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Techno-Economic Analysis of Micro Fuel Cell Cogeneration and Storage

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Authors´ addresses:

Laurens Löbberding
RWTH Aachen University
Templergraben 55
52056 Aachen, Germany
E-Mail: laurens.loebberding@rwth-aachen.de

Reinhard Madlener
Institute for Future Energy Consumer Needs and Behavior (FCN)
School of Business and Economics / E.ON Energy Research Center
RWTH Aachen University
Mathieustrasse 10
52074 Aachen, Germany
E-Mail: RMadlener@eonerc.rwth-aachen.de

Publisher: Prof. Dr. Reinhard Madlener
Chair of Energy Economics and Management
Director, Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center (E.ON ERC)
RWTH Aachen University
Mathieustrasse 10, 52074 Aachen, Germany
Phone: +49 (0) 241-80 49820
Fax: +49 (0) 241-80 49829
Web: www.eonerc.rwth-aachen.de/fcn
E-mail: post_fcn@eonerc.rwth-aachen.de

Techno-economic analysis of micro fuel cell cogeneration and storage

Laurens Löbberding[a], Reinhard Madlener[b,*]

[a] *RWTH Aachen University, Templergraben 55, 52062 Aachen, Germany*
[b] Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University, Mathieustrasse 10, 52074 Aachen, Germany

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Abstract

In this paper, the effectiveness of support schemes for micro fuel cells in Germany is analyzed with regard to the latest market conditions, support schemes, and legislative changes. Specifically, we analyze whether polymer electrolyte membrane fuel cells (PEMFCs) are a feasible investment option for residential usage in Germany, or whether they are likely to become so soon. Furthermore, we investigate whether electric energy storage could be a useful extension to the domestic fuel cell system by supplying short-term peak demand, and thus increasing self-consumption and potentially the overall economic merit. We find that PEMFCs are unlikely to become a competitive technology by 2020, and it may take quite some time to achieve a substantial market diffusion. Finally, we find that electric energy storage in combination with an FC system is found not to be a worthwhile investment in a grid-connected scenario.

Keywords: CHP; Micro fuel cell; PEMFC; Battery storage; Economic evaluation; Market diffusion Germany.

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[*] Corresponding author. Tel.: +49-241-8049-820; fax: +49-241-8049-829. *E-mail address:* RMadlener@eonerc.rwth-aachen.de (R. Madlener)

Nomenclature

AC	Alternating current
CHP	Combined heat and power
DC	Direct current
FC	Fuel cell
HT	High temperature
HHV	Higher heating value
LHV	Lower heating value
NPV	Net present value
PEMFC	Polymer electrolyte membrane fuel cell
RGB	Reference gas-condensing boiler
SOFC	Solid oxide fuel cell

1. Introduction

Combined heat and power (CHP) plants simultaneously produce electrical and thermal energy, the latter of which is used on-site or by means of district heating. CHP systems are of interest from a research and policy perspective due to their potential primary energy savings in comparison to conventional power systems with separate electricity and heat production [1]. In Germany, reaching the emission reduction target by 2020, which was set by the Paris Agreement of 2015, seems unrealistic at the moment [2]. Micro-CHP systems are seen as a part of the solution to mitigate carbon dioxide emissions. Promising Micro-CHP technologies include Stirling engines, gas turbines, and fuel cells (FC) [1]. FCs stand out because they can achieve substantially higher efficiencies than those of other mature small-scale CHP technologies [4], and because they can potentially rival even the most energy-efficient large-scale power plants.

Pehnt et al. state a 21% to 27% CO_2 emission reduction compared with a modern reference gas-condensing boiler (RGB) in a single-family house in Germany and electricity from the grid that is generated from the current power generation mix in Germany [5]. In addition, the absence of an internal combustion engine avoids critical emissions of nitrogen oxides and sulfur dioxide [6]. Not only in light of the recent diesel emissions scandal, where car manufacturers deliberately violated nitrogen emission laws by cheating with engine software, but given a generally high public awareness of local air pollution and global climate change in Germany, this is a great advantage to the other available technologies. In light of the benefits CHP technology can offer, the German government has set the goal of achieving a share of at least 25% of CHP electricity production by 2020 in Germany, especially supporting the FC CHP technology.

A recent study analyzing the economics of micro FCs for the case of Germany in 2012 is [5]. From their results, the authors expect market competitiveness with other CHP and heating technologies by 2020. However, despite of the fact that the German federal government promotes the market integration of micro FC CHP plants with subsidies, no rapid diffusion is taking place in Germany in the residential sector, with only some 1,000 installations so far [7]. Prices of FC systems are still very high, mainly due to high material costs, low production volumes, and higher system complexity when compared to engine- or Stirling-based micro-CHP systems [8]. In comparison, in Japan, where governmental policy support is also provided, already more than 150,000 FCs have been installed for domestic use by the end of 2015 [7,9,10]. But despite of the strong policy support there, actual market diffusion seems to be way below expectations and set targets of 1.4 million units by 2020, so that it seems unrealistic to reach this goal with the current deployment dynamics.

From the review of the existing literature, it becomes clear that there is scope for further research. For instance, the models introduced so far have not been sufficiently detailed, leaving out cell degradation, which reduces the power capacity over time, or by setting system boundaries only to the FC unit itself, thus ignoring the energy losses from the fuel reformation process. In contrast to previous work, in the present analysis scrutinizes the dynamic behavior by means of a detailed FC system simulation. Napoli et al. [11] reviewed the minimum level of subsidies needed in Italy to achieve a positive net present value (NPV) within 5 years for two different micro FC technologies including a battery storage. They find an optimal tariff of 0.095 €/kWh paid for self-consumed electricity produced by the fuel cell throughout the entire operating life. However, in their analysis no investment comparison is made with other commercially available technologies. Because the investment in a heating system usually leads to a negative NPV, the question is which technology among a number of alternatives has the lowest overall lifetime costs. Therefore, our research offers some new results not only based on new market data but specifically because the system is modeled including the dynamic fuel cell operating behavior and by using an improved simulation approach by comparing the performance to a reference system on the market.

In [4], the authors anticipate market competitiveness of micro FC systems by 2020 with the other CHP and heating-only technologies if FC system prices decrease further up to 2020 due to learning and economies of scale effects, and assuming an average electricity price increase of 4% per year. The situation has changed by now: micro FC systems have shown a slower deployment rate than projected and a slower cost development than assumed; the stock price for gas and electricity has decreased, which was neither expected by most forecasts nor was it considered in the authors’ scenarios. New support schemes have led to a different investment environment. This makes clear the need for a new, refined assessment.

2. Methodology

The main contribution of this paper is the development of a detailed white-box simulation model for residential micro FC systems. Two different types of systems are modeled, a (1) standard FC system and (2) a standard FC system with the addition of an electric energy storage unit. Based on the proposed simulation model, an analysis of the current economic viability of domestic micro FCs in Germany is carried out by comparing the two types of FC system with an up-to-date gas-fired condensing boiler used as a reference (referred to as RGB), both with and without subsidies. For the analysis, the net present value (NPV) methodology is used, i.e. a static approach that allows the calculation of an investment’s market value within a specific timeframe. The NPV represents the overall value of a project, determined by the present value of the expected future net cash flows of costs and revenues (minus investment costs). [8] have shown that the cost development of FCs can be well described with a learning curve. According to the learning curve model, unit costs decrease with cumulative production of a new technology. In order to estimate the required number of future installations for achieving market competitiveness, the learning curve concept is used to further interpret the results of this study.

To estimate the necessary future installations for achieving market competitiveness, the learning curve concept is applied, assuming a learning rate of 16% [5] and the economic results of the study.

3. Model specification

3.1. Selection of technology and optimizing system operating strategy

[12–14] offer a detailed review of the fuel cell technology including the technological progress made so far. For domestic micro-CHP plants, two main FC technologies are currently being deployed [9,13]: Polymer Electrolyte Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs). The most widely deployed technology is the PEMFC. PEMFCs presently account for approximately 90% of the globally installed micro FC devices [13]. They offer the highest guaranteed lifetime operating hours (70,000-80,000 h) [15,16] and a comparably low electric power output degradation from 0.5% till 1.5% per annum in leading PEMFC systems [14]. Consequently, in the following, a PEMFC system is simulated in detail. Leadbetter and Swan [17] analyze the optimal selection of a battery technology able to support grid-integrated renewable energy use of private households. They provide a detailed status of the currently most widespread and promising battery technologies. Lithium-based batteries, and in particular the mainly used lithium-ion batteries, offer a high power capability, good cycle life, high energy density, and high efficiency. Therefore, a lithium battery storage unit is analyzed as an extension to the PEMFC system.

In general, there are two main operating strategies for CHP systems which need to be considered when selecting the technology and dimensioning the system: (1) electricity-oriented plant operation and (2) heat-oriented plant operation. Depending on either the current electricity or heat demand (i.e. operating strategy (1) vs. (2)) of a private household, the CHP system modulates its power output. Simpler operational approaches – like no modulation, day-night modulation or interval modulation – are also possible. Typically, however, they are outperformed by an electric-load- following strategy both from an economic and environmental perspective [11]. This still leave the two alternative operating strategies (1) and (2), next to more simplified approaches. To assess which strategy performs best overall,we make a separate economic pre-assessment. Feed in electricity from the fuel cell without subsidies is only remunerated at an electricpower price of 0.028 €/kWh [18] with fuel cost of 0.067 €/kWh [19]. For micro CHPs (electric power smaller than 2 kW), using the simplified remuneration approach, an upfront capital grant [20] is preferable in both operating scenarios to taking advantage of the available feed-in tariff [20]. With the current spread between the electric power price and the paid fuel price, feeding in more surplus electricity with the heat-following strategy is consequently not the economically most viable proposition. Therefore, the electric-load-following operating strategy (1) is found to have a better economic performance for micro-CHP systems in Germany and was thus adopted in the subsequent study.

After having chosen an operating strategy, the recommended approach is to optimize the CHP system size by using an annual electric load duration curve [21]. Choosing an optimal system size is important for the economic outcome because the investment costs and the system capacity utilisation are correlated with the size of the system. We aim at assessing the status quo with a representative system commercially available (a PEMFC CHP plant with 700 W electrical and 1,000 W thermal peak output [8,12]).

3.2. Load profiles and energy demand Model assumptions

As an input for the technical simulation model, we use daily load profiles in 1-minute resolution from the VDI Guidance 4655 [22]. A detailed description of the methodology used for the load profile measurements can be found in [22,23]. Note that the quality of the chosen load profiles is very important for an accurate simulation outcome. If the temporal precision is low, load profile peaks decrease, and valleys increase, thus enabling the FC to better follow the demand. This distorts the results of the simulation. The economic outcomes varied by up to 8% and environmental outcomes by up to 40% when taking 5-minute data instead of hourly data for a fixed system capacity of a stand-alone CHP plant [3]. For FCs, this effect is even stronger because they cannot adopt their power output as quickly as Stirling- or engine based CHPs. To minimize the effect, more granular load data input is required. Many previous studies of CHP systems do not use data as accurate as that and often rely on hourly data only [5,24–27]. The effect becomes clear when looking at figure 1, where a 1-minute load profile is compared to a 15-minute load profile. It must be noted that peak shaving and valley filling is only of secondary importance for the heating load due to the nature of space heating demand with thermal storage in both the heating system and the building envelope [3].

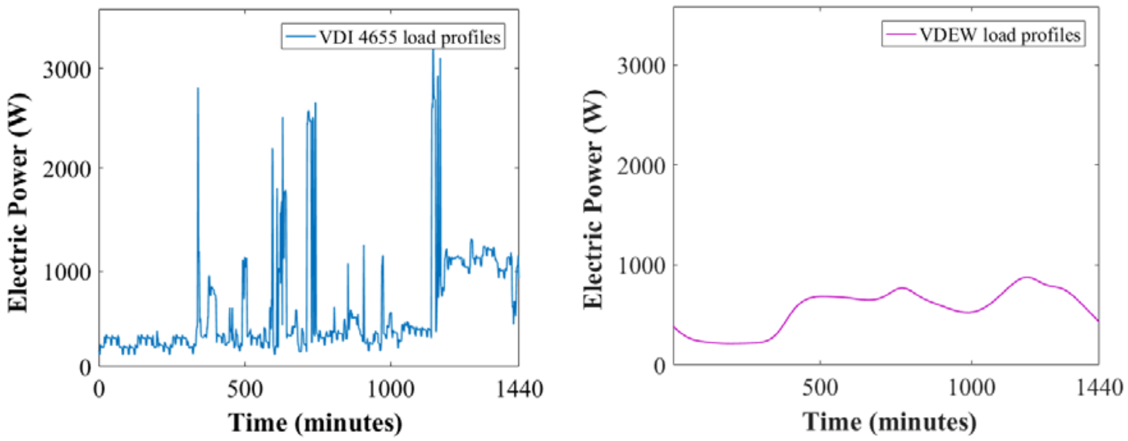

Figure 1: One-minute interval VDI 4655 and comparable 15-minutes interval VDEW daily electric load profile both normalised to 13.41 kWh

The load profiles from the VDI 4655 guidance are not ready to use but must be scaled to the considered use case and aggregated to a yearly profile. The yearly demand profile will differ over time due to changes in the illustrative household analyzed. Since those changes can hardly be anticipated, the created yearly profile is assumed to remain constant throughout the operating life. To ensure that only little heat is dissipated and, therefore to achieve a high fuel utilisation, the system will be switched off during the summer period in which no heating demand is required (amounting to 81 days of FC system off time per year). Table 1 provides a detailed overview of the thermal and electric load assumptions made for the type of building and household studied.

Table 1: Model input data used

Input Data	Value	Comment / References
Type of building	Single family house	Only micro-CHPs analyzed
Climate Zone	5	See norm [22] for more details, same region where measurement were taken
Number of occupants in household	3	Average size is two in Germany [28], assuming that relatively larger households purchase a PEMFC system
Yearly thermal demand	11,000 kWh	[22,29] average consumption with a correction based on [30,31]
Yearly electricity demand	5,250 kWh	[22,32]
Yearly domestic hot water demand	1,500 kWh	[22]

All values used in this analysis are normalized to the Higher Heating Value (HHV). The used ratio of the Lower Heating Value (LHV) to HHV is 1.11 [31,33].

3.3. Fuel Cell Model

In a first step, the daily load profiles in 1-minute resolution were aggregated into a yearly profile, and then scaled to the assumed household demand. Furthermore, based on the input of the load profiles, a plant control system was created which enables the simulation of the operational capabilities of a PEMFC following the electric load of a household. The main PEMFC system characteristics are summarized in Table 2.

The PEMFC consists of three primary subsystems: the fuel processor, the fuel cell stack, and the power conditioning system. The fuel processor converts the fuel, for example natural gas, into a hydrogen-rich feed stream, which is transformed in the fuel cell stack from chemical energy into electrical and thermal energy. The power conditioning system transforms the direct current (DC) from the fuel cell stack into alternating current (AC) which is required by the end user [12]. Current commercially available systems also have an additional auxiliary boiler to supply the peak demand of the household. In addition, they contain a heating buffer storage and a domestic water buffer storage. Therefore, when discussing the PEMFC system, auxiliary devices are also included in the following.

Table 2: PEMFC system characteristics

Characteristic	Value
Electrical / thermal / overall efficiency (HHV)	31.3% / 44.7% / 76.0% (a)
Initial cell voltage	666 mV [34]
Ramp up speed	30 W/s [11]
Minimum / maximum initial electric output	250W / 750W(b)
Maximum initial thermal output	1,000W(b)
Efficiency peak load gas-condensing boiler (HHV)	93%(c)
Usable thermal buffer storage size	3.5 kWh

(a) Best current system characteristics according to manufacturer specifications [13]. Discounted by ratio 1.11 [31] as gas is priced according to the higher heating value (HHV) definition. Additional compensation by 10.9% for average difference observed between manufacturer specifications and field performance, as found in [14] leading to the above stated values.

(b) All commercial suppliers offer systems with about 700 W electrical, and 1,000 W peak thermal output [8,12].

(c) The highest manufacturer-stated thermal efficiency for auxiliary gas-condensing boiler is 98% (HHV) [35]. A 5% discount based on annual efficiencies reported in [36] is added (accounting for different return flow-temperatures). The same efficiency is used for the reference system.

As the FC follows the electric demand of the household, the system usually produces more or less heat than is consumed by the household. Therefore, a thermal storage as a buffer is included which can be charged and discharged. If the storage is empty and the thermal demand is higher than the heat produced by the PEMFC, the additional thermal demand is supplied by the peak-load boiler.

A major advantage of FC stacks is their high efficiency at partial load. However, the energy consumption from auxiliary devices, components, and the inverter do not scale linearly with the power output and thus present high losses at partial load. The functions presented in eqs. (1) and (2) were implemented into the model in order to account for the partial load efficiency based on the experimental analysis of 8 real- PEMFC systems [14] where P is defined as the ratio of current to maximum power output:

$1.183-\frac{0.1756}{P}$ for the normalized *electrical* efficiency (1)

$1.096-\frac{0.0927}{P}$ for the normalized *thermal* efficiency (2)

The degradation rate defines how the cell efficiency evolves over time and strongly depends on the way the system is operated. If not taken into consideration, the marginal value of a system may be overestimated by up to 45% [37]. Due to the degradation, the electrical efficiency decreases while the thermal efficiency increases. We postulate that the system shows a linear degradation rate of 3 μVh^{-1} throughout the operating lifetime, putting it at the lower end of the range stated by [37] of 1 μVh^{-1} till 100 μVh^{-1}, whilst still acknowledging for the recent progress made [14]. In an ideal scenario, the loss of electrical power would lead to an equal increase in thermal output: $\Delta Q_{th} = -\Delta Q_{el}$. However, the amount of useful heat will not have the same magnitude as the decline in electrical efficiency. We account for this by using the thermal utilization ratio introduced in [34]:

$$v_{th} = \frac{\text{heat extracted}}{\text{heat available}} = \frac{\eta_{th}}{1-\eta_{el}} \qquad (3)$$

For an initial electrical efficiency of 31.3% (HHV) and an initial thermal efficiency of 44.7% (HHV), the resulting ratio is 0.65. The beginning of life efficiency has been taken for the first operating year, the first-year characteristics for the second operating year, and so forth. After the tenth year of operation, the cell stack has operated 77,000 h and needs to be replaced thereafter, achieving the initial system characteristics again. As fuel cells for domestic micro-CHPs are still not a mature technology, one might expect unreliable operation. However, the systems which were tested in the Callux project in Germany achieved system availability rates of more than 96% [38]. Also, scheduled maintenance can take place during system off-time, making the overall impact of operational downtime negligible. In addition, FCs need energy for the start-up process. For this, the impact of an arbitrary number of 30 start-ups is analyzed based on data from [37]. The start-up processes require 48 kWh of additional gas and a negligible amount of electrical energy, the latter of which has to be purchased at a higher price from the grid. From this, we infer that the impact of start-up costs on the results can be neglected for the case of our electric load-following PEMFC.

While the FC follows the electric demand of the household, the system usually produces more or less heat than is consumed in a particular moment, the remainder of which is buffered by a thermal storage unit. If the storage is empty and the thermal demand is higher than the heat produced by the PEMFC, the additional thermal demand is supplied by the peak-load boiler. The modeled thermal storage water tank has a size of 200 l, with a maximum water inflow temperature of up to 50 ℃ and an outflow temperature of 30 ℃ [35]; it is assumed to be adiabatic.

The battery system has in principle the same objective as the thermal storage: to maximize the local use of the produced energy. If the electric energy storage unit is included, a similar logic is used as for the thermal storage unit, but with the following alterations: instead of having to dissipate surplus heat, electricity can be sold to the grid. Instead of heat supplied from the auxiliary boiler, electricity is bought from the grid whenever the storage unit is empty. The battery storage model includes inverter efficiencies, the battery cycle efficiency and standby losses, as outlined in table 3. The assumptions are based on the recent report from the German monitoring program for hybrid photovoltaic battery storage systems from 2016 [39]. The system build-up is the same for the FC system with battery, which is why the report's data can be directly transferred to this use case. In contrast to [11], the results examined for this work are considered to be more realistic with a 77% instead of a 90.2% overall cycle efficiency based on real system performance with less optimal operation points.

Table 3: Battery system characteristics

Characteristic	Value	Comment / References
Inverter charging [(a)]	91% (constant)	No significant dependence on battery charging status (± 0.5%) and charging rate (± 2%), however higher variation depending on the systems reviewed: systems efficiencies ranged between 87% and 96% [39].
Discharging efficiency [(a)]	94% (constant)	No significant dependence on battery charging status (± 0.25%) and charging rate (± 1.5%) except of higher losses at very low power output [39].
Battery efficiency (charge and discharge) [(a)]	90% (constant)	Based on average battery long term efficiency measurements of up to a year as an addition to a PV system [39].
Overall cycle efficiency [(a)]	77% (constant)	
Standby electricity consumption	100 kWh p.a.	Average standby consumption of 15 Watt [39] leading to a use of ≈100 kWh during 6,800 hours of operation p.a.
Usable capacity	3 kWh	Size was optimized so that it sustains during the entire operating time. Based on a simulation calculating the number of cycles with different depths of discharge using [40,41].

(a) Inverter system build-up: Charge: FC to DC/AC to AC/DC to battery; Discharge: battery to DC/AC to household. This makes it possible add a battery separately to an existing FC system and it is the most common way to connect a battery to a PV system.

Then, the system is simulated, always accounting for the specific operational point and resulting efficiency, with the state of degradation for every year of operation – first without and then with an electric energy storage system. To enable a better understanding of how the PEMFC follows the electric demand of the household, figure 2 shows an excerpt of a daily load profile, where both the PEMFC electric output and the electricity demand of the household are depicted. The stated electric power limits (dashed black line) and the maximum ramp-up speed of the PEMFC of 30 W/s (gradient of blue line) become clear after inspection of figure 2. The simulation output – i.e. the fuel demand, electricity purchased, electricity sold, and electricity self-consumption – are then implemented into an economic model to compare them against an RGB.

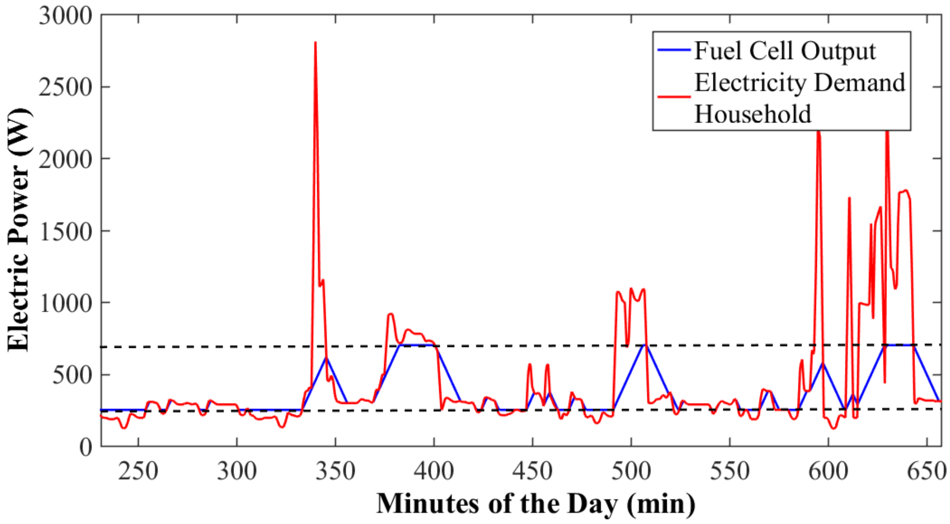

Figure 2: PEMFC following the electric demand of the household analyzed. The horizontal dashed black lines represent the initial electric power range of the PEMFC. The thermal depends on the electrical output of the system.

4. Economic and regulatory Framework

The economic model used is created in line with VDI Guidance 2067 [42]. The assumptions made are described in some detail in this section. For both the PEMFC and the RGB system, it is assumed that their residual value is zero at the end of the estimated operating lifetime of 20 years. A typical household in Germany is analyzed, which already has a gas supply and the choice of either renewing the gas heating system or investing in an FC CHP unit. Furthermore, local subsidies additional to the nationwide KfW 433 support scheme and CHP Act 2016 were excluded from the analysis, as comparability is not given within Germany and because they are usually rather small, and thus only having a minor impact on the results. Tables 4 and 5 give an overview of the input data to the model, including the price assumptions made for the FC system and the cost of an RGB.

Table 4. Economic data PEMFC system

Input Data	Value	Comment / References
PEMFC: system / installation costs	€19,500 + €6,000 = €25,500	[8,43] / [5]
Support scheme available	€8,850 + €1,680 upfront payment	KfW Development bank [44]; CHP Act 2016 [20], the simplified remuneration is the preferred one in this use case
Cost of the battery storage system	€3,750	[39] including all system components (inverter, sensor etc.) and additional installation costs
Fuel stack replacement	€2,850	[8] 15% of stack costs; replacement after 10th year of operation
Equity capital	€7,500	
Interest rate	2.5% fixed rate	[45] good conditions due to supported credit program of KfW
Cost of electricity	0.312 € kWh^{-1} / 3% increase p.a.	[19] based on historical development over the last 10 years and regarding short-term trend
Natural gas price	0.068 € kWh^{-1} / 1% increase p.a.	[19] based on historical development over the last 10 years and regarding short-term trend
Maintenance costs	€300 p.a. for the first 10 years, then €360 p.a.	[43,46]
Quarterly baseload price	0.02826 € kWh^{-1} / 1% increase p.a.	[18], used for calculating the revenue of the feed-in electricity
Discount rate for NPV	2%	Interest rate of a 20-year federal government bond (0.4%) [47] plus 1.6% risk premium.

Table 5. Reference gas-condensing boiler

Input Data	Value	Comment / References
System costs	€5,000	Reviewing different online prices and direct feedback from suppliers, price of 2016 with a 20 kW to 30 kW peak thermal output.
Installation costs	€2,500	[5]
Equity capital	€7,500	
Maintenance costs	€140 p.a. (for the first 10 a), then €170 p.a.	[5,46]
Electricity / Gas price	See table 4.	
Discount rate for NPV	2%	Interest rate of a 20-year federal government bond (0.4%) [47] plus 1.6% risk premium.

The fuel cell price development is modeled with a learning curve [8]. In Japan, a higher deployment of fuel cells has already taken place and, therefore, data is available that can be used to assess the progress made so far. It is estimated that until now about 150,000 fuel cells were installed in residential households. The learning rate for all PEMFC systems observed was 16% in the period from 2004 until 2012. This learning rate applies to an entire fuel cell system, already including the fuel reformation unit, an auxiliary boiler and a thermal storage unit [8], and thus identical to the reference PEMFC system analyzed in this work. This learning rate of 16% will be used later to give an orientation onto the number of system installations needed until the PEMFC becomes cost-competitive against an RGB (cf. section 5.3).

5. Results

5.1. Reference system compared to PEMFC

The results are summarized in Table 6. Due to the nature of a heating system investment, the returns of the project will be negative, which renders the technology with the highest NPV (i.e.

with the lowest negative value) preferable. Even though the FC is supported by a total subsidy of €10,530, the economic performance of the state-of-the-art PEMFC system is still lower than the performance of the reference system in a typical German household.

The observed gap of €1,413 between the NPV of the RGB and the PEMFC with subsidies (stated in table 6), is however, relatively minor, showing that the current governmental support via the CHP Act 2016 and KfW 433 support scheme is high enough to narrow the gap between the PEMFC and RGB investment alternatives considered for the case of Germany.

Table 6: Economic results analysis

System Type	Annuity	Net Present Value
Reference gas condensing boiler (RGB)	€-3,807	€-62,555
PEMFC with Subsidies	€-3,894	€-63,668
PEMFC without Subsidies	€-4,557	€-74,516
PEMFC without Subsidies and with Battery	€-4,758	€-77,803

When no subsidies are granted, the economic performance of the PEMFC system considerably lags behind the performance of the RGB system. In the absence of subsidies, the total costs of the PEMFC would have to be drastically reduced by €12,261 relative to the current best available technology system characteristics as shown in fig. 3. If the installation costs can be reduced by €3,261 with a better system integration, system prices would still have to fall by about €9,000 to a level of €10,500 (cf. fig. 3).

Adding a battery system to a PEMFC following the electric load of a household strongly deteriorates the economic performance by €3,287 at a battery system price of €3,750. The performance of the battery system can be explained with the sufficient capability of the FC to follow the electric demand, leaving only small amounts of surplus energy as a residual to be stored. The low overall cycle efficiency of 77% and standby losses of the battery system even worsen the result.

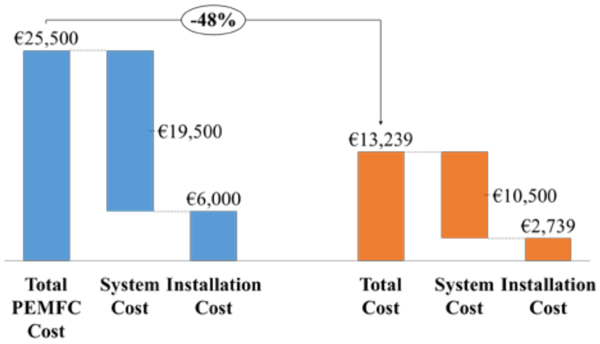

Fig. 3. (a) Financing structure PEMFC with subsidies compared to RGB; (b) Necessary PEMFC cost reduction for market competitiveness without subsidies

5.2. Sensitivity analysis

The price developments of both electricity and gas are identified as the uncertainties with the largest impact on the economic outcome. Therefore, it is interesting to know which technology benefits from which price development scenario. An analysis has been carried out for the reference system compared to the PEMFC system, omitting the subsidies in order to obtain the results without distortion through support policies.

To estimate the influence of the gas price development, the electricity price was fixed to a 3% growth rate p.a. while varying the growth rate of the gas price from -4% to 4% p.a. for the observation period of 20 years. The results are summarized in figure 4. The higher the annual growth rate of the gas price is, the worse the PEMFC system performs compared to the gas-condensing boiler as a reference. This is because the FC system relies on low-cost natural gas to be able to produce electricity at a price lower than the retail market price.

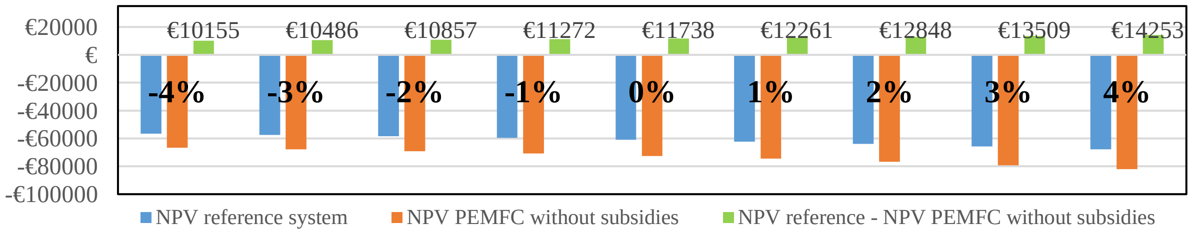

Figure 3: Impact of gas price development on the NPV (electricity price growth 3% p.a., 20-year period)

The same approach was taken to assess the influence of the electricity price development: the gas price was fixed at an estimated 1% growth rate p.a. while varying the electricity price increase from -4% to 4% p.a. The results are depicted in figure 5. For the consumer electricity price development, the opposite is true: The higher the annual growth rate of the electricity price, the better the PEMFC system performs relative to the reference gas-condensing boiler. The own electricity production enables the operator of the FC to buy less electricity from the grid, thus reducing the influence of any electricity price increases. However, if the prices fall, this advantage becomes smaller until at some point the electricity purchased from the grid becomes cheaper than the self-produced electricity from the FC.

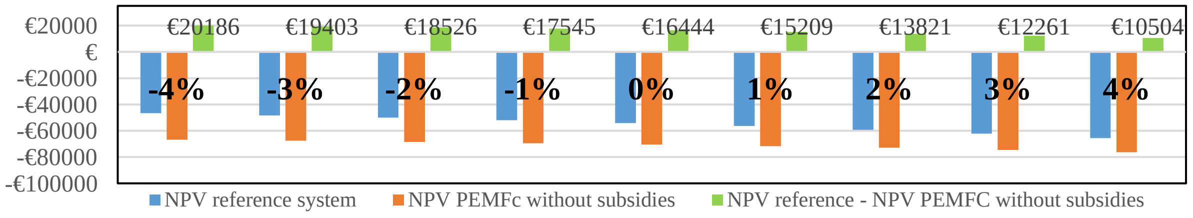

Figure 5: Impact of electricity price development on the NPV (gas price growth 1% p.a., 20-year period)

Still, for both cases and in all analyzed scenarios, the PEMFC without subsidies shows a lower economic performance than the RGB. Usually, the financing structure may have a high influence on the overall outcome of a project (due to the WACC and the leverage effect). In a very low interest environment, where currently a 2.5% interest rate is realistic for a 20-year loan, this effect is much smaller especially because in the NPV method future cashflows are discounted.

5.3. Estimated installations needed before market competitiveness is reached

To estimate how many installations would be needed before the technology can become competitive on the market, the learning curve model is utilized for the price and quantity of the base year, P_{base} and Q_{base}, versus those after n doublings of cumulative power output, P_n and Q_n. The target price of €10,500 was derived from the previously analyzed economic performance of the PEMFC against an RGB with currently 150,000 installations worldwide.

$$Q_n = Q_{base} \times \left(\frac{P_{base}}{P_n} \right)^{\frac{1}{b}} = 150,000 \times \left(\frac{19,500€}{10,500€} \right)^{\frac{1}{0.16}} \approx 7,200,000 \tag{4}$$

This broad estimation shows that, *cet. par.*, 7,200,000 installations would have to take place until the PEMFC technology becomes competitive against an RGB. Therefore, it is highly unlikely that FCs will become competitive in the near future, since we are looking at only 150,000 installations worldwide [7,9,10].

6. Discussion and outlook

We find that PEMFCs will not have become competitive in Germany by 2020. In actual fact, it may even take much longer to unleash substantial market diffusion dynamics given the anticipated only relatively minor future cost advantages of the PEMFC system. This strongly contrasts with the findings of [5], who already foresaw a market competitiveness by 2020 compared to the other conventional heating technologies. The difference can be explained by the authors’ underestimation of the dynamic system characteristics. As discussed, efficiencies from FCs supplied with natural gas are low at partial load due to high auxiliary losses, mainly related to the fuel reformation process. This was factored into the detailed simulation model of this paper in contrast to previous studies. In addition, cell stack degradation is found to have a major impact on the economic outcome [37] and was considered in our work. Furthermore, the underlying hourly data profiles in [5] let to a better outcome of the study due to the explained peak-shaving and valley-filling trough effect. Furthermore, the underlying hourly data profiles in [4] additionally improved the outcome due to the discussed effect [37]. Thereby, the load peaks and valleys are averaged out over the time intervals between the different data points. By using more accurate, minutely based data profiles in this study, more precise and novel results are obtained. In the conducted sensitivity analysis in this work, even with a beneficial market development with increasing electricity prices and decreasing gas prices, the economic gap between the two technologies without subsidies remained high. Likewise, if competitive pressure from the fuel cell technology leads to price reductions and/or further technical progress on competing conventional technologies (in the innovation literature known as “sailship effect”), the gap could remain wider than (optimistically) expected. Considering alternatives, the less mature SOFC systems are also a promising future technology with higher overall electrical efficiencies in both partial- and full-load operation. However, they have not shown high enough operation times yet (and with current prices, we do not expect a very different economic outcome for the foreseeable future).

When only looking at the sheer number of 7,200,000 systems which would have to be deployed, one might expect that the technology might never become competitive. The required subsidies, although getting lower with every deployed system, could be too high to promote the technology at all. However, this line of thinking is not looking at the issue taking a holistic approach, and neglects three aspects. First, technical parameters will still improve, thereby decreasing the number of necessary subsidized systems. Therefore, especially the cell degradation should decrease, such that the fuel cell stack sustains throughout the entire lifetime. Second, and particularly important, PEMFCs are not solely limited to a domestic application. Although battery electric vehicles seem to make the race in the discussion of decarbonizing the mobility sector, the question on how to create a comprehensive charging infrastructure with a high market penetration of battery electric vehicles, especially for long distance traveling, is not answered yet. Vehicles which use a PEMFC supplied with hydrogen could solve this problem. Thereby, the development of PEMFCs in the domestic sector could go hand in hand with the development for mobility applications, thus drastically increasing the economies of scale and enabling potential synergy effects. Third, currently deployed PEMFC systems use natural gas as a fuel and therefore require a fuel reformation unit. With increasing fluctuating renewable energy production, power to hydrogen production is evaluated as a future solution to use produced surplus energy. By supplying pure hydrogen to the FC instead, system parts could be reduced because it does not need the fuel reformation unit anymore. This would lower the costs while improving the overall system efficiency. For future analysis, we therefore propose to take a closer look at the potential synergies and how they could help to enhance the technology for domestic applications.

Although the less mature SOFC systems have not shown high operation times yet, they may still be a promising future technology with higher overall electrical efficiencies in both partial- and full-load operation. In future research, a SOFC system should therefore be analyzed in detail as well. The model set up in this work can easily be adapted to the system characteristics of an SOFC.

7. Summary and Conclusion

FCs offer an environmental benefit compared to conventional heating systems in terms of lower pollutant and CO_2 emissions. Therefore, several governments around the world are supporting the market integration of the technology as a measure that can help to mitigate climate change. The aim of our study was to analyze whether micro FCs are a feasible investment option for domestic usage, or whether they are likely to become so soon. The

PEMFC system simulation followed by an economic assessment led to the following three main findings:

- The technology is still far removed from competitiveness in domestic application in Germany, and PEMFC system costs need to be at least halved before the technology can compete on the market without any subsidies.
- Current support schemes in Germany are found to be just about high enough to make an up-to-date PEMFC cost-competitive against an RGB.
- Batteries in addition to a PEMFC system are not a worthwhile investment in a grid-connected scenario yet.

It will therefore take a higher input than generally assumed to make the PEMFC technology not only an environmentally but also an economically preferable alternative. Hence, the results indicate that before scaling up the PEMFC technology with costly subsidies, the focus should still be on enhancing the PEMFC system performance, especially at partial load and reducing cell degradation, by conducting more research. However, this input may also come from fostering synergies with the automotive sector or by creating a hydrogen grid, where surplus renewable energy could be used to as an energy source for the PEMFC. Otherwise, by subsidizing PEMFCs for domestic usage alone, a very high number of subsidized systems will be required to bring down the costs to a competitive level, which would take a very long time.

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