ENERGY AND FINANCIAL PERFORMANCE OF MICRO-CHP IN CONNECTION WITH HIGH-PERFORMANCE BUILDINGS

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ABSTRACT

This paper deals with the issue of using micro-Combined Heating and Power plants (mCHP) in high-performance houses in terms of energy conservation and cost savings. On the one hand, since mCHP systems have only a modest electrical conversion efficiency, effective exploitation of the thermal output is critical to achieving high levels of energy efficiency. On the other hand, modern high-performance residential buildings display a heat-to-power load ratio that does not match well with the heat-to-power supply ratio of mCHP. First, results of whole-year simulation will confirm that current performance of available mCHP products is not enough to make them competitive with standard high-performance energy converters. A way to increase their efficiency is to integrate the mCHP system judiciously into the HVAC system. Based on previous R&D experience, several integration concepts will be described and assessed with simulation. Some of the results will be presented in the second part of the paper.

NOMENCLATURE

E	Expense
i	Current density
M	Mass flow rate
P	Primary energy
Subscript	
El	Electric
NG	Natural gas
Superscript	
Exp	Export
FC	Fuel cell
GB	Auxiliary gas burner
Imp	Import

INTRODUCTION

Energy consumption in the residential sector can be considerably reduced 1) by improving the thermal performance of the buildings or 2) by enhancing the efficiency of the energy supply.

On the one hand, new construction practices focus on lowering the room heat load of buildings by increasing the insulation layer of the envelop, reducing heat losses by ventilation and favoring passive solar gains. Research conducted within the framework of the joint activity IEA-SHC Task 28 and IEA-ECBCS Annex 38 show that households in newly erected buildings in countries with mild climate tend to need less final energy for heating purposes than for operating their domestic appliances (IEA 28/38, 2005). The heat-to-power ratio on the consumer side is consequently less than 1.

On the other hand, innovative supply technologies such as the micro-Combined Heat and Power (mCHP or residential cogeneration) are said to be the solution for the future because of their comparatively low environmental impact and high efficiency. The IEA/ECBCS Annex 42 declares that "the concurrent generation of electricity and heat from a single fuel source can reduce primary energy consumption and associated green house gas emissions" (IEA/ECBCS Annex 42, 2004). Moreover mCHP may contribute to alleviate the issue related to the general rise of electricity demand. Promising technologies for building cogeneration include fuel cells, Stirling engines, reciprocating engines and micro-turbines.

However, as mCHP systems have only modest electrical conversion efficiency values, the effective exploitation of the thermal output is critical to realising high levels of energy efficiency and the associated environmental benefits. The IEA/ECBCS Annex 42 has identified the following factors that may drastically influence the performance of the mCHP plant: the volume and thermal characteristics of the storage tank, the occupants' electrical usage patterns, the house's thermal characteristics, and the prevailing weather. Moreover, mCHP must compete against more traditional technologies on the marketplace such as condensing gas boiler, wood/oil furnaces, district heat, distributed electricity and renewable energy converters.

This paper deals especially with the issue of using mCHP in high-performance buildings (HPB). In this case, building construction design and HVAC design can not be handled separately but must be considered as a whole, taking the interaction between building thermal behavior and HVAC into account (integrated design). New simulation tools have been developed to balance the production and the consumption of both heat and electricity in residential buildings in terms of energy and of costs. The goal of the computation was to minimize the overall consumption of primary energy or the energy bills. New models have been worked out for different mCHP applications and linked with a whole-building model, that is able to describe several levels of thermal insulation.

First, simulation results will demonstrate that current performance of available mCHP products is not enough to make them competitive with standard high-performance energy converters such as condensing gas boiler in association with electricity from large-scale combined-cycle gas turbine. A way to improve their performances is to integrate the mCHP system wisely into the HVAC system, designed especially for HPB. Based on previous R&D experience, several integration concepts have been assessed by simulation. Some of the results will be presented in the second part of the paper.

CHP MODEL DESCRIPTION

SOFC plant

The Solid Oxide Fuel Cell (SOFC) operates generally between 800 and 1000 °C and belongs to the category of high-temperature fuel cells. At these temperatures the solid ceramic electrolyte is able to conduct ionized oxygen molecules. While hydrogen is oxidized at the anode, liberated electrons flow via an external circuit towards the cathode. If the SOFC is fuelled with natural gas, hydrogen is gained from reforming the hydrocarbons with steam. Because of kinetic and mass transport issues, not all hydrogen molecules can be converted by the cell. Therefore, it is assumed that the SOFC plant is equipped with a afterburner where the unconverted fuel is burnt. While electricity can be drawn at the cell terminals, useful heat is produced by cooling down the flue gas of the cell.

This study has been carried out by using a dynamic characteristic curve approach since fuel cells will be operated under nearly stationary conditions and the change in partial load occurs relatively slowly. The curves are presented in Fig. 1 and the dynamic features are gained from a highly detailed model, that can be found in (Sicre, 2004). Parameters of the model are given in Table 1. Efficiency hypotheses are taken from (Krewitt et al., 2004). These figures have been specifically released for SOFC mCHP but may be regarded as appropriate for other mCHP core technologies as well. It has been assumed that the SOFC system can be modulated in the range 20 to 100% of the nominal electrical power. Below 20%, the SOFC is held in the hot-standby mode, where it produces no electricity. The fuel consumption in hot-standby is dictated by the heat losses of the stack at around 1000 °C. These amount to approx. 200 W fuel (low heating value LHV) according to manufacturer's statement.

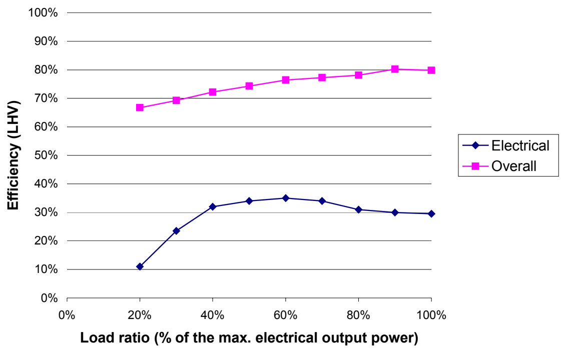

Fig. 1: electrical and overall efficiency characteristic curve of a 1 kWel natural gas fired SOFC system (according to (Erdmann, 2002) and adapted according guidelines of (Krewitt et al., 2004)

It is known that a SOFC plant at rest needs a while before reaching the operating temperature. Consequently a delay element has been included in the model to describe the start-up behavior of the plant. The plant can not deliver any useful energy (except exhaust heat) for 8 hours after turning the device on.

Table 1: Parameters of SOFC characteristic curve model

Nominal net power output	1000 W
Warm-up time for the stack initially at room temperature	8 hr
Thermal losses of the stack to the surrounding air through the thermal jacket	0.16 W/K
Maximal load variation rate	55 W / Min
Electrical efficiency at nominal power (LHV)	29.5%
Thermal efficiency at nominal power (LHV)	50.5%

High-level CHP controller

A controller model capable of matching the cogeneration system output to electrical demand, thermal demand, economic, or environmental criteria has been developed and implemented.

Independently of the objective criterion a peak load heater[1] is activated additionally as a backup, when

[1] In the case of high-performance houses, this will be a low-priced electric heating lance in the water storage tank, This choice will be justified later.

the temperature falls below the lower limit[2]. Similarly, whenever the heat demand vanishes, the SOFC plant is turned into the hot standby mode.

Three control modes (i.e. criteria) have been designed in order to modulate the output power of the plant optimally. The regulating variables are the natural gas mass flow rate M_{NG} and the current density in the stack i. The SOFC performance data in terms of electrical and thermal efficiency versus fuel input and current density are provided to the controller in the form of fitting curves.

The prediction of the household electricity consumption is derived from the previous time step value provided by a metering system.

Thermally driven mode

The control variable is the temperature inside the water storage tank. The set value can be maintained by varying the thermal output of the plant while operating the plant at the highest overall efficiency.

Mode minimizing usage of primary energy

Primary energy consumption occurs when natural gas[3] is fed to the SOFC or to the peak load heater or when electricity[4] is imported from the utility grid. Inversely, when surplus electricity is exported to the grid, this acts as a sink for the primary energy budget (see eq. 1). The task of minimizing the consumption of primary energy can be described as a function minimization problem with two independent variables. It is assumed that the plant is operated at maximal overall efficiency. Under that condition, the current density is known. This simplifies the problem greatly. The function minimization problem with one variable is solved by calculating the function value at defined operating points within the admissible power range and retaining the lowest value.

$$P_{NG}^{FC}(i, M_{NG}) + P_{NG}^{GB} + P_{el}^{Imp} - P_{el}^{Exp} \rightarrow \min \qquad (1)$$

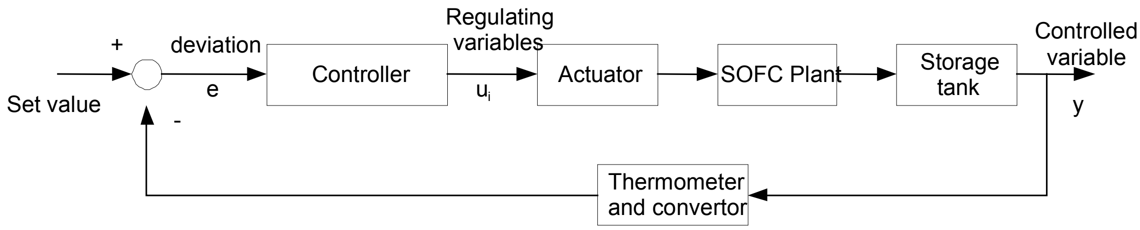

Fig. 2: Flowchart of control loop

Mode minimizing operating costs

Costs occur when the SOFC or the auxiliary heater is operated and when electricity is purchased from the utility. Inversely, the electricity exported to the grid is causes a financial bonus (see Table 2). The expense minimization task is summarized in eq. 2. Similarly to the primary energy task, the problem is simplified by adjusting the current density at the value for maximum overall efficiency. The solution procedure is identical to the one described above.

$$E_{NG}^{FC}(i, M_{NG}) + E_{NG}^{GB} + E_{el}^{Imp} - E_{el}^{Exp} \rightarrow \min \qquad (2)$$

Table 2: : Pricing of energy according to (Krewitt et al., 2004) (without VAT)

ENERGY	PRICING
Natural gas	3.8 c€/kWh (LHV)
Electricity from the grid	13 c€/kWh
Electricity exported to the grid	8 c€/kWh

HEAT AND ELECTRICITY LOADS

The heat load, that must be met by the heating system, consists of the space heating demand and the heat requirement for the production of domestic hot water (DHW).

Building model

This paper deals specifically with high-performance residential buildings. The "passive house" construction standard has been retained for this study. This kind of buildings is characterized by a very low space heating load (about 15 kWh/(m²a)) and a peak load typically below 10 W/m² (IEA 28/38, 2005). These specifications require a building envelope that is well insulated and airtight. For hygienic reasons, fresh air is delivered by a mechanical ventilation unit, that usually preheats the outdoor air in the winter. Even in Europe, it has become a trend in HVAC practice to distribute all of the heat required for space heating in HPB by means of hot air. Thanks to the low heating load, the temperature of the supply air does not need to exceed 50 °C. This

[2] The plant is operated at the efficiency point giving the highest thermal output.
[3] Primary energy conversion factor: 1.1
[4] Primary energy conversion factor: 3 (German national mean value)

practice is cost-effective since there is no need for radiators and heating circuits.

As the space heating load is comparatively low, heat losses during storage or distribution contribute strongly to the energy bills and therefore can not be neglected in the simulation. Moreover, internal gains such as electric appliances or solar radiation through the windows on one hand, and building and supply system interactions, such as slight rises of room temperature on the other hand, all lead to the necessity to use coupled building and HVAC transient models. The approach presented in this paper is the following: a simplified three-zone[5] building model with ideal heat distribution was believed sufficient for the preliminary feasibility study. Heat losses due to storage can be partly recovered thanks to heat flow to adjacent rooms. For the detailed analysis, a real apartment was described in a comprehensive five-zone building model including multi-zone airflow paths (s. Fig. 3). Heat was transported by means of air in the case of HPB.

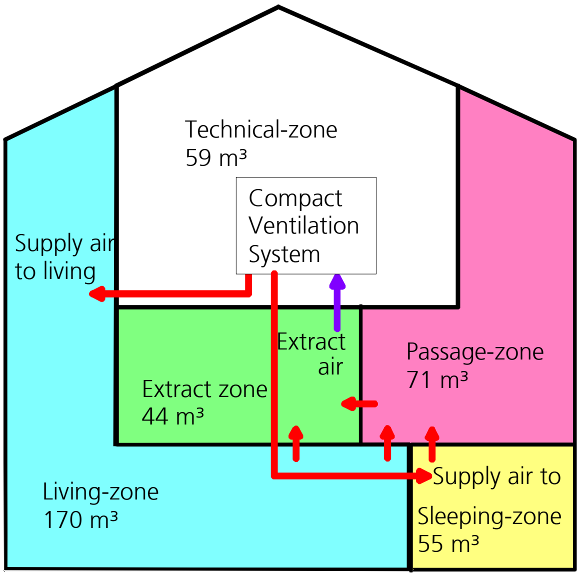

Fig. 3: Building with five zones and air flow paths of ventilation system (Ullah, 2004)

Domestic hot water profile

Generally, the consumption of DHW depends strongly upon the number of building occupants. Whole-year data set for DHW were read with a time step of 15 minutes. Data were derived from a statistical study conducted in 920 homes over several years (Mack et al., 1996). These data are divided into annual profiles (month values), and weekly profiles (daily values). In order to increase the data resolution, an hourly profile from the Central Swiss Laboratory of Lucerne, Switzerland was added. The mean DHW consumption amounts to 25 liters per day and per person at a temperature level of 60 °C. In the case study, the heat load for DHW approaches 2.6 MWh/a.

Electricity profile

Regarding the power load of the household, a rather advantageous pattern for CHP application has been opted for. With approx. 5.5 MWh, the annual consumption of the five-people household lies well above the German average. The reason for this was to depict a family that displays an advantageous power requirement for the operation of mCHP devices. The load pattern has been derived from a statistical investigation conducted by the German Electricity Association (VDEW, 1985). Data are available on a hourly basis. As a result short peak load, for instance when the electric kettle is operated, could not be considered fully dynamically in the simulation. Therefore the power export and import balances are slightly biased compared to real operation, but the precision of the calculation is sufficient to assess the annual performance of the CHP system within the framework of this feasibility study.

FINANCIAL VIABILITY OF MICRO-CHP

Operation and investment costs are the major issues affecting commercial success and broad market uptake of mCHP. Since mCHP technologies are in an early phase of development, retail prices are not known yet. Therefore, this study employs the method of allowable retail price. The allowable price is defined as the upper limit at which the mCHP can be offered in order that the customer gets the same benefit as if he used the baseline technology. The retail price basically depends upon the technology employed and upon the specification of the building. The income drawn from electricity export or household electricity substitution plays a major role and helps to offset the additional costs due to the more complex technology. The allowable retail price for the mCHP device is derived from the accumulated difference of annual total costs over a period of 15 years (expected lifetime of the mCHP). Simulation results such as fuel consumption, running time of the mCHP and the amount of exported or imported electricity serve as input for the operation costs. A more detailed explanation can be found in (Sicre et al., 2005)

[5] North zone, south zone and boiler room.

SYSTEM SIMULATION

Preliminary analysis

In order to rank the performance of the mCHP coupled with residential buildings, analogous simulation was conducted with different construction standards beginning with poorly insulated buildings (from the German building stock) labelled BS up to HBP. The former are seen as best-case buildings in term of heat load, the latter in terms of energy conservation. A medium construction standard called “low-energy house” (LEH) has been added to the investigation since it corresponds essentially to the current mandatory construction regulations for Germany.

They all have the same household electricity and DHW load pattern. The overall HVAC configuration remains very similar for the three houses. (s. Fig. 4) and only differs in the way the heat is distributed to the rooms: by means of hot air for HPB, with radiators for the rest. It consists essentially of a pressurized water heating system. In order to optimize the operation cycle of the mCHP, a large heat storage tank of 750 liters has been included. Domestic hot water is produced from a flat-plate heat exchanger. The temperature setting is 45 °C. Seasonal variation of the water inlet temperature is taken into account. The heat loads of the BS and the LEH are derived from measured load patterns. In the case of the HPB, the heat load is calculated by the three-zone model described above. The setting for the room temperature is 20 °C.

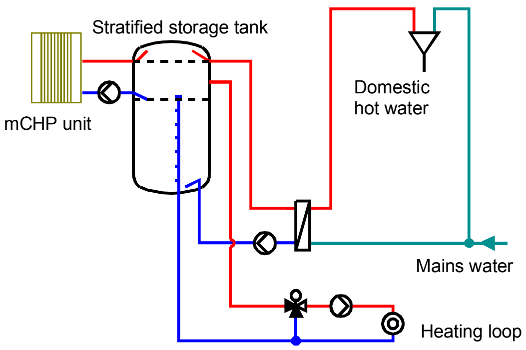

Fig. 4: Schematic diagram of the HVAC system

Detailed analysis

The scope of the detailed analysis is restricted to the HPB. The goal was to assess the benefits of integrating the SOFC stack into the ventilation systems using simulation-based results. The motivation to do so was primarily to make use of the heat lost from the stack operating at 800 °C by transferring it directly to the supply air. The expected result is a significant raise in fuel utilization efficiency.

Beside this, several system simplifications were carried out in order to lower the cost of the balance of plant (see Fig. 5). The air used to oxidize fuel is taken directly from the exhaust air stream of the ventilation system. In this way, a ventilator can be saved. The dosage of air for combustion is realized via a three-way valve (labelled Diverter) regulated by the SOFC controller. It is assumed that line gas pressure is sufficient to overcome the pressure drop of the stack. A flow control valve is used to regulate the fuel flow. This valve is also controlled by the SOFC controller. The exhaust heat from SOFC system is considered as the main heat source to meet the total heat demand of the storage tank. The released heat warms up the water of the tank (300 liters) that is used to meet both the space heating and domestic hot water demand of the household.

The thermal energy is taken from the hot flue gas of the SOFC system and is transferred to the storage tank by circulating water through an air-to-water heat exchanger. A 25 W variable-speed pump (Load Pump) circulates water in this loop, maintaining the temperature in an useful range. Operation of both the SOFC system and the load pump are controlled by the SOFC controller.

Besides the SOFC heating system, an electric lance (Electric Heater) is also used as a heat source. The lance adds heat to stored water if the SOFC heating system is not able to meet the total heat demand of the storage unit. The operation of the auxiliary heater also controlled by the SOFC controller that decides the rate of power at which the auxiliary heater must be run.

In the detailed study, the baseline system is a similar ventilation system but based on an exhaust-air heat pump, that is equipped with two condenser heat exchangers. One delivers heat to the supply air while the other provides heat to the water storage tank. This concept has been investigated comprehensively in (Buehring, 2001). It has been successfully implemented in commercial products. It is estimated that between 30% and 50% of German passive houses are equipped with such devices.

Simulation software

The preliminary analysis was carried out in ColSim, a modular simulation environment that has been developed at the Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany. ColSim has been primarily designed for the development of controllers for solar thermal systems. ColSim is available as public domain software and is delivered with its source code. It is written in ANSI-C.

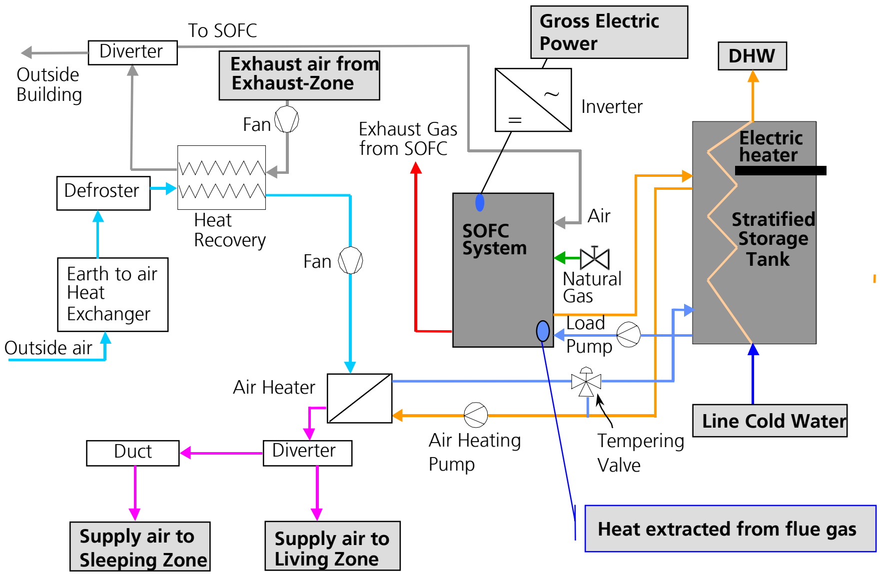

Fig. 5: Ventilation system with integrated SOFC for supplying heat and electricity to HPB.

The detailed analysis was made using TRNSYS and its comprehensive multi-zone building model.

The SOFC model and the CHP controller were developed in C++ and were compiled in the form of a DLL file, that was accessible for both programs.

Boundary conditions

The climate details are gained from a TMY[6] meteorological data set for the city of Frankfurt, Germany. Frankfurt is a representative location for average weather condition in Germany.

RESULTS ANALYSIS AND CONCEPT ASSESSMENT

mCHP boiler

The standard mCHP boiler (as conceived by many manufacturers) was modeled and simulated a whole year according to the settings documented in Fig. 4 for three different kind of space heating load. The baseline system for the computation of the retail price was a condensing natural-gas boiler and electricity from the public grid. The results have been summarized in Table 3. In the BS, the operation of the mCHP is barely restricted by the heat load. The running hours achieve a satisfactory value of more than 6000 hours a year. This is reflected positively in the allowable retail price. Compared to a condensing boiler that is priced at, say, 3100 EUR, the resulting price margin can reasonably cover the additional costs incurred by the rather complicated SOFC technology. As shown in Table 3, this statement is no longer true regarding LEH and HPB. From an environmental point of view, HPB features the lowest overall primary energy consumption[7], even if the 1360 kWh of produced electricity only meet approx. 25% of the domestic electricity consumption. Indeed the import of electricity from the public grid certainly adds to the primary energy balance, but not as much as the enormous space heating load of BS.

Keeping in mind that a condensing boiler in the same HPB would lead to a overall primary energy consumption of only 19 MWh/a (s. Sicre, 2004), the mCHP boiler in HPB is not convincing, neither from a point of view of energy efficiency nor from a point of view of financial viability.

Table 3 shows that an auxiliary heater is not necessary in the case HPB. To ensure security of supply, an electric lance will be added to the water storage tank in order to back up the SOFC during peak load periods.

Compact dwelling SOFC ventilation system

As seen in the previous paragraph, the computed allowed retail price of SOFC mCHP boiler in HPB seems to be definitively prohibitive from a point of view of manufacturing costs. If people do buy a SOFC mCHP boiler at the regular price, they should not expect to get any return of investment within the lifetime of the plant. This fact has motivated the attempt to simplify the SOFC system by mounting it in a ventilation system, developed especially for HPB. The baseline product for this study is a similar ventilation system but based on an exhaust-air heat pump.

The results of a whole-year simulation for both systems are summed up in Table 4. In order to provide heat to the HVAC system, the heat pump need 1.9 MWh of electricity. For the same heat load, the mCHP requires 9.6 MWh of natural gas, while producing significant amounts of electricity. In fact, in the case of the electric heat pump, almost twice as much electricity must be imported from the grid as in the case of mCHP. Both systems come up with a yearly primary energy consumption of 19 MWh as a

6 Typical Meteorological Year

7 Sum of primary energy due to usage of natural gas and electricity (household and HVAC)

result of the significantly different primary energy conversion factor for gas and electricity.

Table 3: Results of a whole-year simulation with the SOFC thermally controlled vs. the space heating load.

		BS	LEH	HPB
Space heating load	(kWh/ m²a)	220	78	11
Natural Gas CHP	(MWh/a)	25.1	20.0	8.6
Natural Gas Auxiliary	(MWh/a)	29.2	6.5	0
Net power output	(MWh/a)	6.2	4.7	1.4
Operation hours	(hr/a)	6220	4730	1360
Primary energy	(MWh/a)	59.0	32.0	20.1
Allowable price	(€)	4800	3360	1956

From the point of view of costs, the allowable retail price amounts to approx. 2.500 EUR for a 1 kW SOFC stack unit. It is difficult to draw conclusions on the viability of such a price since real production under mass-market conditions is hard to predict.

Compared to the preliminary analysis case, the compact dwelling SOFC ventilation system does achieve better results on average than the SOFC in the boiler with respect to both primary energy and economy. This is primarily due to a better utilization rate of the stack that results in a higher power production and secondly to a greater difference in total costs between the SOFC application and the baseline product.

A next step to raise the heat load (i.e. the operation hours of mCHP) is to dispense with the earth-to-air heat-exchanger (EHE). A way to do this is to equip the ventilation fresh-air inlet with an electric heater to prevent the incoming air from freezing and blocking the heat recovery with an ice layer. During the whole year, this additional heater requires as little as 40 kWh of electricity under Frankfurt weather conditions. This measure does not lead to significant rise in operation hours so the imported amount of electricity remains almost the same. However the consumption of natural gas increases slightly. Consequently, the overall primary energy consumption increases by almost 3%. However this measure may seem financially attractive since it eliminates the costs for burying an EHE in the garden.

Table 4: Results of the energy economy analysis of thermally controlled SOFC-mCHP application with 1 kW_{el} power output in combination with HPB. (EHE: Earth-to-air heat-exchanger)

		HVAC WITH HEAT PUMP	HVAC WITH MCHP	HVAC + MCHP - EHE
Electricity consumption	(MWh/a)	1.9	-	-
Natural gas consumption	(MWh/a)		9.6	9.7
Electricity import	(MWh/a)	7.4	3.9	3.9
Primary energy	(MWh/a)	19	19.2	19.7
Allowable price	(€)		2540	-

CONCLUSION

This paper deals with the issue of using mCHP in HPB. It presents a method to analyse the competitiveness of mCHP on the market-place in terms of energy conservation and costs. A prerequisite is a good knowledge of the eventual performances of the technology. Whole-year simulations provide information on the fuel consumption and yield of the mCHP. An economic analysis including capital and maintenance costs in comparison to a baseline technology, provides the allowable investment costs of the developed system.

This paper deals exclusively with SOFC mCHP systems, but the proposed method can be applied to other energy conversion systems for residential applications. It has been shown that, under the assumptions made, an SOFC ventilation system is in close competition with the baseline technology in terms of energy conservation. The commercial success of SOFC mCHP in HPB depends strongly on the actual production costs of the SOFC stack.

This paper has shown how integrated building and HVAC simulation can provide assistance to equipment manufacturers in their decision-making process about target customer and reasonable retail prices. Whole-year simulation gives insight into potential system simplification in terms of costs and energy saving.

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