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Optimization of the heat output of high temperature fuel cell micro-CHP in single family homes

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Abstract

Micro cogeneration units are a very efficient way to supply buildings with heat and electricity. In addition to conventional powered CHP units, there are also SOFC powered units. In opposition to conventional CHP their thermal efficiency is strongly dependent on the return temperature from the DHW and heating system. The efficiency is invers to the return temperature, hence this temperature should be lowered to a minimum. Therefore a new DHW and heating system was designed. To quantify the effects a SFH supplied by a high temperature fuel cell was simulated using a standard DHW and heating system as well as an optimized one. The results show that the heat energy output and thus the thermal efficiency of the fuel cell can be increased significantly. However the annual costs also slightly increased due to the extra equipment for the new system. The optimum for energy efficiency and costs is the standard system where the storage temperature has been lowered to the minimum.

Keywords: Fuel cell; micro CHP; energy building simulation; heating systems

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Nomenclature

CHP	combined heat and power
SFH	single family home

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TRY	test reference year
SOFC	solid oxide fuel cell
CB	condensing boiler
DHW	domestic hot water

1. Introduction

The combined generation of heat and power is a very efficient decentralized technique to simultaneously supply buildings with electricity and heat. In addition, CHP plants can compensate expected future power fluctuations caused by increasing percentage of renewable wind and solar energy production. Therefore, the German federal government has set the goal of 25% share of electricity generation from CHP by 2020 [1]. Currently the proportion is only at about 16% [2], so there is a great need for new installations. Recently, conventional CHP, small high temperature fuel cell CHP units have become available on the market. This paper focuses on such a system, which has a constant electrical output of 1.5 kW and a varying thermal output of up to 0.85 kW. Thus the system is particularly suited to highly insulated single-family or two-family houses to efficiently provide them with electricity and heat. A characteristic feature of the system is its heat output which depends on the temperature of the returning water from the buildings DHW system. If the return temperature in the fuel cell is high, the heat power is low and vice versa [3]. Previous studies have shown that the annual heat output of the CHP plant is less than one-third of the potential [4], which is due to the high return temperatures to the fuel cell, in this case set by the hot water storage. The return temperature to the fuel cell decreases to a level where the fuel cell has a noticeable heat output only when the storage is partly charged. Which happens primarily during heating season. In summer, when little domestic hot water is being tapped from the storage, the return temperature drops only for a short time until the fuel cell reheats the storage. Hence, the storage temperature has to be decreased, or at least the temperature of the storage layer from which the fuel cell receives its water. For this purpose the already low tank temperature is decreased further, just enough to satisfy the temperature demand of the tap water. Furthermore, the storage tank temperature is even reduced to the level of the underfloor heating system and the required temperature for domestic hot water will be reached with a continuous-flow electric water heater at the tap. The SFH was modeled and simulated over one year with the three above mentioned configuration (see in table 1). Finally the results will be analyzed and compared with regard to electricity, heat, primary energy and costs.

Table 1. Considered system configurations.

Case	Supply storage	Supply DHW	Supply electricity	Storage temperature
Reference	SOFC, CB	Storage	SOFC, grid	60°C
45°C	SOFC, CB	Storage	SOFC, grid	45°C
35°C	SOFC, CB	Storage, electrical heater	SOFC, grid	35°c
Without a fuel cell	CB	Storage	grid	60°C

2. Modeling and simulation

The fuel cell should supply a modern well insulated SFH with electricity and heat. Since it is impossible to generate an exact image of the reality there are some boundary conditions and assumptions, which are documented in this chapter. The modeling and simulation is done with modelica based SimulationX. It was used with the commercial GreenBuilding library and a self-written type for the fuel cell. The time steps are one second and the simulation runs over one year. The equation system generated by SimulationX is solved with the CVODE-solver.

2.1. Building

As mentioned previously the fuel cell is well-suited to a modern highly insulated SFH. To obtain a realistic heating profile for such a house, it was modelled and simulated in SimulationX. The house has two stories and meets the German building standard “EnEV 2009”[5]. It was modelled as a one zone building with the footprint of 69 m² and a height of 5.5 m. The u-value is 0.15 W/m²K with additional losses through heat bridges of 0.03 W/m²K [6]. The window properties were optimized due to solar gains and heat losses, depending on the orientation. The north and the east sides with only a few sun hours are better insulated hence the solar gains are lower. Together the window area is 7 m² with an u-value of 0.81 W/m²K and a g-value of 0.5. Whereas the large sunny south and west orientated windows were less insulated with higher solar gains. The u-value is 1 W/m²K and the g-value is 0.63. The inner heat transfer coefficient in the zone is assumed to be 7.7 W/m²K and the outer to be 25 W/m²K [7]. The flat roof has the same area as the footprint and has an u-value of 0.15 W/m²K. The simulation took inner masses into account, which were estimated with a volume of 13.8 m³, a density of 1800 kg/m³ and a heat capacity of 0.92 kJ/kgK. The ventilation losses were assumed to be 0.5 1/h [8].

The building location is Dresden and the weather file used is the matching Test Reference Year 2011.

2.2. Occupation

The house is occupied by a family of four, two adults and two children. The presence profile for the house is in 30 minutes steps, which differentiate between week days, Saturdays and Sundays/holidays. The profile is visualized in figure 1. It was assumed that per person 100 W [9] of heat are emitted.

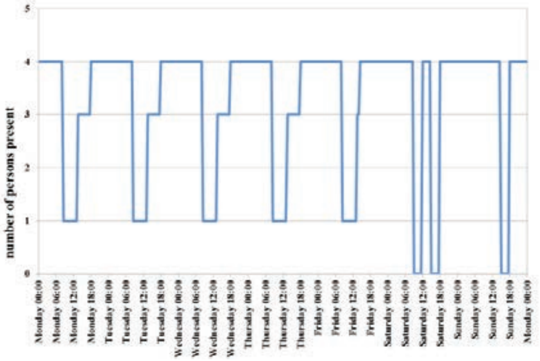
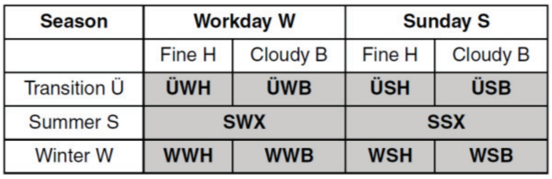


Fig. 1. Presence profile of the SFH.

2.3. Domestic hot water and electricity demand

The domestic hot water and electricity demand were calculated with the VDI 4655 [10] guideline. According to this guideline the annual energy demand for domestic hot water is 2000 kWh for a family of four. For electricity demand 3800 kWh/a [11] was assumed, which is a lot less than the 7000 kWh/a from the guideline, but far more realistic in a modern house. This amount was distributed over a year with the help of ten different type-days.



Season	**Workday W**		**Sunday S**	
	Fine H	Cloudy B	Fine H	Cloudy B
Transition Ü	**ÜWH**	**ÜWB**	**ÜSH**	**ÜSB**
Summer S	**SWX**		**SSX**	
Winter W	**WWH**	**WWB**	**WSH**	**WSB**

Fig. 2. Type-days according to the VDI 4655 [10].

Each type-day has its two specific normalized demand profiles for DHW and electricity in kWh/min which were calculated into l/s (hot water) or kW (electricity). The water volume flow was calculated with 45°C as tapping temperature and 10°C as incoming temperature. The type-days were distinguished between three characteristics: season, day of the week and cloud cover. In figure 2 the ten type-days and their characteristics are shown. With the help of the TRY of Dresden and a calendar the days of the year 2011 were divided into one of the ten type-days and an annual domestic hot water and electricity profile was generated.

2.4. Heating system

The SFH was heated by an underfloor heating system. The heat output was 4.9 kW since the heating system has twice the area of the building's footprint and 35 W/m² specific heating power. The system flow temperature is 35°C and runs with water (system capacity 150 l). The room set-temperature was 21°C controlled by a hysteresis of -1 K.

2.5. Hot water storage

The storage of 750 l supplies hot water for tapping and the heating system. It was loaded by the SOFC and a condensing boiler. It was simulated with ten layers and the model took into account that there is heat exchange between the layers and mixture of layers because of the bouyancy force, both due to temperature differences in the layers [12]. The heat losses of the insulated storage were assumed to be 1 W/K, while the boundary temperature of the storage was 18°C. The heat storage management differed for all three simualtions with the SOFC. For the reference case and the case without a fuel cell, the 8th layer of the storage should supply 60°C with a temperture hysterese of +-3 K. For the 45°C case the 6th layer should have 45°C and for the 35°C case the 5th layer should have 35°C, each with an hysterese of +-5K.

The heat for the domestic hot water is extracted out of the storage by an heat exchanger which works like a continuous-flow water heater. The inlet of the flow water heater is at the bottom (1st layer) and the outlet is at the top of the storage (10th layer). The underfloor heating system is connected directly to the storage. It gets its water from the 7th layer and returns it to the 3rd layer. The fuel cell is also connected directly to the storage and since the fuel cell needs cold return temperatures the inlet of the return temperature is at the bottom. The outlet was located only a little higher at the 3rd layer due to the low thermal power. Finaly the condensing boiler is directly connected to the cold water at the bottom, so that the condensing boiler receives low temperatures. The return of the condensing boiler was fed into the storage at the top.

2.6. Fuel cell

The SOFC is fueled by natural gas. Its electrical output is a constant 1.5 kW and cannot be switched off. The thermal output varies with the return temperature of the water to the fuel cell. The formula for the thermal power is given in equation 1 [3].

$$P_{th} = \text{-}0{,}3205 \times \mathrm{t}_{\mathrm{return}}{}^{2} + 3.8134 \times t_{\mathrm{return}} + 863.05\,[\mathrm{W}] \tag{1}$$

2.7. Condensing boiler

The condensing boiler is also fueled with natural gas and has a power of 13 kW. The annual efficiency was assumed to be 96 %. The boiler is operated by the storage management. The condensing boiler only switches off independently as the flow temperature reaches 65°C or the return temperature 60°C. The volume flow is regulated by the flow temperature. At 60°C the volume flow was maximum of 3 m³/h and at 50°C minimum of 0.9 m³/h. The values between were linear interpolated.

3. Results

3.1. Electricity

The simulation results in table 2 show that in all cases the fuel cells provide nearly the complete electricity demand for the SFH. Only a maximum of 3703 kWh/a (28 %) of the produced electricity was self-consumed, which will later have a great economically impact on the SOFC. The maximum of the total electricity demand occurred in the 35°C case, because extra electric energy was needed for the continuous-flow water heater.

Table 2. Electricity of the SFH.

Electricity	Reference case	45°C case	35°C case	Without SOFC case
Total demand [kWh/a]	3800	3800	3974	3800
Demand from the grid [kWh/a]	101	101	271	3800
Self-consumption [kWh/a]	3699	3699	3703	0
Produced by the fuel cell [kWh/a]	13140	13140	13140	0
Feed into the grid [kWh/a]	9441	9441	9437	0

3.2. Heat

The heat output of the fuel cell increased significantly with the configurations of the storage management. While in the reference case 35 % of the possible heat output of the fuel cell was reached, in the 45°C case it rose to 48 % and in the 35°C case to 56 %. The results are shown in table 3. It is also remarkable that less heat for domestic hot water was needed in the 35°C case than in the others. This gap was filled by the surplus electricity needs of the continuous-flow water heater from the grid and from the fuel cell (see table 2).

Table 3. Heat of the SFH.

Heat	Reference case	45°C case	35°C case	Without SOFC case
Total demand [kWh]	9200	9200	9030	9200
Demand of heating system [kWh]	7190	7190	7190	7190
Demand of domestic hot water [kWh]	2010	2010	1840	2010
Total production [kWh]	10112	9978	9674	9540
Production of the peak CB [kWh]	7488	6386	5515	9540
Production of the fuel cell [kWh]	2624	3592	4159	0

3.3. Primary Energy

The primary energy demand of the SFH without a fuel cell would be 10931 kWh/a. This can be reduced sustainably to 1134 kWh/a with the fuel cell in the Reference case, mainly due to the high primary energy factor of electricity of 2.4 compared to 1.1 of natural gas. In the other cases it was even reduced to 0. Theoretically it would produce primary energy as stated in the brackets behind the 0 in table 4, but that is practically not possible.

Table 4. Primary energy demand of the SFH.

Primary energy	Reference case	45°C case	35°C case	Without SOFC case
Demand [kWh/a]	1134	0 (-129)	0 (-1128)	10931

3.4. Costs

The first economic conclusion of the cost calculation done according to the guideline VDI 2067 [13] is that the cheapest system is the one without the fuel cell. Furthermore, the maximization of the heat output is economically not feasible. This is due to the higher electrical demand from the grid for the electrical heater. The demand cannot be satisfied by the fuel cell, because of the high power of the electrical heater. In addition the heater is an extra investment. In the economic context the 45°C case is the best solution with a fuel cell.

Table 5. Cost of the SFH heating system.

Costs/proceeds	Reference case	45°C case	35°C case	Without SOFC case
Capital-related costs [€]	2924	2924	3029	426
Demand-related costs [€]	1907	1834	1775	638
Operation-related costs [€]	827	827	858	113
Other costs [€]	145	145	145	145
Proceeds [€]	2080	2080	2081	0
Annual total costs [€]	3723	3649	3725	1320

4. Summary

This paper shows that the heat output of the fuel cell can be increased significantly by lowering the storage temperature to 35°C. This is also the best for reducing the primary energy usage. But when it comes to the costs of the cases the 45°C cases is the optimum. Nevertheless, this case is not directly transferable to reality since each SFH has its specific tapping profile, which impacts the required storage temperatures. Hence for each application the lowest possible temperature has to be determined, to increase the heat output of the fuel cell.

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