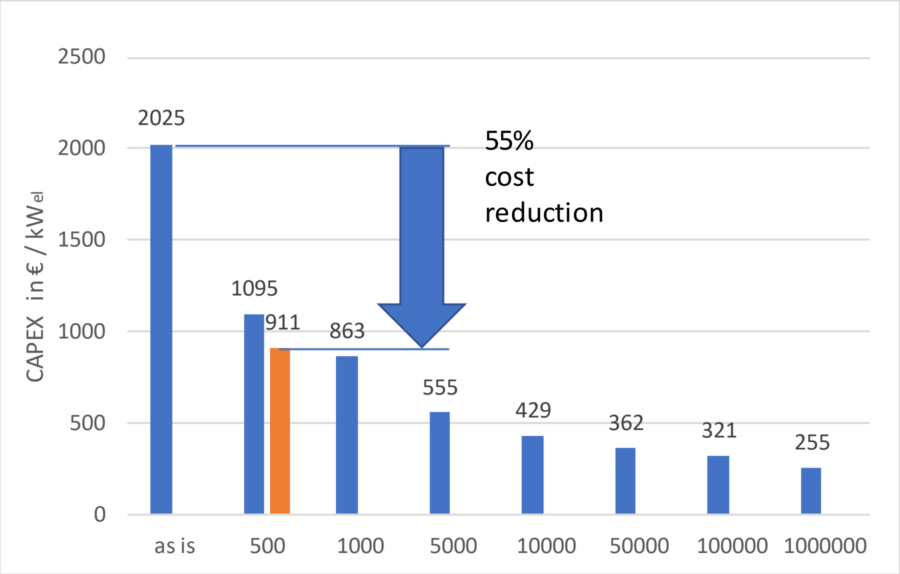

Figure 2: Cost of cathode air preheater as projection of 15% of the system costs in the Roland Berger Study compared to HEATSTACK cost reduction

In the HEATSTACK project, the cost of the CAPH was reduced by about 55%. This means, that the cost reduction projected in the Roland Berger study was achieved for this conservative approach with even distribution. But since the cost reduction potential is supposed to be higher for the CAPH, further cost reduction is possible here.

The glass sealing inside the stack is estimated to be responsible for about 10% of the stack production costs. Again, actual costs cannot be shown here, but Figure 3 shows the production cost of the seal assuming to have a constant share with the numbers projected in the Roland Berger study.

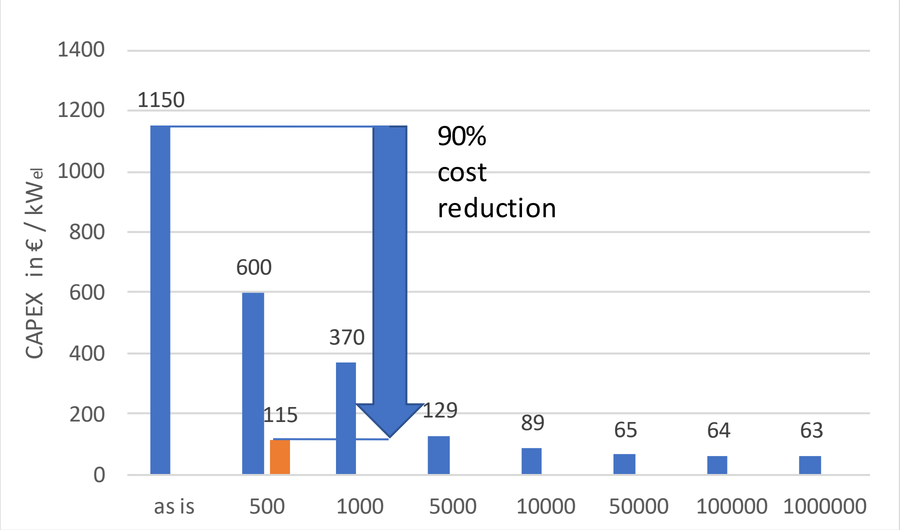

Figure 3: Cost of glass sealing as projection of 10% of the stack costs in the Roland Berger Study compared to HEATSTACK cost reduction

The development in the HEATSTACK project, showed the potential to reduce the production cost of the sealing by 90% (See Deliverable D3.3). This is more than the average projected cost reduction in the Roland Berger study.

In terms of cost reduction for end-customers, one also has to take overhead costs and sales margins into account. If we take the numbers shown by Roland Berger study, we have to increase the cost savings by about 26%. This leads to CAPEX cost reduction for the end-customer of about 2720 € per kW_{el}[2] only due to the outcome of the HEATSTACK project.

The development of the AluChrom CAPH also had the goal to reduce chromium contamination of the cells and of the off-gas. This measure leads to reduced degradation of the cells and a longer duration of the overall system. Since degradation processes are long-term by nature, reliable statements can only be made after long-term tests, which was not possible in the project (as these will take place for some considerable time beyond the project’s end date). In order to assess the project impact in this dimension, we estimate the durability of the overall system to be increased by a factor of about 15%. This means that the system lasts 15% longer until a stack replacement is needed.

LCOE heavily depends on the end-customer application. In order to break HEATSTACK results down to energy costs, we use the Roland Berger case studies as a basis and apply the cost reduction to identify LCOE level cost savings. Figure 4 shows the LCOE of Roland Berger cases with and without the above-mentioned improvements of the HEATSTACK project (CAPEX cost reduction and higher duration).

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[2] Again, this number reflects the conditions on the Roland Berger study and brings no insight into actual business plans, production costs and margins.

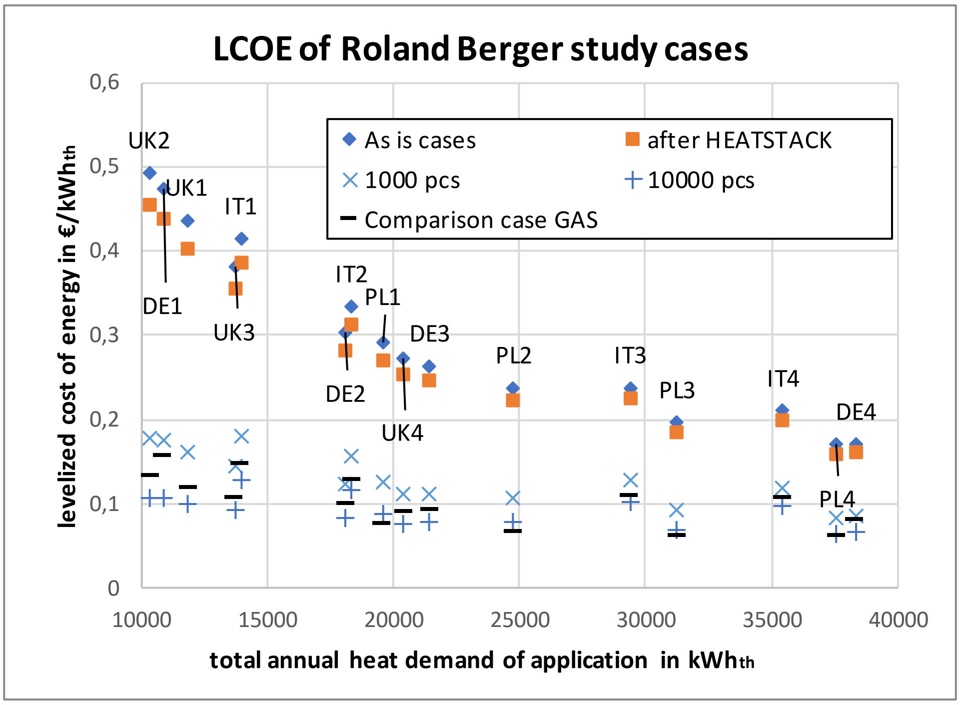

Figure 4: Cost of glass sealing as projection of 10% of the stack costs in the Roland Berger study compared to HEATSTACK cost reduction

The average reduction of LCOE for the 16 Roland Berger study cases is 6.6%. This only accounts for cost reductions identified in the HEATSTACK project. Other developments in similar projects and independent developments and funding are not included. This demonstrates, that the ambitious cost reduction projections of the study can be met when properly addressed. When production numbers of fuel cell systems increase and the needed investments into the cost break down development was included, fuel cells can be, not only the environmentally more friendly solution. When fuel cells reach property goals pointed out at the “10000 pieces per manufacturer” case, it can even be cheaper for the customers than the standard condensing boiler, shown in the comparison case “GAS”.

5 Life Cycle Analysis (LCA)

The HEATSTACK budget and time for the LCA was very limited. In order to present some meaningful information and to help evaluating the project outcome, the following analysis is based on, and in direct comparison with an LCA done and reported by Staffell et al. (2012). The aim of this LCA was to identify payback-times of carbon dioxide emission and primary energy resource investments.

As manufacturer of fuel cells and fuel cell systems, Sunfire has a deep in-house value creation and therefore an overview of all different stages of production from printing and sintering of cells to stack assembly, system manufacturing and also of installation, maintenance, repair, dismantling and recycling of materials. This insight is used to specify some of the assumptions and estimations that were made in the original LCA by Staffell et al. (2012).

Table 3: Main Specification of Sunfire-Home 750 as base of LCA

Electric output	450 - 750 W
Electrical efficiency	> 33 % BOL
Thermal output	1.25 kW at full load, return temperature 40 °C
Total system efficiency	Up to 88 % depending on heat and condensate recovered at customer site.

Table 4: Typical operation conditions as base of LCA

Typical operation characteristics	
Full operating hours per year	5500 h
Reference operation duration	15 years
Operation time until stack exchange	40 000 h
Share of electricity self-use	60 %
Annual heat demand	20 000 kWh
Thermal efficiency of peak burner and alternative burner	95 %

Table 5: Emission and primary energy factors according to DIN V 18599-1

Emission factors	
Propane gas	270 g_{CO2} / kWh
Electricity for self-consumption (electricity mix)	550 g_{CO2} / kWh
Electricity grid feed in (displacement mix)	860 g_{CO2} / kWh
Primary Energy factors	
Propane gas	1.1
Electricity	2.8

The LCA is divided into the production phase (including installations and commissioning) and the usage phase. Recycling is already considered in the production phase, so the lifecycle inventories of the product already foresees the later recyclability of the different materials. The functional unit is defined as the product Sunfire-Home 750 with the specifications in Table 3, which is operated at conditions shown in Table 4. For the inventory impact assessment of the operation, emission and primary energy factors of Table 5 were used. The balance of plant (BoP) is divided into internal BoP, which is included in the product (heat utilization heat exchanger, hot water pump, inverters, etc.) and external BoP, which is generally needed to use the product (auxiliary burner, hot water storage tank, pipes, etc.) but it depends more on the specific application. This is why the inventory in this analysis is structured as shown in Figure 5.

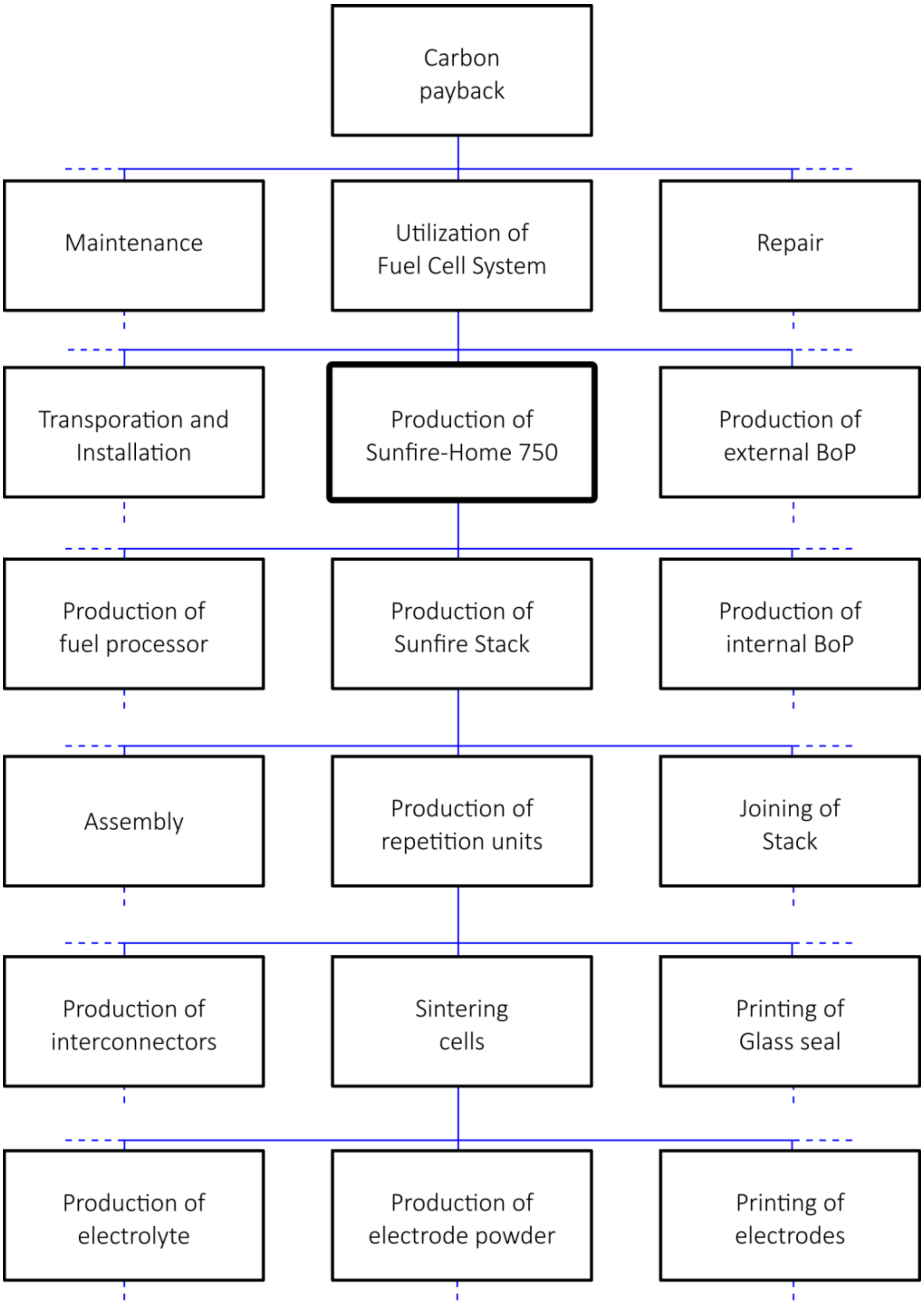

Figure 5: Production steps of Sunfire-Home Lifecycle Analysis including utilization similar to Figure 1 in Staffells LCA. Similarly, this example is not exhaustive; dashed lines indicate that additional inputs can be considered for every stage, and that every process could be expanded in a similar way as the central column to produce a complex yet exhaustive hierarchy.

The main task of the LCA was to identify every part of the fuel cell product, to find out the weight of every part and to estimate the composition in a set of pre-defined material groups. An exemplary extract of the resulting material list is shown in Table 1 of the annex. Columns “material” and “percentage” were estimated by looking at the individual parts. The stack production process was reviewed in more detail, because the expected impact of energy consumption for some of the production steps is higher and similar to the analysis of Staffell. Data collected for another LCA in the GrinHy project was used.

The same investigation was done for the units that come in place after production (external BoP, transport, installation, operation/use, etc.). An exemplary part of the resulting inventory list is shown in Table 2 of the annex. Both inventory lists were weighted by inventory impact factors given by Staffell et al. (2012) and by Nuss et al. (2014) for some specific functional material mostly used in the stack and then summarized in the groups shown in Table 6.

Table 6: Results of LCA for Primary Energy depletion and greenhouse gas emission

	Fuel Cell System		**Alternative (Burner)**	
	Primary Energy [MJ]	**GHG-Emissions $[kg_{CO2eq}]$**	**Primary Energy [MJ]**	**GHG-Emissions $[kg_{CO2eq}]$**
investment				
SOFC Stack	3550	212		
Fuel Processor	6879	431		
internal BoP	18947	1145		
external BoP	19386	1103	12830	735
Installation	120	9	120	9
Transport	0	17	0	6
SUM invest	48881	2918	12950	750
operation per year				
Maintenance	498	42		
Repair	1214	74		
Use	59895	4139	83368	5684

	Fuel Cell System		**Alternative (Burner)**	
	Primary Energy [MJ]	**GHG-Emissions [kg_{CO2eq}]**	**Primary Energy [MJ]**	**GHG-Emissions [kg_{CO2eq}]**
SUM operational	61606	4255	83368	5684
payback time	1,65 years	1,52 years		

The investments in the production of a fuel cell system amortise compared to a case of a much simpler peak load burner installation after about 1 ½ years in terms of primary energy use and greenhouse gas emissions. After 15 years of operation, a fuel cell system saves 290 GJ of primary energy and 19.2 tonnes of CO_2-Equivalent greenhouse gases, considering all investments that were necessary during production.

6 Conclusions

As shown above, the fuel cell µCHP solution Sunfire-Home 750 reduces emissions of heating applications heavily, even when considering the higher emissions during the production phase of the more complex installation and the repair (mainly stack replacement) at the same time as it reduces the cost of energy production for end-customers.

The HEATSTACK project mainly supported the foundation of a new partnership between a fuel cell manufacturer looking for industrialized mass production and an automotive OEM always looking for new markets. The natural challenge of such a partnership is the lack of a product already in mass-production. HEATSTACK mainly helped to cover costs for development, testing and production optimization, which would have been the entry barrier for the partnership. The result is the availability of equipment supply at low cost and high quality.

In chapter four, it is shown, how these production cost reductions are translated to end-customer energy cost savings. Only the two cost saving measures of HEATSTACK were assessed to account for a cost reduction of 6.6% in average to the end-customer.

7 References

Ammermann, H., et al. "Advancing Europe’s energy systems: Stationary fuel cells in distributed generation." *Fuel Cells And Hydrogen Joint Undertaking (FCH JU) & Roland Berger* (2015).

Nuss, Philip, and Matthew J. Eckelman. "Life cycle assessment of metals: a scientific synthesis." *PLoS One* 9.7 (2014).

Staffell, Iain, Andrew Ingram, and Kevin Kendall. "Energy and carbon payback times for solid oxide fuel cell based domestic CHP." *International Journal of Hydrogen Energy* 37.3 (2012): 2509-2523.

8 Annex

Art. Num.	Article Name	group	P&ID Reference	mass measured [kg]	Material	percentage	material mass [kg] or power [kWh]
02900A00	Radial blower	Internal BoP	GB1401	0,775	Aluminium	20	0,155
					Steel	10	0,0775
					Electronics	10	0,0775
					Plastics	60	0,465
01527A01	2/2 way valve	Internal BoP	MV2101	0,4775	Aluminium	30	0,14325
					Copper	50	0,23875
					Plastics	10	0,04775
					Electronics	10	0,04775
					Power	-	1
[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]
03068A03	Heat exchanger bracket	Fuel Processor		0,1135	Stainless Steel	100	0,1135
03242A00	Support frame	Fuel Processor		6,863	Stainless Steel	100	6,863
[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]

Table 1: Exemplary rows of material list of product material for LCA

item	group	Inventory	mass [kg] / PE [MJ]	amount per life cycle
typical peak load burner 20 kW	external BoP	Stainless Steels	7,68	1
		Plastics	5,23	1
		Insulation	0,516	1
		Aluminium	3,25	1
		Steel	14,8	1
		Chromium Alloy	0,091	1
		Copper	3,23	1
		Electronic Components	0,78	1
typical 3-way valve for installation 1"	external BoP	Copper	0,6	2
		Plastics	0,1	2
		Electronic Components	0,1	2
1 m water pipe 22x1,2	external BoP	Stainless Steels	0,65	30
1 pcs. Pressfitting (e.g. 90° viega 22mm)	external BoP	Stainless Steels	0,03	10
1 pcs. pipe fixing	external BoP	Steel	0,05	20
1m insulation (e.g. PE-Isolation 13 mm around 22mm pipe)	external BoP	Plastics	0,033	30
[…]	[…]	[…]	[…]	[…]
1 year Operation of Fuel Cell System Propane consumption	Use	CO2-Emission	6 918,75	15
		PrimaryEnergy MJ	101 475	15
1 year self-consumed Electricity	Use	CO2-Emission	-1 361,25	15
		PrimaryEnergy MJ	-24 948	15
1 year fed-in Electricity	Use	CO2-Emission	-1 419	15
		PrimaryEnergy MJ	-16 632	15

item	**group**	**Inventory**	**mass [kg] / PE [MJ]**	**amount per life cycle**
[…]	[…]	[…]	[…]	[…]
Transport of Fuel Cell System to installation site	Transport	CO2-Emission	11,11	1
Transport of external BoP to installation site	Transport	CO2-Emission	6,1	1
Stack for replacement	Repair	Steel	15,3	2,1
		Chromium Alloy	3,83	2,1
		Binders	0,012	2,1
		Solvents	0,172	2,1
		functional materials	6,672	2,1
		CO2-Emission	7,923	2,1
		Electricity (kWh)	341,3	2,1
[…]	[…]	[…]	[…]	[…]

Table 2: exemplary rows of material list outside of fuel cell product