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Performance assessment of fuel cell micro-cogeneration systems for residential buildings

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Abstract

The reduction of greenhouse gas emissions in the building sector to a sustainable level will require tremendous efforts to increase both energy efficiency and the share of renewable energies. Apart from the lowering of energy demand through better insulation and fenestration, small combined heat and power (micro-cogeneration) systems may help improve the situation on the supply side by cutting both the non-renewable energy demand for residential buildings and peak loads in the electric grid. Though still on the brink of market entry, fuel cells are the focus of interest as the prime technology for such systems. In this study, a methodology for assessing the performance of such systems in terms of primary energy demand and the CO_2 emissions by transient computer simulations is established, and demonstrated for a natural gas driven solid oxide fuel cell (SOFC) and, to a lesser extend, a polymer electrolyte fuel cell (PEFC) home fuel cell cogeneration system. The systems were evaluated for different grid electricity generation mix types and compared to traditional gas boiler systems. The interaction with hot water storage and solar thermal collectors, and the impact of storage size and predictive control was analyzed. Typical heat and electricity demand load profiles for different types of residential buildings and occupancy were considered, and the sizing of the fuel cell system in relation to the heat demand of the building was analyzed. Primary energy savings decline for cases with lower heat demand and for cases with solar thermal systems, and peak for fuel cell systems sized in accordance with the heat demand of the building. Future assessments of fuel cell systems will need a refined methodology, and depend on realistic performance characteristics and models that accurately consider dynamic conditions.
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Keywords: Fuel cell systems; Micro-cogeneration; Thermal solar system; Performance assessment methodology

1. Introduction

The achievement of sustainability in the building sector necessitates a tremendous effort to reduce energy demand, boost energy efficiency and increase the share of renewable energy sources. While, on the demand side, it is widely accepted that the improvement of fenestration, heat insulation and air tightness in the building envelope takes top priority, wide-ranging options exist on the supply side for the combined provision of home electricity and heat and the integration of renewable energies (Fig. 1).

One option is cogeneration (combined heat and power generation). Oil and gas boilers are replaced by building-integrated micro-cogeneration units. The ‘‘waste’’ heat from electricity production is thereby fully integrated in the fossil energy supply for space and domestic hot water heating. Micro-cogeneration systems with internal combustion engines and stirling engines are available on the market. Though still on the brink of market entry, fuel cell systems are the focus of interest due to their potential for high electrical efficiency, low emissions and low noise. Various fuels may be considered in conjunction with the technology. Internal combustion engines mostly run on petrol (gasoline) or natural gas. Stirling engines accommodate a wide range of heat sources, ranging from fossil fuels to biomass and waste heat. Fuel cells normally run on hydrogen, but can also be used with natural gas or other fuels by external or internal reforming.

Micro-cogeneration fuel cell systems face a highly competitive environment that embraces traditional heating

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Nomenclature

Abbreviations and indices

Build	building
CC	combined cycle (gas and steam power plant)
DHW	domestic hot water
FC	fuel cell system, building equipped with fuel cell system
FCU	fuel cell cogeneration unit
El-Grid	electricity supplied from the grid
El-Surplus	net excess of electricity produced locally and delivered back into grid
GB	gas boiler, gas boiler system
LHV	lower heating value (of natural gas)
MFH	multi-family house
NG	natural gas
NGE	natural gas equivalents
NRPE	non-renewable primary energy
PEFC	polymer electrolyte fuel cell (or proton exchange fuel cell)
PH	Passive House
PI	proportional-integral
SC	solar collector
SFH	single-family house
SH	space heating
SIA	Swiss society of engineers and architects (building standards)
SOFC	solid oxide fuel cell
th	thermal
UCTE	Union for the Co-ordination of Transmission of Electricity

Parameters

DD	annual delivered energy demand per energy reference floor area (MJ/(m^2 a))
ND	annual net energy demand per energy reference floor area (MJ/(m^2 a))
PD	annual non-renewable primary energy demand per energy reference floor area (MJ/(m^2 a))
pef	primary energy factor (primary energy to delivered energy)
$Q_{\text{th-FCU}}$	annual thermal energy output of fuel cell per energy reference floor area (MJ/(m^2 a))
η_{NRPE}	primary energy performance factor

systems, such as condensing gas boilers or heat pumps and, for renewable energies, solar thermal and photovoltaic systems and biomass heating systems. A number of studies deal with building-integrated cogeneration systems and their environmental and economic performance in comparison to other supply options. In a study on municipal energy systems, Bruckner et al. [1] show that, alongside improved insulation to residential buildings, cogeneration offers considerable scope for energy savings and that the potential achieved by combining cogeneration and solar thermal systems is lower than the aggregate potential of the individual technologies. In a study on solar and hybrid district heating systems, Lindenberger et al. [2] show gas internal combustion engine micro-cogeneration units to achieve cost savings and 20% (non-renewable primary) energy savings compared to a configuration with gas-fired condensing boiler and national grid electricity with the German electricity production mix. The micro-cogeneration units also surpass the solar thermal system in terms of both cost and energy savings. In a more recent study, the same authors again single out cogeneration as a favourable option for supply-side reduction measures in local energy systems [3]. Decentralized cogeneration with small district heating networks may be a valuable alternative to micro-cogeneration units. The technological and environmental aspects of building-integrated cogeneration are also covered by Entress [4] and, comprehensively, by Pehnt [5,6]. The results of a German project on the role of fuel cells in cogeneration in terms of life cycle analysis, scenarios and market aspects are summarized in [7]. Buildings complying with the Passive House Standard [8] have a very low space heating demand. The energy demand is focused on electrical appliances and domestic hot water. Compact multi-functional units (for heating/cooling, ventilation and hot water) with an integrated heat pump are emerging [9]. The interaction with active solar systems (solar collectors and photovoltaic panels) is a key issue both for these compact units and for integrated micro-cogeneration systems [10].

Apart from the considerable potential of fuel cell units, a number of shortcomings require consideration when evaluating micro-cogeneration and, in particular, fuel cell systems: the problem of meeting peaks in electrical and heat demand (making, e.g. connection to electric grid and hot water storage), the lower electrical efficiency compared to larger power plants, the requirement for as few on/off operations as possible and low heat-up and cool-down rates, narrow ranges for power modulation and (still) high investment cost, high maintenance requirements and low durability. Energy management is necessary for both heat and electricity (see Fig. 1). Energy management algorithms for fuel cell systems must include demand and cost optimizations, hot water storage management and the prevention of unnecessary load cycles. Adaptive and predictive controls are applied in certain cases. Control is also a key factor when combining fuel cell and solar systems. As an approach to establish a methodology for the performance assessment of residential fuel cell systems, this paper highlights some of the critical issues surrounding the technologies for sustainable domestic buildings and shows the influence of key building, occupant and system parameters on the performance of a fuel cell micro-cogeneration system. In order to identify critical issues and promising configurations, the interaction of the fuel cell

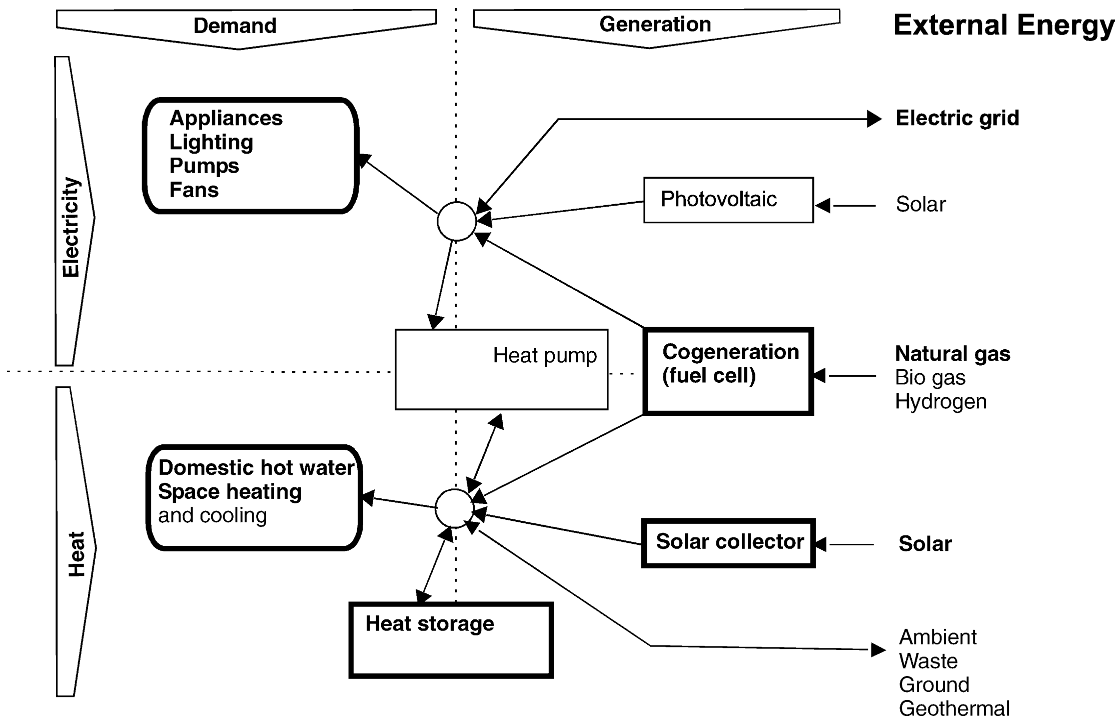

Fig. 1. Management of electricity and heat demand and generation for typical home energy systems. Energy resources and systems considered in this paper are depicted in bold.

system with the water storage and thermal solar collectors was analyzed using computer simulations and evaluated in terms of energy demand and CO_2 emissions. Typical heat and electricity demand profiles for different types of residential buildings and occupants were considered and compared with data for traditional gas boiler systems. While the study focuses mainly on conditions in Switzerland, many of the results and conclusions equally apply to a more general context. In addition, within the framework of IEA ECBCSAnnex 42 [11], the work presented in this paper is extended to take in other micro-cogeneration systems, buildings and demand profiles, and allow for additional boundary conditions and evaluation criteria.

2. Evaluation methodology

To facilitate assessment, a framework with evaluation cases and criteria was first established. Various configurations were then defined and modelled for simulation with the TRNSYS transient building and systems simulation code [12]. Third, the cases were simulated for typical periods or for a full year with hourly time step and then evaluated in

Table 1
Parameters and configurations considered in this study

Climate	Climate in Basel, Switzerland (moderate European climate)
Building types	(a) Single-family house (SFH) and (b) multi-family house (MFH)
Energy efficiency levels of building	(a) Building according to present average energy level of Swiss building stock, (b) building complying with target value for new buildings of present Swiss standard and (c) building complying with Passive House standard
Domestic hot water demand	Two profiles: (a) two-person household, both working and (b) four-person family; hot water for washing machine
Electricity demand for domestic appliances	In relation to energy efficiency level of building
Micro-cogeneration units	(a) SO fuel cell (1 kW_{El}) and (b) PEM fuel cell (4.5 kW_{El})
Additional heat generation	(a) Condensing gas boiler and (b) solar thermal collectors
Hot water storage size	(a) 300 L/dwelling, (b) 700 L/dwelling and (c) 1000 L/dwelling
Control options	Heat use is optimized for each configuration. Predictive algorithms and PI control
Operational options for micro-cogeneration unit	(a) Modulation range and (b) start/stop options
Fuel	Only natural gas is considered
Electricity mix	Non-renewable primary energy demand for generation of grid supplied electricity (a) European average (UCTE), (b) Swiss average incl. import and (c) state-of-the-art combined cycle power plant

terms of non-renewable primary energy (NRPE) demand and CO_2 emissions.

2.1. Description of evaluation cases

The parameters and configurations considered in this study are briefly outlined in Table 1 and described in more detail in the next section.

To allow clear identification of the impact of individual parameters, only single (or two) parameter sensitivities were determined. Hence, the selected configurations do not represent the type of finely tuned solution achievable through the application of multi-criteria optimization, e.g. as presented by Burer et al. [13] in the context of large-scale power supply. However, the control strategy and algorithms were adapted for each configuration so as to optimize operation in terms of heat use. The potential of predictive control algorithms was also analyzed.

2.2. Performance evaluation criteria

2.2.1. Non-renewable primary energy demand and CO_2 emissions

The different system configurations were evaluated in terms of the annual non-renewable primary energy demand and the related CO_2 emissions. The NRPE demand is expressed in terms of natural gas equivalents (NGE). A factor was applied to allow for the distribution losses of natural gas, as the supplied energy source. For grid electricity, the NRPE demand and respective CO_2 emission rates depend on the electricity mix. Three electricity mixes were considered: (a) European average (UCTE [14]), (b) Swiss average (Switzerland incl. import) and (c) an energy ratio for a state-of-the-art gas and steam combined cycle power plant (CC power plant). Facing the wide range of possible electricity mixes, the CC power plant mix suits best as a reference, as it is related to an electricity generation which is based on the same fuel as the cogeneration systems analyzed (mostly natural gas), it is clearly identifiable by its technical processes and it may be seen as another innovative substitution technology. The energy ratios used are taken from Ref. [15] and shown in Table 2. More recent energy ratios are given in the ecoinvent inventory for life cycle analyses [16]. They include a factor for the distribution of primary energy to the electric power plant plus a factor assuming 10% distribution losses in the electric grid. The Swiss mix is mainly based on nuclear and hydro power. Therefore, the CO_2 emission factor as well as the non-renewable energy factor are low, as hydro power is generally considered a renewable energy. For the CC power plant, an electrical efficiency of 58% (in relation to the LHV of NG fuel; this is the value used by the Swiss department of energy for a state of the art CC power plant), a factor of 13% for primary energy to plant losses according to the value for NG and a factor of 10% for grid distribution losses were assumed. A 10% loss factor was also applied for home-generated electricity delivered into and re-supplied from the grid. Unless otherwise stated, the results assume the UCTE electricity mix as the basic mix.

In the diagrams showing the NRPE demand, any net surplus of electricity delivered back into the grid (total electricity delivered to grid reduced by the above mentioned grid loss factor – total electricity supplied from grid) appears in the negative sector of the primary energy axis. Hence, the net surplus of electric energy, generated locally in the home and supplied to the grid, is considered in terms of the amount of NRPE, which it substitutes. The value for the net amount of electric energy supplied back to the grid is thus multiplied by the NRPE factor corresponding to the electricity mix considered. The same applies for the CO_2 emissions, where a negative value is the amount of CO_2 emissions, which can be saved by using the home-generated electricity. Embodied energies are not considered in this study; nor are any other types of emission, such as NO_x, CO and SO_2, as these are assumed to be of less importance for fuel cell units than for IC engine driven micro-cogeneration units. Also, in reality, the electricity mix (and also electricity prices) may vary quite much between peak demand times and night time, resulting in quite different primary energy demand figures. This has to be addresses in future studies.

2.2.2. Non-renewable primary energy performance factor

In order to evaluate how efficiently non-renewable primary energy is utilized to meet the annual electricity and net heat demand in buildings, a dimensionless non-renewable primary energy performance factor η_{NRPE} is

Table 2
Primary energy factors (primary to end energy ratios) and CO_2 emission factors

	Electricity mix for low-voltage electricity supply			Natural gas supply
	UCTE/ecoinvent	Switzerland incl. import	CC power plant	
PE factor pef (based on LHV) (MJ primary/MJ end energy)				
Renewable energy	0.25	0.61	0.00	0.00
Non-renewable energy	3.36	2.48	2.14	1.13
CO_2 factor (kg/MJ end energy)	0.154	0.0418	0.1288	0.0072
CO_2 factor, including combustion (kg/MJ end energy)				0.0697

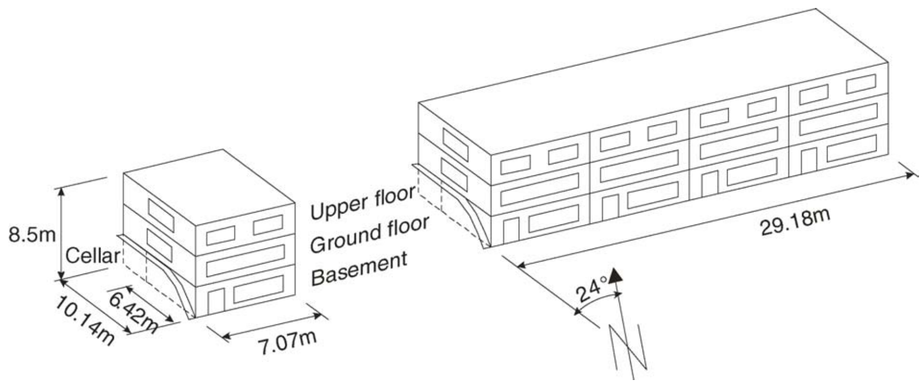

Fig. 2. Geometry and orientation of SFH building (left) and MFH building (right).

defined (Eq. (1))

$$\eta_{\mathrm{NRPE}} = \frac{\mathrm{ND_{El}} + \mathrm{ND_{SH}} + \mathrm{ND_{DHW}} + \mathrm{ND_{El\text{-}Surplus}}}{\mathrm{PD_{El\text{-}Grid}} + \mathrm{PD_{NG}}} = \frac{\mathrm{ND_{El}} + \mathrm{ND_{SH}} + \mathrm{ND_{DHW}} + \mathrm{ND_{El\text{-}Surplus}}}{\mathrm{pef_{El\text{-}Grid}}\mathrm{DD_{El\text{-}Grid}} + \mathrm{pef_{NG}}\mathrm{DD_{NG}}} \quad (1)$$

using annual net energy demand ND, annual delivered energy demand DD, non-renewable primary energy demand PD and primary energy factor (non-renewable primary energy to delivered energy) pef, in conjunction with indices for electricity (El), space heating (SH), domestic hot water (DHW), net excess of electricity produced locally and delivered back into the grid (El-Surplus), grid electricity (El-Grid) and natural gas (NG).

3. Building description and occupant-driven demand

3.1. Geometry and floor plan

Two building types are considered: (a) a single-family house (SFH) and (b) a multi-family house (MFH) with four dwellings. The geometric layout of the MFH is basically a multiplication of the SFH type building geometry (Fig. 2). All dwellings have the same useable floor area (188.8 m^2). The thermal properties of the building envelope (insulation and glazing), and the building equipment and appliances are adapted to the different energy demand levels of the buildings (Table 3). The energy reference floor area is the sum of the floor areas of all heated or air-conditioned rooms, based on the outer dimensions of the building including the exterior walls. Therefore, the values for the energy reference floor area for space heating differ slightly for the different building types due to the varying insulation and wall thicknesses.

3.2. Energy demand levels

Three energy demand levels, identical for the SFH and MFH building types, are considered: (a) energy level based on the average for the Swiss building stock (Swiss average), (b) target energy level for new buildings stated in the Swiss building energy standard SIA 380/1 [17] (SIA target) and (c) energy level compliant with the Passive House Standard, defined by the German Passive House Institute [8] (PH). The Passive House standard requires a space heat demand of less than 54 MJ/(m^2 a) (15 kWh/(m^2 a)) per net useable floor area (equivalent to 81% of the energy reference floor area for the SFH and 86% for the MFH building type), and a total demand for non-renewable primary energy of less than 432 MJ/(m^2 a) (120 kWh/(m^2 a)), with assumed primary to end energy ratios of 2.97 for electricity and 1.07 for natural gas. Occupant-driven energy demand profiles were adapted for the different building types such that the overall energy demand values given in Table 3 were met. The net space heat demands used for the evaluations are derived from the dynamic building and systems simulations.

Table 3
Energy demands per m^2 energy reference floor area, heat transfer coefficients (*U*-values) of exterior walls and glazing and solar heat gain coefficient (*G*-value) of glazing of the different building types

Building type	Swiss average building stock (Swiss av.)		SIA 380/1 target value (SIA target)		Passive House (PH)	
	SFH	MFH	SFH	MFH	SFH	MFH
Space heat demand (MJ/(m^2 a))	425	450	155	132	44	46.5
Electricity demand (MJ/(m^2 a))	120	130	80	100	52.8	55.6
U-value exterior walls (W/(m^2 K))	0.7	1.1	0.2	0.3	0.15	0.16
U-value roof (W/(m^2 K))	0.35	0.58	0.16	0.2	0.11	0.15
U-value glazing (W/(m^2 K))	2.8	2.8	1.4	1.4	0.7	0.7
G-value glazing	0.76	0.76	0.59	0.59	0.59	0.59

Table 4
Heat distribution and ventilation for the individual building types are as follows

Building type	Heat distribution	Ventilation
Swiss average	Water-based radiators/convectors (27% radiative)	Natural ventilation by window airing (2.1 $m^3/(h\ m^2)$)
SIA 380/1 target value	Floor heating, similar to concrete core cooling/heating	Natural ventilation by window airing (0.7 $m^3/(h\ m^2)$)
Passive house	Air heating	Mechanical balanced ventilation with heat recovery (heat recovery efficiency: 68%) (120 m^3/h per dwelling) 0.1 h^{-1} infiltration in zones with external doors

3.3. Heat distribution and ventilation

The assumed heat distribution and ventilation systems for the individual building types are described in Table 4 (similar for SFH and MFH).

3.4. Occupancy

Two occupancy profiles are considered: (a) two-person household, both partners working and (b) four-person family. Unless explicitly noted in the results, the four-person profile is the basic case for the SFH. The two-person profile is used only for the sensitivity analysis. In the MFH, two dwellings are assumed to be occupied by (a) and two dwellings by (b) type occupants. The occupancy profiles are defined on a weekly basis.

3.5. Domestic hot water demand

Two domestic hot water demand profiles are defined on a weekly basis in accordance with the occupancy profiles: (a) two-person household, both partners out at work during weekdays and (b) four-person family. The average hot water demand per person is taken as 40 L (10–60 °C; 3053 MJ/(a person)) for all building types. The washing machine is assumed to require an additional 36 L/week. Demand profile (b) is based on measurements [18], while profile (a) (Fig. 3) is adapted accordingly. For the MFH building type, two dwellings adopt profile (a) and two dwellings profile (b) with a shift between the two profiles of 1 h for the daily profile and of 1 week for the holidays (Fig. 4).

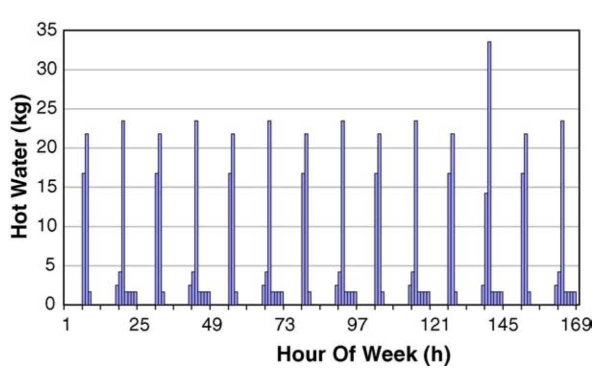

Fig. 3. Hot water demand profile for two-person household.

3.6. Electricity demand

The electricity demand is the cumulative demand imposed by household appliances, lighting and the power requirement for mechanical ventilation (0.4 $W/(m^3\ h)$ air supplied). The demand for household appliances was defined in relation to the occupancy, while the lighting demand was adjusted according to the available daylight. The dishwasher was assumed to be electrically heated. The washing machine was assumed to be connected to the domestic hot water system for all building types. Hence, the electricity demand is about 1.8 MJ (0.5 kWh) per complete washing cycle. No allowance was made for a tumbler. For each building and occupancy type, the demand profiles were defined according to these assumptions and adapted individually to meet the overall energy demand value given in Table 3.

3.7. Internal and external heat loads

Hundred percent of the heat from electrical appliances, lighting and occupants was assumed to contribute to the internal load, while heat gains from cooking and washing were only partially factored in. External loads were calculated by the TRNSYS building model. Sixty to 80% solar protection was applied with due consideration to the day-lighting requirements. Excessive indoor air temperatures in summer were reduced by increased natural ventilation.

4. System components

The installations considered basically comprise a home energy system, storage tank for space heating and domestic

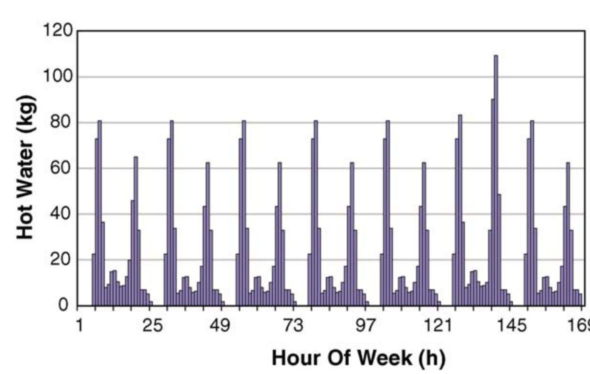

Fig. 4. Hot water demand profile for MFH (12 persons).

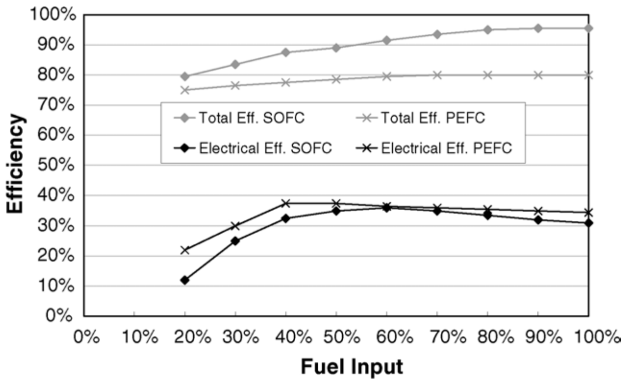

Fig. 5. Electrical and total (thermal and electrical) efficiency performance characteristics for SOFC and PEFC. Efficiencies are in relation to the lower heating value of the fuel.

hot water plus controls. The following home energy systems were considered: (a) solid oxide fuel cell (SOFC), (b) SOFC combined with thermal solar collector, (c) polymer electrolyte fuel cell (PEFC) and, as reference cases, (d) condensing gas boiler and (e) condensing gas boiler combined with thermal solar collector. The generation systems were characterized according to their thermal and electrical efficiencies as a function of the fuel input ratio (modulation rate) (see Fig. 5), and the control strategies and algorithms used.

4.1. FC systems

Many fuel cell system models are already available, some of which give detailed consideration to the electrochemical processes in the cell, the stack and the thermo-chemical processes in the fuel processor and other auxiliary components [19]. Fuel cell models are also integrated into tools for the development of controls for solar-assisted cogeneration [20]. More simplified models, adapted to the needs of system integration and overall system performance analysis, have been described in Refs. [21,22].

For the purposes of this study, the fuel cell system is modelled as a simple black box characterizing the energy input and the respective thermal and electric output. As many home fuel cell systems are only in the prototype or pre-series development phase, accurate and up-to-date performance characteristics are not available or prone to frequent modification. For this study, performance characteristics were defined on the basis of manufacturer data, Ref. (e.g. [23]) and the authors' own assumptions. They reflect the performance of today's prototype and pre-series products, while also allowing for the potential performance of future systems (this, for example, applies to the assumed modulation range). The nominal electric and thermal power sizes for the selected SOFC and the PEFC, respectively, are quite different, however, they are adapted to two existing products. Two different power sizes were also selected to study the influence of the power size on the performance. The focus of the study is on the SOFC system, however.

4.1.1. SOFC

The considered SOFC has a nominal rating of 1 kW electric and 2.5 kW thermal power output. The assumed performance characteristics are given in Fig. 5 as electrical and thermal efficiencies (in relation to the LHV of NG fuel) in function of the modulation ratio (ratio of actual to nominal fuel input). A back-up heater (see Section 4.2) was assumed to cut in automatically if additional thermal power was needed. The generated electricity was directly used in the house or else delivered back into the electric grid. The electric grid was also used to cover peak demand.

A wide modulation range and instantaneous power output change capability (on the 1 h time step basis used in the simulations) were assumed. No dynamic effects were considered, neither for operation within the modulation range nor for start/stop, as only one stop cycle was assumed, in the SFH during holidays.

4.1.2. PEFC

The considered PEFC generates 1–4.5 kW electric and 1.5–7 kW thermal power. An additional heater was integrated as an additional thermal power supply (see Section 4.2). The generated electricity was directly used in the house or else delivered into the electric grid. The electric grid was also used to cover peak demand. A wide modulation range and instantaneous power output change capability was assumed (see Fig. 5). No dynamic effects were considered for operation within the modulation range. A maximum start-up and shutdown time of 1 h is assumed. No allowance was made for the losses from cooling after shutdown or for the additional heating energy needed for start-up. A large number of start/stop cycles may, therefore, lead to an underestimation of energy demand.

4.2. Gas boiler system

State-of-the-art gas boilers, condensing and modulating in a wide range, were used as benchmarks and as back up

Table 5
Lowest modulation power and nominal power of the gas boilers used for the different buildings

Building type	Swiss average building stock (Swiss av.)		SIA 380/1 target value (SIA target)		Passive House (PH)	
Lowest and nominal power (kW)	SFH	MFH	SFH	MFH	SFH	MFH
Reference used as benchmark	2.0–12.6	10.6–50.4	0.9–9	10.6–50.4	0.9–9	0.9–9
Back up heater for the FC system	0.9–9	10.6–50.4	0.9–9	2.0–12.6	0.9–9	0.9–9

heaters. The lowest modulation power and the nominal power for the different buildings are given in Table 5. The nominal utilization ratio is 108% (LHV) for all types. Dynamic thermal effects were modelled in relation to the capacities of the boiler and water circuit involved.

4.3. Storage tank

For all systems and building types, a cylindrical, stratified combination storage tank was assumed for the space heating and domestic hot water installation. The basic size was 700 L for SFH (tank height = 1.5 m) and 2800 L for MFH, which corresponds to 700 L per dwelling unit (height = 2.0 m). Sizes of 300 and 1000 L per SFH or dwelling unit (with similar heights) were used for the sensitivity evaluations. Eight-centimetre rock wool insulation (thermal conductivity 0.04 W/(m K)) was assumed for all storage sizes.

4.4. Combination with solar thermal collector system

The SOFC and gas boiler systems described above were additionally combined with a solar thermal collector and a stratified storage tank for heating and DHW, adapted to this application. The solar thermal system was dimensioned to cover 60–65% of the DHW heat demand. The solar collector is a typical modern flat plate collector, positioned on the roof along the building axis and with an inclination angle of 40°. Six-metre square of collector area per SFH or dwelling unit in the MFH were assumed. Pump and valve controls were optimized for each configuration, and predictive control was again applied. In the summer period, the SOFC was shut down for 125 days. The residual heat needed was, however, provided by the gas burner of the SOFC. For the cases considered, the residual heat requirement was in fact very low.

4.5. Control

For all cases, only a heat-following control strategy was considered. Given the adverse effects of start/stop operations on today's SOFC systems in terms of material deterioration, lifespan and maintenance cost, continuous operation was envisaged. This requires special control strategies. Fuzzy logic control seems a promising option to minimize cycled operation [24]. In this study, predictive energy management and control were considered as a means of fully exploiting the heat produced and avoiding heat dumping. While no predictive algorithms were implemented in the simulation, an ideal predictive control was emulated. In contrast to the real-life situation, climatic data were available in the simulation. The profiles of space heating, domestic hot water, electricity demand and gain from the solar collector were calculated in a first step with a separate pre-run, assuming an ideal control of the room temperature at 21 °C. Then the actual simulation was performed in a second step, considering the values calculated in the first step for a fixed prediction period of 5 days. To emulate a realistic predictive control, a tolerance band was then applied to this ideal control parameter values by a superposition of a random value with a linear increase of the deviation to ±20% at the end of the prediction period. Additionally, a random time shift was introduced with a linear increase of the deviation to ±25% with respect to occurrence in time at the end of the prediction period. This emulated predictive control was used in most of the cases analyzed. A proportional-integral (PI) control was implemented as a reference case for the predictive control. An individual heating curve was determined for each building. A target value for the storage loading, established on the basis of this curve and the 24 h average outside air temperature was used by a PI controller with anti-wind-up functions to define the actual modulation rate for the fuel cell or the gas boiler system.

5. Results

This chapter presents the results of the TRNSYS simulations for the different configurations and boundary conditions outlined above.

5.1. Non-renewable primary energy demand and performance factor

The SOFC and PEFC systems considered were evaluated in terms of their non-renewable primary energy demand when installed in SFH and MFH building types (Fig. 6). The results for the condensing gas boiler system are included as the reference case. Negative values for grid electricity demand result where a net surplus of electricity is delivered by the fuel cell into the electric grid. The overall MFH energy demand is slightly higher than for SFH due to the different occupant related demand profiles.

Fig. 7 shows, for the three types of electricity mix, the annual NRPE performance factor of the SOFC system and the reference gas boiler system (left) and the same figures as the percentage improvement compared to the gas boiler system (right).

Compared to gas boiler systems as the benchmark, the two fuel cell systems allow a reduction in NRPE demand and an increase in the NRPE performance factor for all building types and electricity mixes considered. The SOFC system achieved an up to 30% drop in NRPE demand and an up to 40% rise in the NRPE performance factor for low-energy buildings. Generally, the most significant reductions in NRPE demand result for SFH with UCTE mix.

The results for SOFC and PEFC are not directly comparable as the power sizes of the FC units are quite different. The PEFC can meet a large part of the demand in buildings with a high space-heating requirement. This, however, entails the generation of large amounts of surplus electricity, which is delivered into the grid. For the UCTE

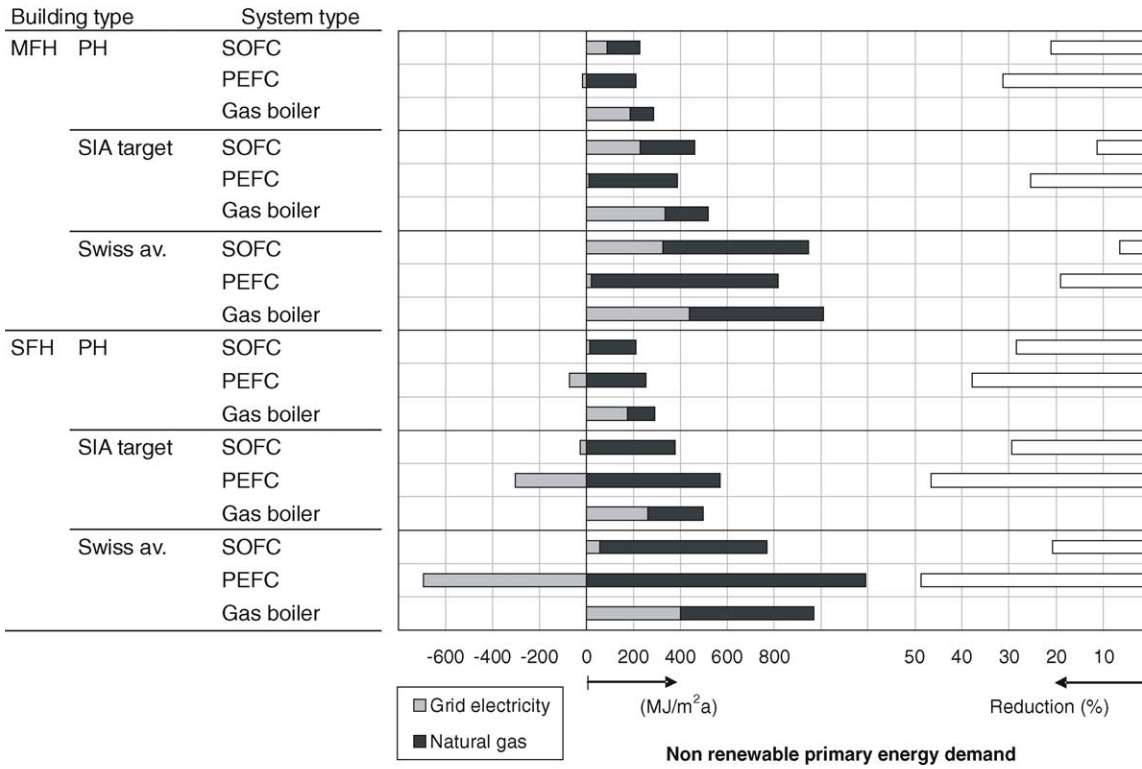

Fig. 6. Annual non-renewable primary energy demand (MJ per energy reference floor area) for SFH and MHF, equipped with SOFC, PEFC or condensing gas boiler system (left), and percentage reductions for SOFC or PEFC system compared to gas boiler system (right). UCTE electricity mix.

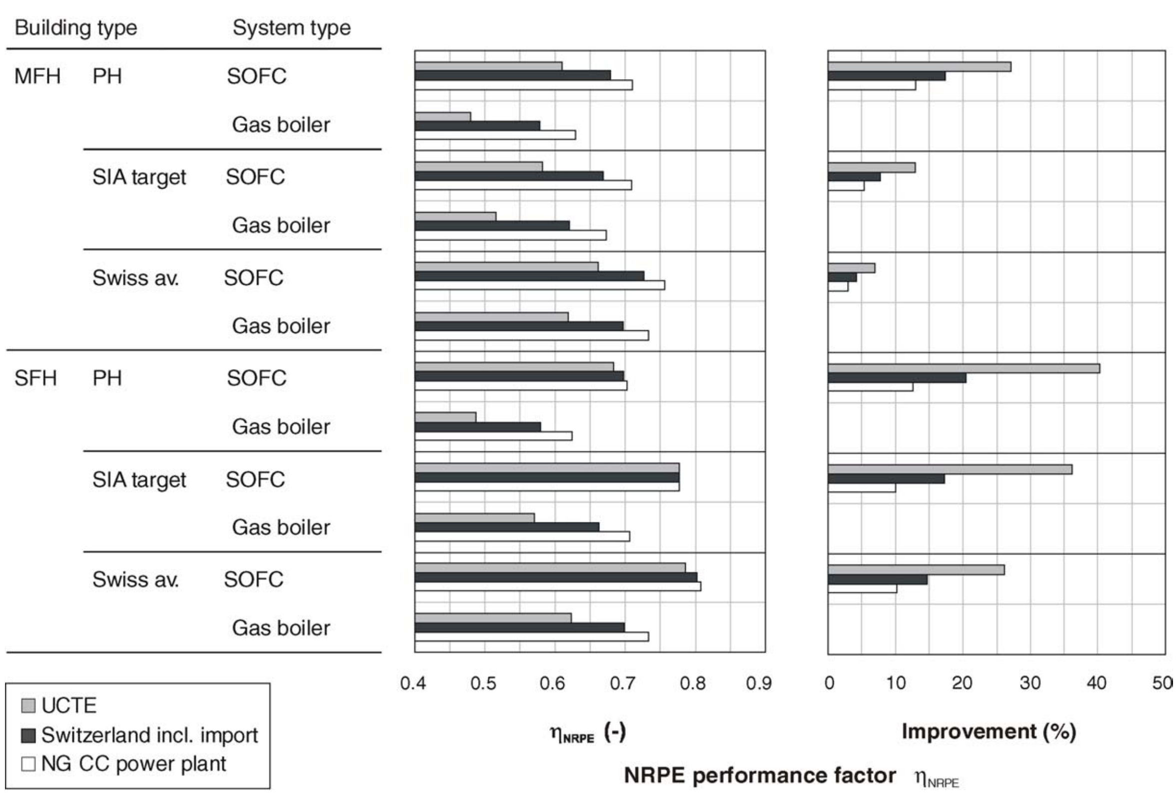

Fig. 7. Non-renewable primary energy performance factors for SFH and MHF, equipped with gas boiler and SOFC system. Absolute values (left); improvements in relation to gas boiler system (right).

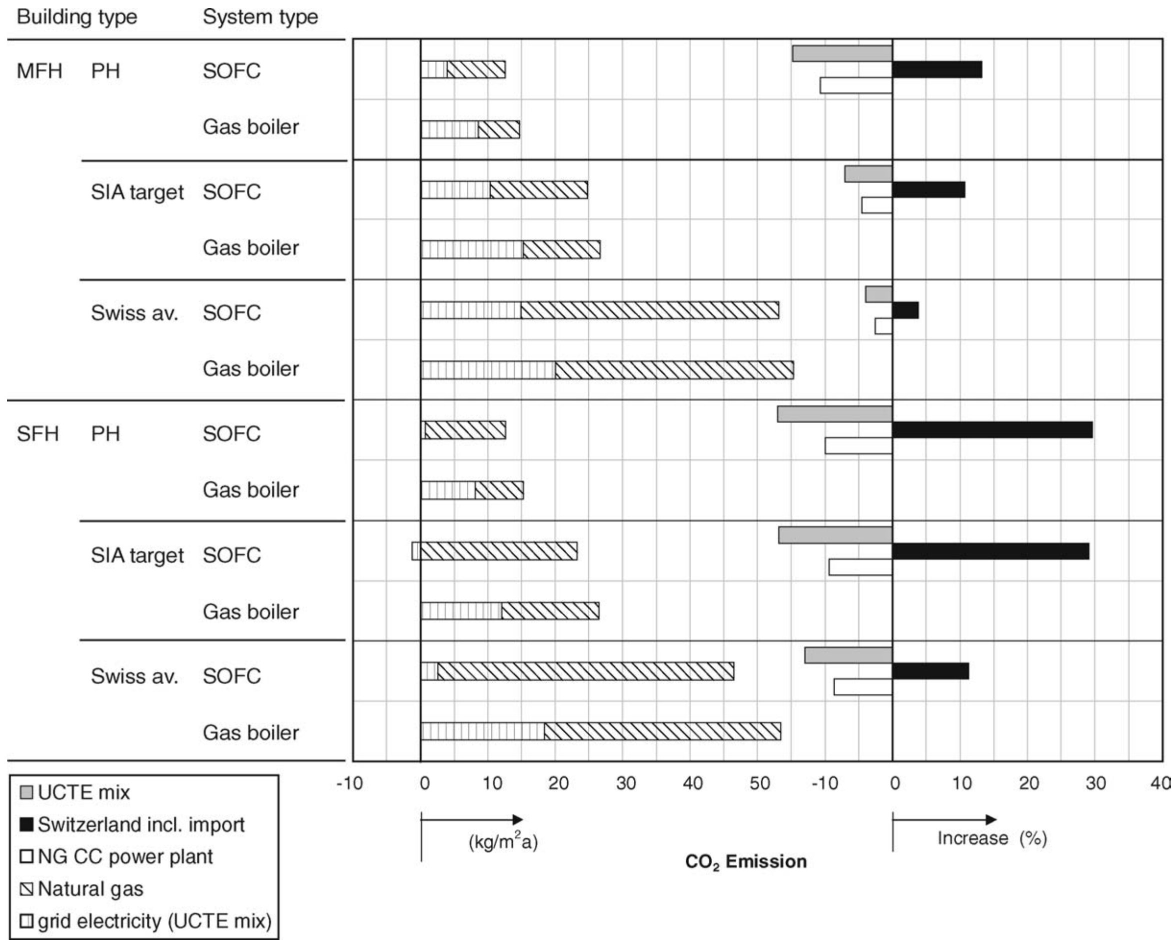

Fig. 8. CO_2 emissions for SFH and MHF, equipped with SOFC and gas boiler system for UCTE mix (left) and percentage reduction achieved by SOFC system compared to gas boiler system, for the three different electricity mixes.

electricity mix, this leads to even larger reductions (see also Section 5.7 and Fig. 14).

5.2. CO_2 emissions

The CO_2 emissions were calculated for the same SOFC and reference gas boiler systems using the primary energy demand and the emission rates specified for the different electricity generation mix scenarios given in Table 2 (Fig. 8).

For the UCTE and CC power plant electricity mixes, the CO_2 emissions are lower for SOFC than for the gas boiler system. However, for the Swiss mix, with its large proportions of nuclear and hydro power, higher emissions are clearly inevitable.

5.3. Combination with solar collector

The four system configurations without and with solar collectors (GB, GB&SC, SOFC, SOFC&SC) were compared in terms of NRPE demand for the SFH and MFH building types. Fig. 9 shows the reduction in NRPE demand between pairs of configurations, expressed as a percentage of the demand for the reference gas boiler system without solar collector (Eq. (2))

$$\frac{PD_{\text{System II}} - PD_{\text{System I}}}{PD_{GB}} \times 100\% \tag{2}$$

Starting from the gas boiler system, an initial reduction can be achieved through one of the following two options: (a) replacement of gas boiler by SOFC or (b) combination of gas boiler with solar collector (GB&SC). Which of these two options is more favourable depends on the NRPE factor of the grid electricity. A further cut can be achieved through combination of the fuel cell with a solar collector (SOFC&SC). The resulting reduction in the second step is much smaller if the more favourable option was selected in the first step (compare, e.g. first data set ‘‘(SOFC-GB)/GB’’ with third data set ‘‘(SOFC&SC-SOFC)/GB’’ in Fig. 9).

In general higher reductions result for SFH. Not surprisingly, the integration of solar collectors always lowers the NRPE demand. However, in the summer period, the heat provided by the solar collectors increases, thereby pushing down the number of annual full-load operating hours of the FC and raising the amount of the electricity supplied from the grid (with a high NRPE factor). Hence, the benefits of the fuel cell system compared to the gas boiler

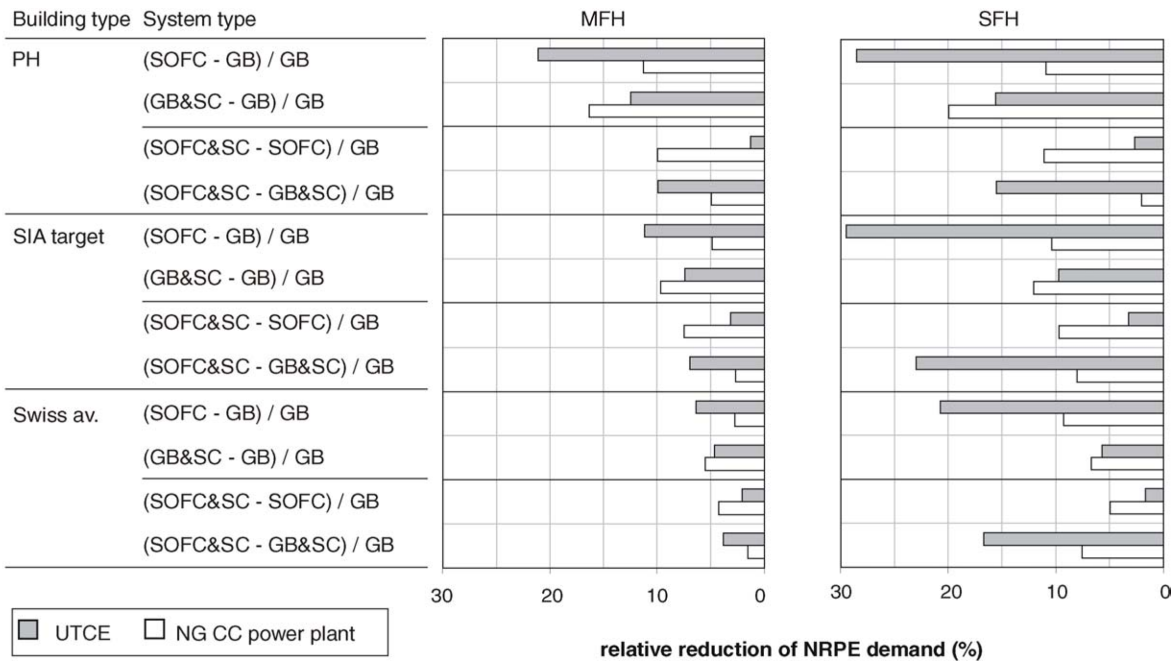

Fig. 9. Comparison of different systems without and with solar collectors (“&SC”) in terms of NRPE demand, expressed as percentage of NRPE demand reduction in relation to standard gas boiler system without solar collector (GB). Example: “(SOFC&SC-SOFC)/GB” is NRPE demand reduction for SOFC system with solar collector (SOFC&SC) compared to SOFC system without solar collector (SOFC), in relation to demand of gas boiler system (GB).

system are less significant for configurations with than for configurations without solar collectors (compare, e.g. first data set “(SOFC-GB)/GB” with fourth data set “(SOFC&SC-GB&SC)/GB” in Fig. 9).

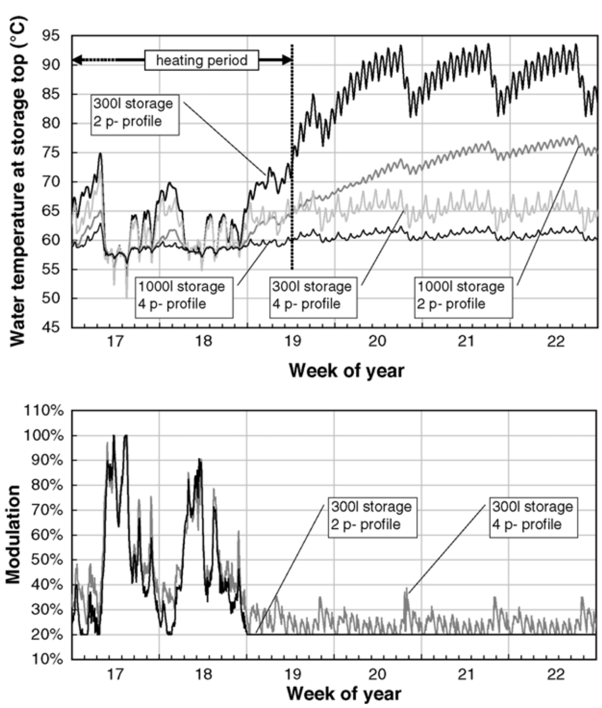

Fig. 10. Typical sequence of water temperature at top of hot water storage tank (top) and respective modulation of FC unit (bottom) for a few weeks in summer period, considering two demand profiles and two storage sizes. SIA target value, SFH building type with SOFC system.

5.4. Influence of water storage size

Especially in the case of the SOFC system, where on/off operations were to be avoided, the size of the hot water storage tank was expected to have a major impact on the quantity of FC heat output convertible into useful heat. Typical evolutions of the water temperature at the top of the stratified storage tank are shown in Fig. 10 (top) for the SOFC system over a period of several weeks in summer. The respective modulation ratios of the SOFC are given in Fig. 10 (bottom). The water temperature in the storage tank reaches high levels in the case of 300 L storage/two-person profile and only remains below 95 °C on account of the increase in the assumed DHW demand at weekends.

While, for smaller storage tank sizes, the FC has to run at low power for longer periods, storage losses also decline. The impact of storage size on NRPE demand and NRPE performance factor is illustrated in Fig. 11 for three tank sizes and the two DHW demand profiles considered (building type: SFH/SIA target). The size of the hot water storage is shown to have no significant influence on the NRPE demand for the analyzed systems. A large storage capacity improves the operation of the fuel cell. However, in the cases studied, these gains are more than offset by larger heat losses from the vessel. For better-insulated tanks, this would be different. With predictive control, the smallest storage performs best.

5.5. Influence of predictive control

Fig. 12 shows the NRPE demand for SFH equipped with SOFC and either emulated predictive control or PI control.

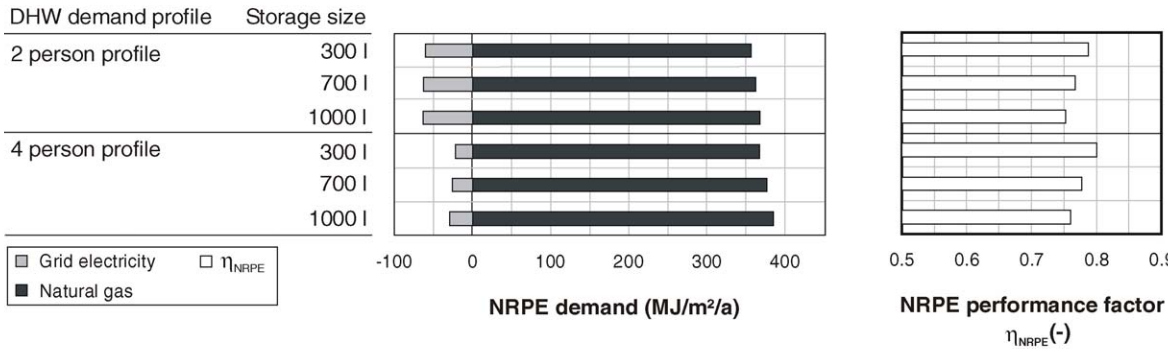

Fig. 11. Influence of storage size on primary energy demand for SIA target/SHF building type, for two-person and four-person family DHW demand profile.

Predictive control was assumed to be particularly important in the case of SFH, where an empty building, and consequently zero DHW demand may result in the hot water generated by the SOFC exceeding the storage capacity. However, the results show that the type of control has little effect on the primary energy demand for the systems analyzed, only for the low energy houses the predictive control leads to improved energy efficiency. The reasons for this have to be further investigated.

5.6. Part-load operation and equivalent annual full-load operating hours

Fig. 13 (left) gives the distribution of the modulation ratio (ratio of nominal to actual part-load fuel demand) of the SOFC system, operated under the premise that as much of the SOFC-produced heat as possible is used in the building. Fig. 13 (right) gives the modulation distribution for the combined SOFC-solar thermal system, operated under the same premise. Table 6 gives the equivalent annual full-load operating hours for the different buildings and the two occupant demand profiles in SFH, for both SOFC and combined SOFC-solar collector system.

It is evident that, for the SFH buildings with low heat demand, the FC operates at part-load for a large proportion of the year, which in turn suggests that the SOFC considered is somewhat over-sized. The SOFC can meet a large part of the demand in buildings with a high space-heating requirement. This, however, entails the generation of large amounts of surplus electricity, which is delivered into the grid. With the solar thermal system, the percentage of equivalent full-load operation time decreases even further.

5.7. Influence of the power size of the fuel cell unit

In order to get a qualitative impression of what fuel cell system power size achieves the maximum NRPE reduction for a given building energy demand, a simplified approach was selected, based on steady state spreadsheet calculations for annual energy values, not on detailed TRNSYS simulations. First, the difference between the annual NRPE demand of the building equipped with the fuel cell system (PD_{FC}) and the annual NRPE demand of the reference building with the gas boiler system (PD_{GB}) is normalized to the annual demand with the fuel cell system (PD_{FC}). This normalized difference is then plotted as a function of the ratio of the annual thermal output of the fuel cell cogeneration unit ($Q_{th\text{-}FCU}$) to the annual heat demand of the building (space heating and domestic hot water) ($ND_{th\text{-}Build} = ND_{SH} + ND_{DHW}$) (Fig. 14). The ratio of electric demand to heat demand is kept constant at the level valid for the respective building type, as specified for the detailed simulations with TRNSYS. Also, the values for the electrical and thermal efficiencies of the fuel cell unit as well as the thermal efficiency of the gas boiler and the amount of the electric energy cell instantly consumed from the fuel cell

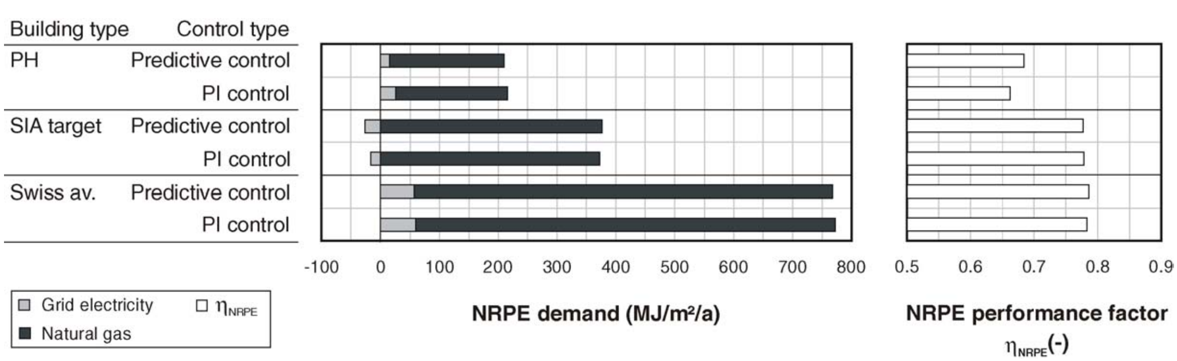

Fig. 12. Non-renewable primary energy (NRPE) demand and NRPE energy performance factor for SFH equipped with SOFC system with predictive and PI control.

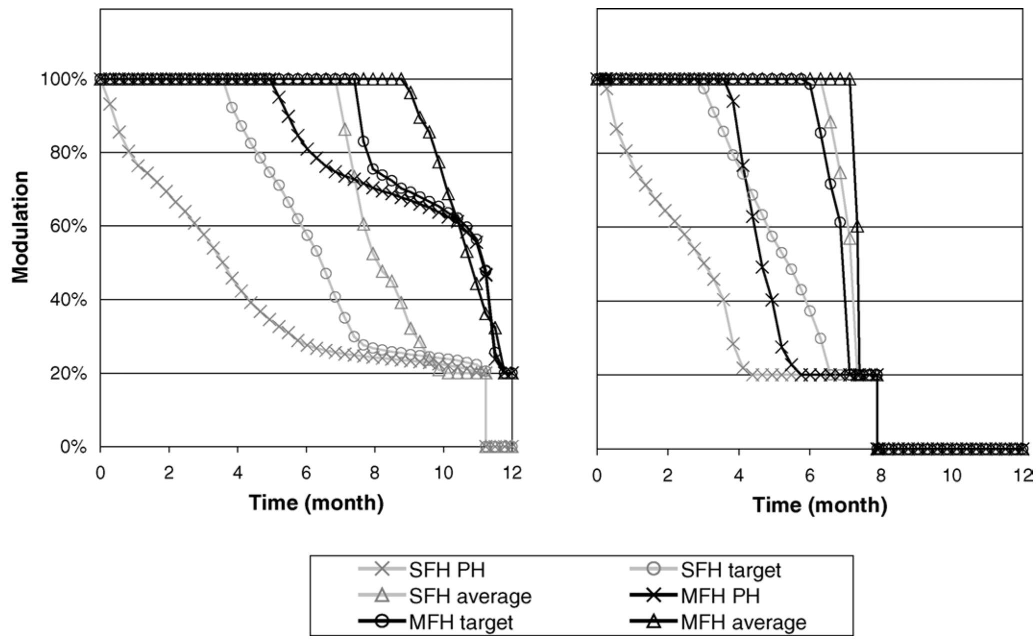

Fig. 13. Histogram of part-load (modulation) ratios for SOFC system in heat-following mode, for 1-year operation period for building types considered: without solar collector (left), with solar collector (right).

(without ''storing'' it in the grid) are derived from the annual energy values of the TRNSYS simulations. Fig. 14 shows the curves for the three SFH building types, for the UCTE mix (left) and CC plant mix (right).

The most significant reductions in NRPE demand result for cases where the thermal energy output of the fuel cell matches the building heat energy demand (space heating and domestic hot water). With dynamic consideration this maximum reduction in NRPE demand would be reduced by storage and additional grid losses as the output and demand have also to be matched in terms of instantaneous power. While reductions are achievable for a wide range of fuel cell power sizes for the electricity mix with a high NRPE factor (UCTE), the achievement of NRPE reductions in the case of the mix with a low NRPE factor (CC power plant) depends on more accurate dimensioning of the fuel cell unit to reflect the thermal demand of the building. Heat recovery becomes irrelevant for substantially over-sized units and the achievable NRPE demand reduction (or increase) approaches a value, which is purely a function of the NRPE factors for grid electricity and for NG, and a function of the electrical efficiency of the fuel cell unit.

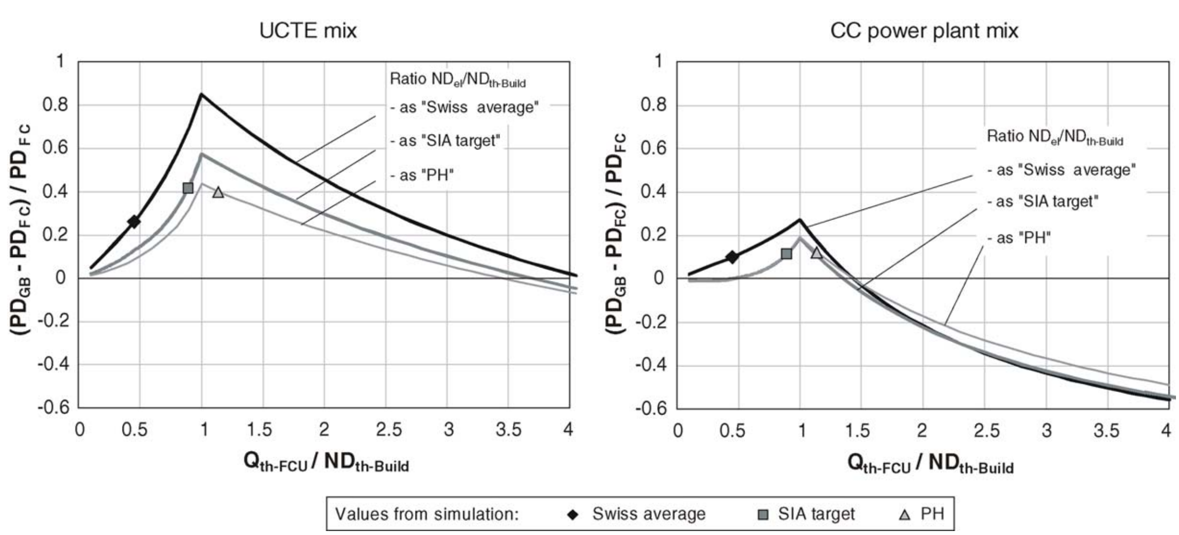

Fig. 14. Difference between NRPE demand of fuel cell system equipped building PD_{FC} and NRPE demand of reference building with gas boiler system PD_{GB}, weighted with PD_{FC}, as a function of ratio of specific annual thermal output of fuel cell cogen unit ($Q_{th\text{-}FC}$) to total annual heat demand of building ($ND_{th\text{-}Build}$), for three ratios of electric to heat demand according to SFH building types. Electricity mix UCTE (left), CC plant (right).

Table 6
Equivalent annual full-load operating hours of SOFC system and of combined SOFC-solar system

Equivalent annual full-load operating hours (h)	Swiss average building stock	SIA 380/1 target value	Passive House
SOFC only			
SFH: two-person demand profile	5947	4901	3243
SFH: four-person demand profile	6285	5124	3426
MFH	7839	7458	7027
SOFC and solar thermal collector			
SFH: two-person demand profile	5172	3893	2470
SFH: four-person demand profile	5193	3967	2438
MFH	5441	5057	3770

6. Conclusions

A methodology for assessing the performance in terms of primary energy demand and the CO_2 emissions has been demonstrated for two types of a natural gas driven home fuel cell systems. Compared to gas boiler systems as the benchmark, the fuel cell systems studied achieve a reduction of 6–48% in non-renewable primary energy demand for all building types and electricity mixes considered. The strong dependence of the achievable savings and, to an even greater extent, the resulting CO_2 emissions on the grid electricity generation mix was confirmed. The potential of the fuel cell systems to achieve primary energy reductions declines when used in combination with solar thermal systems. The influence of storage size and predictive control was much smaller than anticipated, even if continuous operation of the SOFC was assumed. The most significant reductions in non-renewable primary energy demand result for cases where the thermal energy output of the fuel cell matches the building heat energy demand (space heating and domestic hot water). For future work the methodology has to be refined and extended to further assessment criteria. The assessments then should consider different power sizes of the FC, the dynamic effects of fuel cell operation and the influence of time dependant energy generation mix and energy cost, local heat grid systems serving a number of low-energy houses and solar coverage for space heating as well as domestic hot water. Moreover, fuel cell systems should be compared with other micro-cogeneration systems, such as internal combustion engine and stirling engine driven units. However, the plurality of factors influencing system performance, coupled with the wide divergence between energy codes and electricity mix data at national, even regional level, makes it very difficult to compare systems and draw generally valid conclusions. Cases need to be studied individually by dynamic simulation. The availability of detailed models and simulation tools in the field of building-integrated cogeneration is thus of paramount importance.

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