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Vialetto, Giulio; Rokni, Masoud

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A NEW COGENERATION RESIDENTIAL SYSTEM BASED ON SOLID OXIDE FUEL CELLS FOR A NORTHERN EUROPEAN CLIMATE

Giulio Vialetto and Masoud Rokni*
* Technical University of Denmark, Department of Mechanical Engineering
Section for Thermal Energy, Copenhagen 2800, Denmark
MR:mek.dtu.dk

ABSTRACT

Energy saving is an open point in most European countries where energy policies are oriented to reduce the use of fossil fuels, greenhouses emissions and energy independence and to increase the use of renewable energies. In the last several years, new technologies have been developed, and some of them received subsidies to increase installation and reduce cost. This article presents an innovative cogeneration system based on a solid oxide fuel cell (SOFC) system and heat pump for household applications with a focus on primary energy and economic savings using electric equivalent load parameter which is a function of the electricity and heat demand of the user, and allows different operation strategies to be considered. The proposal is to maximize the efficiency of the system and to make it profitable, even though technologies with a high purchase cost are considered. Simulations of the system are performed under different strategies at a resort located in a northern European climate (Denmark) to cover electricity, space heating and domestic hot water (DHW) demands. The results of these simulations are analyzed with thermodynamic and techno-economic benchmarks, considering different economic scenarios. The calculations show the high primary energy saving and profitability of the system.

INTRODUCTION

European countries are working to improve their energy policies: one of the themes is energy saving. Publication of the 2010/31 EU Directive is proof of the importance of energy saving in buildings. Insulation and/or more efficient technology (for example, condensing boilers, heat pumps or district heating related to a cogeneration power plant) could help reach these goals. There is currently an increased interest in developing a distributed system of smaller-scale facilities at a single location, allowing electricity and heat to be produced and distributed close to the end user and thereby minimizing the costs associated with transportation (Sanchez et al., 2008) and (Rokni, 2013). Micro CHP (combined heat and power) for household application falls also within this category. However, micro CHPs face the problem of heat-to power ratio that varies during the day as well as between the seasons due to the different consumption (Lee and Strand, 2009).

Numerous studies have been investigated in the literature on SOFC-based hybrid systems that suggest high thermal efficiencies. The majority of these studies use gas turbines as the bottoming cycle for SOFCs resulting in pressurized SOFC systems see e.g. (Riensche et al, 2000). Steam turbines and organic rankine cycles (ORC) have also been used as a bottoming cycle, which resulted in non-pressurized SOFC stacks, see e.g. (Rokni, 2010). A few studies have been performed that utilize a Stirling engine as the bottoming cycle and the fuel cell as the topping cycle, see e.g. (Rokni, 2013).

However, studies on combined SOFC-heat pumps are very rare, e.g., (Cooper et al., 2014) studied the operating conditions and performance of domestic heating systems with heat pumps and SOFCs as micro-cogeneration systems in buildings. The emphasis was to indicate the effect of operating conditions and methodologies rather than the detailed analysis and performance of the units. Other studies in SOFC for residential applications as cogeneration system can be found in e.g. (Bompard et al., 2008), in which the feasibility of a 5 kW SOFC from economical view was considered. A micro CHP with SOFC for single-family detached dwellings was studied in (Farhad et al., 2010), while the impact of heat-to-power ratio for a SOFC based micro CHP for residential application in European climate was elaborated in (Liso et al. 2011). Variation of the heat to power output ratio to match the electric and hot water demands of a Japanese residence can be found in (Lamas et al., 2013).

In this article, an innovative system is proposed, based on a solid oxide fuel cell (SOFC) and a heat pump. A heat pump, in particular an electric heat pump, is chosen as a backup device to cover the heat demand of the user. The aim of this study is to not only to present a system suitable for residential applications but also to decrease mismatching between the electricity and heating demand of the user, which is a critical problem in cogeneration systems and particularly in small micro CHP systems. Although the electricity consumption of the user increases when a heat pump is used, heat pumps have considerably higher energy efficiency versus conventional electric heaters, such as electric resistors.

OVERVIEW OF THE SYSTEM

The main components of the system proposed here are a solid oxide fuel cell (SOFC) plant, heat pump and water tank. The SOFC plant is fed by natural gas for electricity production and for driving the compressor of the heat pump, while its waste heat is recovered for water heating and is used for space heating and domestic hot water (DHW). Fig. 1 displays how they are connected to each other as well as to the grid. The heat pump is used only when the heat available from the SOFC is lower than the heating demand. The water tank stores hot water when the SOFC produces more heat than the user requests. The system is connected to the grid so that when the electricity requirement (from both user and heat pump) exceeds the electricity production from the SOFC, electricity can be drawn from the grid. In the case where the request is lower than production, electricity will be supplied to the grid without considering any type of subsidy, such as net metering.

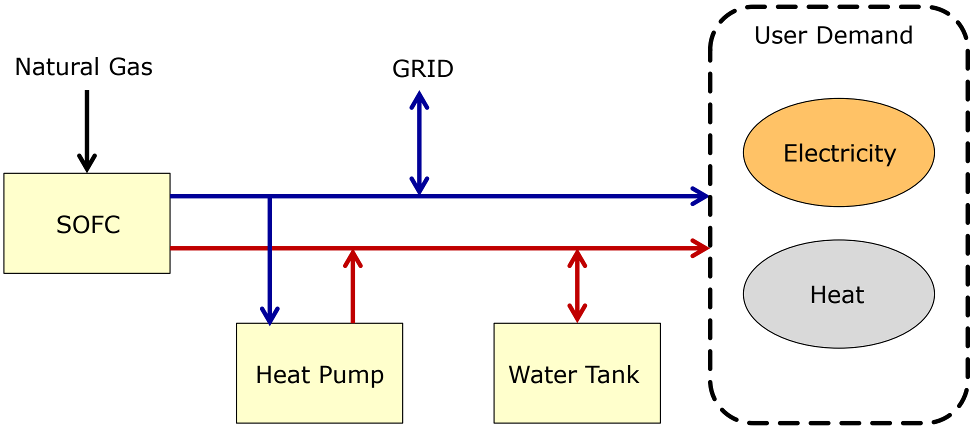

Figure 1. General scheme of the system proposed here with the main component and energy flows: fuel (black), electricity (blue) and heat (red).

SOFC System

An SOFC system fuelled by natural gas is simulated using the in-house program called DNA (Elmegaard and Houbak, 2005). Figure 2 represents the system. Fuel is pre-heated using exhausted off-fuel out of the anode side of the fuel cell using the fuel preheater heat exchangers (FP and AP). FP increases fuel temperature to the desulfurizer operating temperature while AP brings fuel temperature to CPO operating temperature. The fuel is then desulfurized to prevent SOFC poisoning. A catalytic partial oxidizer (CPO) converts fuel heavier hydrocarbons into CH4, H2 and CO. The desulfurized and reformed fuel enters then the anode side of the fuel cell. Air for the CPO is preheated (in AP) using the off-fuel coming out of the anode side of the fuel cell. Such preheating increases plant efficiency by recovering some of the heat from the off-fuel stream. On the cathode side air is first compressed and then preheated in the cathode preheater (CP) before entering the fuel cell. A burner is used to burn the unused fuel out of the anode side of the fuel cell. Heat is recovered by a heat exchanger (HEAT RECOVERY) for both DHW production and space heating. Detailed description can be found in (Rokni, 2014). A SOFC stack model type developed at DTU Risø National Laboratory is used here (Petersen et al. 2006).

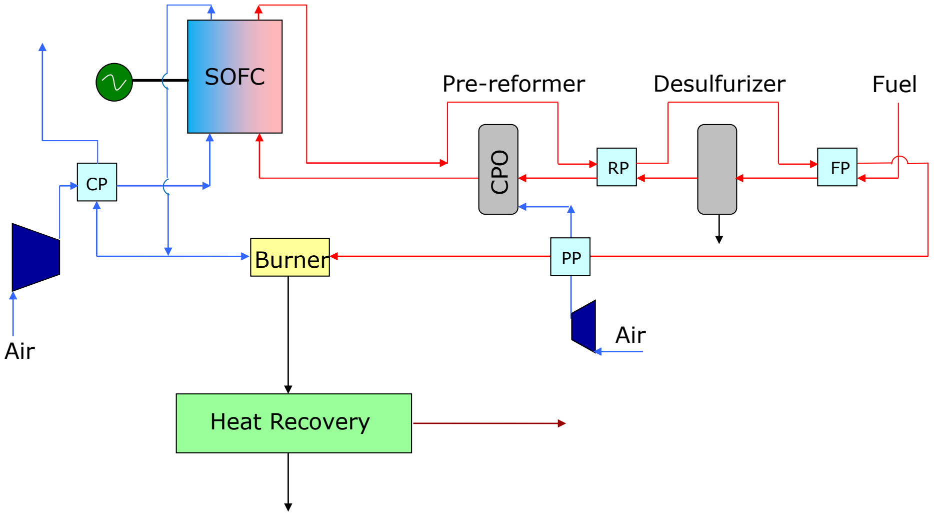

Figure 2. Representation of the SOFC system. CP = cathode preheater, FP = fuel preheater, AP = air preheater, RP = reformer preheater.

The SOFC system has electricity consumption because of auxiliary components (air compressors) and DC/AC conversion (inverter). Results from the study of (Rokni, 2013) shows that the electricity consumption for auxiliaries in the SOFC plant is about 1.5% of the electricity produced by the fuel cell stacks; thus an auxiliary efficiency (η_{aux}) of 98.5% is defined. The inverter efficiency (η_{inv}) is assumed to be 92%, and therefore, the overall transmitted efficiency (η_{trans}) is defined, considering both auxiliaries and inverter efficiencies as,

$$\eta_{trans} = \eta_{aux}\eta_{inv} \tag{1}$$

Under this hypothesis, the η_{trans} can be calculated as 0.9068. If FSOFC is the fuel consumption of the SOFC, HSOFC is the heat available for HEAT RECOVERY, and ESOFC is the gross produced electricity (without auxiliary consumption and inverter efficiency), then, the thermal efficiency ($\eta_{thermal}$) and electrical efficiency (η_{SOFC}) of the SOFC plant are defined as,

$$\eta_{thermal,SOFC} = \frac{H_{SOFC}}{F_{SOFC}} \tag{2}$$

$$\eta_{eletrical,SOFC} = \frac{E_{SOFC}}{F_{SOFC}} \tag{3}$$

Table 1 reports the thermodynamic benchmarks for a simulation of the SOFC system with one stack at full load (1 kW).

Table 1. . Efficiencies of the different components of the system and separate production

Parameter	Efficiency
SOFC (1 kW, full load), thermal efficiency	$\eta_{thermal,SOFC} = 0.4378$
SOFC (1 kW, full load), electrical efficiency	$\eta_{electrical,SOFC} = 0.5299$
SOFC (1 kW, full load), heat-to-power ratio	H/P = 0.8262
SOFC auxiliaries consumption, efficiency on electrical output	$\eta_{trans} = 0.9068$
GSHP, coefficient of performances at W10/W35	COP = 5.1
Boiler	$\eta_{boiler} = 0.9$
Electricity (from grid)	$\eta_{el} = 0.439$

Heat Pump

If waste heat from the SOFC is not sufficient to cover heat demand, then it is necessary to have a backup component, such as a gas-fired burner or electric heater. However, in this innovative system, a heat pump is chosen to cover heat demand instead of a burner or heater. Usually, two different types of heat pump are available on the market; ground source heat pump (GSHP) and air source heat pump (ASHP). ASHPs are cheaper but in countries where winter days with a temperature just above 0°C and a humidity above 50% are more frequent, the possibility of freezing the outdoor section (evaporator) may lead to a decrease in the seasonal performance of the heat pump. Ice has poor heat transfer; therefore, the heat exchange will eventually decrease and then it is necessary to defrost it with, for example, an auxiliary heat source (electrical resistance or gas burner) or by reversing the cycle. A GSHP is chosen for this system because of its higher efficiency, even though it is more expensive. A commercially available GSHP is chosen in this study. To calculate the coefficient of performance (COP) of this heat pump, it was necessary to consider that the working condition differs from the nominal condition. The technical norms of the heat pump used here are:

- UNI-TS 11300-4 to consider different working temperatures at the condenser/evaporator (UNI/TS 11300-4:2010);
- EN 14825 to consider the partial load of the heat pump in heating mode based on (EN 14825:2008).

In this study, a calculation method based on the model of (Busato et al., 2012) is developed to consider the UNI-TS 11300-4 standard. The maximum coefficient of performance (COP$_{max}$) of the GSHP is related to the heat sink temperature ($T_{w,out}$) and the heat source temperature (T_{grd}):

$$COP_{\max} = \frac{T_{w,out} + 273.15}{T_{w,out} - T_{grd}} \tag{4}$$

The performances of real GSHP systems are always lower than theoretical COP_{max}, and an exergy efficiency is defined between COP_{max} and COP, where COP is given in the technical data sheet of the heat pump producer,

$$\eta_{ex} = \frac{COP}{COP_{\max}} \tag{5}$$

Generally, heat pump performances are highly sensitive to the operating conditions (heat sink and heat source temperatures and partial load conditions). Following the study of (Busato et al., 2012) and the method proposed in UNI-TS 11300-4, it is possible to calculate the exergy efficiency of the heat pump if both the nominal performances (COP_{nom}) and nominal temperatures ($T_{w,\,out\,,nom}$, $T_{grd,\,nom}$) are known as,

$$\eta_{ex,nom} = \frac{COP_{nom}}{COP_{\max,nom}} = COP_{nom}\left(\frac{T_{w,out,nom} - T_{grd,nom}}{T_{w,out,nom} + 273.15}\right) \tag{6}$$

The exergy efficiency calculated under nominal conditions is supposed to be constant; therefore, it would be possible to define the GHSP performances (COP, Q_{GHSP}) at different temperatures conditions,

$$COP = \left(\frac{T_{w,out} + 273.15}{T_{w,out} - T_{grd}} \right) \eta_{ex,nom} \tag{7}$$

$$Q_{GSHP} = Q_{GSHP,nom} \left(\frac{T_{w,out} - T_{grd,nom}}{T_{w,out} - T_{grd}} \right) \tag{8}$$

To calculate the partial load, the EN 14825 calculation method is also used in this study. The COP at partial load (COP_{PL}) is thus defined as,

$$COP_{PL} = COP\left[1 - Cd\left(1 - CR\right)\right] \tag{9}$$

where *COP* is the performance at full load at the same temperature conditions. *Cd* is the degradation factor of the heat pump, and *CR* that is the capacity ratio. If the degradation factor is unknown or undetermined, EN 14825 suggests the value of 0.25. The capacity ratio is defined as the ratio between the load required ($Q_{GSHP,req}$) and maximum heating power of the heat pump (Q_{GSHP}) at temperature conditions defined by,

$$CR = \frac{Q_{GSHP,req}}{Q_{GSHP}} \tag{10}$$

For the proposed system, a commercial heat pump is chosen with a COP of 5.1 at W10/W35 conditions (according to EN 14511) and because Cd is unknown, it is assumed to be 0.25 according to EN 14825. To simulate a GSHP, it is necessary to know the temperature of the water coming from the ground out of the heat exchangers. In this case, it is assumed to be 9°C and constant during the year.

Water Tank

A water tank is used to store the waste heat from the SOFC when its heat production is higher than the demand for space heating and/or DHW. The temperature range of the water tank will be between 45°C to 95°C for which the lower limit is the lowest hot water temperature set by the user and the higher temperature limit is to avoid vapor formation. For the very rare case when the temperature of the water tank is at upper limit of 95°C and the waste heat from the SOFC is still available, it is proposed that there is a security system to dissipate the heat. For simplification, there is only one water tank to store the heat for both space heating and DHW. Different criteria could be used to choose the heat capacity of the water tank; however in this study, the heat capacity is assumed to be sufficient to keep heat dissipation below 1% of the total heat production.

DATA COLLECTION

In order to simulate the energy consumption for a normal house in Denmark, data from the domestic hot water and electrical energy profile must be collected. Data for electricity consumption are taken from a study of heat and power cogeneration (Annex 42), which provides the annual consumption of a resort located in the northern countries of Europe, and also the data are logged and stored hourly. Data for the space heating demand is taken from reference ("Typisk varmeforbrug") in which it is assumed that the useful surface of the house is approximately 150 m2 and is located in the Copenhagen area. Fig. 3 shows the hourly annual demand for space heating, DHW and electricity.

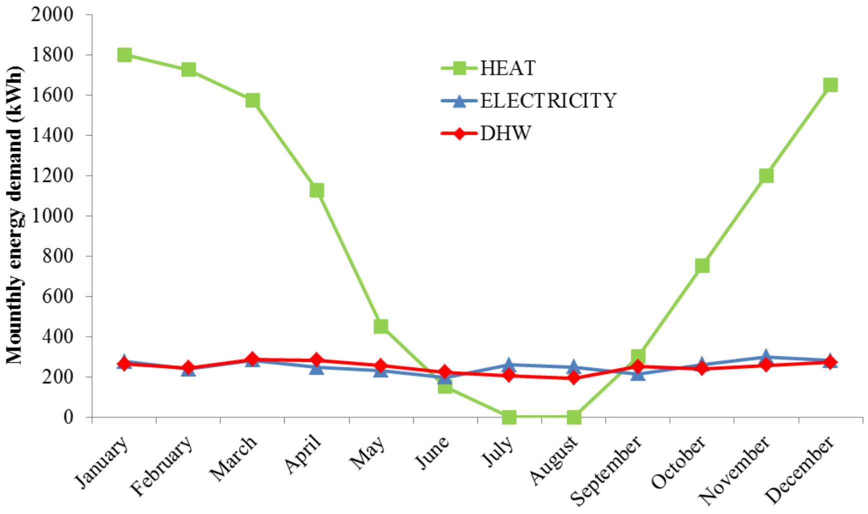

Figure 3. Average monthly demand on electricity, heat and domestic hot water (DHW) for a resort located in Denmark.

The annual total energy demand for space heating is 10725 kWh, for DHW is 2970 kWh and for electricity is 3028 kWh. It shall be mentioned that these data are the average values and may change from household to household depending on the habits and living styles of the tenants.

OPERATING STRATEGY

The operation strategy is an important part of the system designed and proposed here. Thermodynamic and economical performances are strictly related to the operation strategy in cogeneration and trigeneration systems (Kavvadias, 2010). An innovative operation strategy defined and analyzed in (Kavvadias, 2010) is also used here, which does not follow electricity or heat demand separately, but considers both of them together and simultaneously. In this strategy, an electric equivalent load (EEL) parameter is defined, which is the electrical demand for both the user and the heat pump. It considers that user heat demand is covered partly by the waste heat of the SOFC and partly by the heat pump. This parameter is thus a function of:

- electrical (E_{USER}) and heating (H_{USER}) user demand;
- heat-to-power ratio (H/P) and auxiliaries consumption (η_{trans}) of the SOFC;
- heat pump efficiency (COP).

To define the EEL, some assumptions are made to simplify the calculation method. The electrical consumption of the user (E_{USER}) and electricity consumption of the GSHP (E_{GSHP}) are assumed to be covered only by the electricity produced from the SOFC (E) as,

$$E_{USER} + E_{GSHP} = E \tag{11}$$

The heating demand (H_{USER}) is assumed to be covered by both the GSHP (H_{GSHP}) and waste heat of the SOFC (H_{SOFC}) as,

$$H_{USER} = H_{GSHP} + H_{SOFC} \tag{12}$$

It is thus necessary to consider the efficiencies of both the SOFC and GSHP systems. Taking into account the consumption of the auxiliaries of the SOFC, the electricity of the SOFC can thus be found as,

$$E = \eta_{trans} E_{SOFC} \tag{13}$$

By relating the electricity and heat (H_{SOFC}) production of the SOFC using the parameter heat-to-power ratio (H/P) one then finds,

$$H_{SOFC} = E_{SOFC} \frac{H}{P} \tag{14}$$

The heat production of the GSHP (H_{GSHP}) is related to the electricity consumption with the coefficient of performances (COP) through,

$$H_{GSHP} = E_{GSHP} COP \tag{15}$$

The above equations define the EEL under different conditions. If the waste heat from the SOFC is sufficient to cover the heat demand of the user, then the EEL can be defined as

$$EEL = \frac{E_{USER}}{\eta_{trans}} \tag{16}$$

However, if the waste heat of the SOFC is not sufficient to cover the heat demand of the user, then it is defined as

$$EEL = \frac{1}{\eta_{trans}} \times \frac{E_{USER} + \dfrac{H_{USER}}{COP}}{1 + \dfrac{H/P}{COP * \eta_{trans}}} \tag{17}$$

After defining the EEL parameter, different operation strategies can be used: i) continuous operation (CO), where the produced electricity is constant during a period; ii) equivalent electric load following (ELF), where the produced electricity will be equal to the EEL.

Under the CO strategy, the SOFC works at constant power every hour of the day. The advantage of this strategy is that the SOFC produces the same amount of electricity constantly for a period of time (for many hours); therefore, the thermal stresses on the cells are eluded. The disadvantage is that a larger water tank is needed to store the heat when water is produced but not consumed.

The aim of the ELF operation strategy is to follow the EEL and to cover all of the energy requests of the entire system. The advantage would be that the energy requirement from the grid is only a few times. The disadvantage would be that the fuel cell has to change the electricity production during operation time, and consequently, the thermal stresses on the cells would be higher than the CO strategy.

Three different cases are analyzed here: the CO strategy with a 1-kW maximum electrical power, ELF with a 1-kW maximum power of the SOFC and ELF with 2 kW. Figs. 4 through 6 show the hourly EEL for ELF 2 kW, ELF 1 kW and CO, respectively. Each figure represents the electric equivalent load (EEL) and how the corresponding strategy covers it.

The ELF 2-kW (Fig. 4) operation strategy follows the EEL until the demand is lower than the maximum SOFC power, which is 2 kW. If the EEL is higher, then the SOFC works at 2 kW, and the difference between EEL and SOFC electrical production is covered with the grid. Under this strategy, the system is able to cover 96.3% of the total EEL demand. The ELF 1 kW (Fig. 5) is similar to ELF 2 kW but with a smaller nominal SOFC power that is 1 kW instead. It follows the EEL until 1 kW but when EEL is higher than 1 KW, the SOFC works at 1 kW. Because of a lower nominal power, ELF 1 kW covers 77.1% of the EEL demand. The CO (Fig. 6) strategy does not follow the EEL because the SOFC works continuously at a set power. The set point is the monthly average of the EEL. If the average is higher than 1 kW (maximum power of the SOFC) then the SOFC works at 1 kW.

The size of each component of the system is related to the operation strategy. ELF 1 kW has a smaller SOFC size than ELF 2 kW (1 kW and 2 kW, respectively); therefore, in the first case, it is necessary to have a larger heat pump for covering the heat demand.

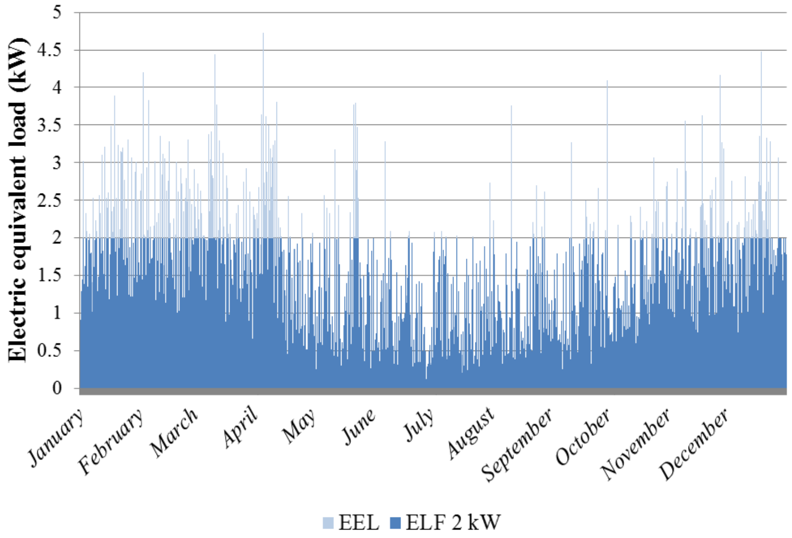

Figure 4. Electric equivalent load with ELF 2 kW, annual overview. ELF 2 kW follows EEL until it is lower or equal to 2 kW (the darker color).

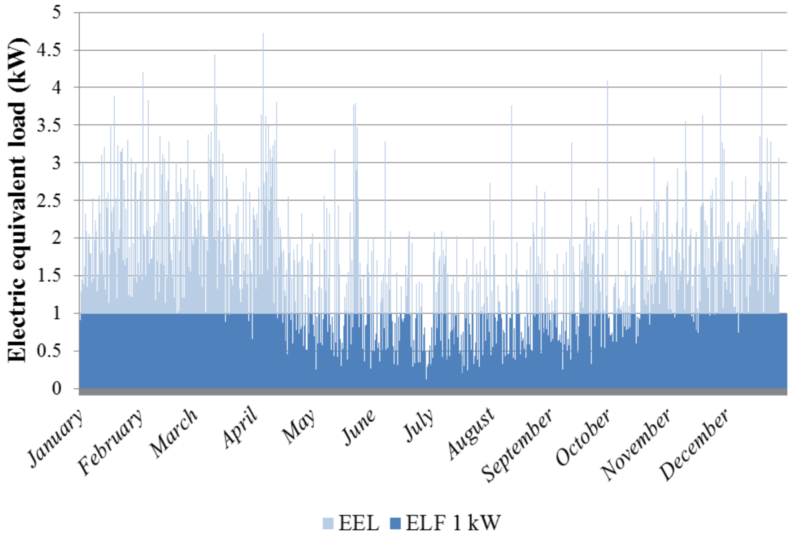

Figure 5. Electric equivalent load with ELF 1 kW, annual overview. ELF 1 kW follows EEL until it is lower or equal to 1 kW (the darker color).

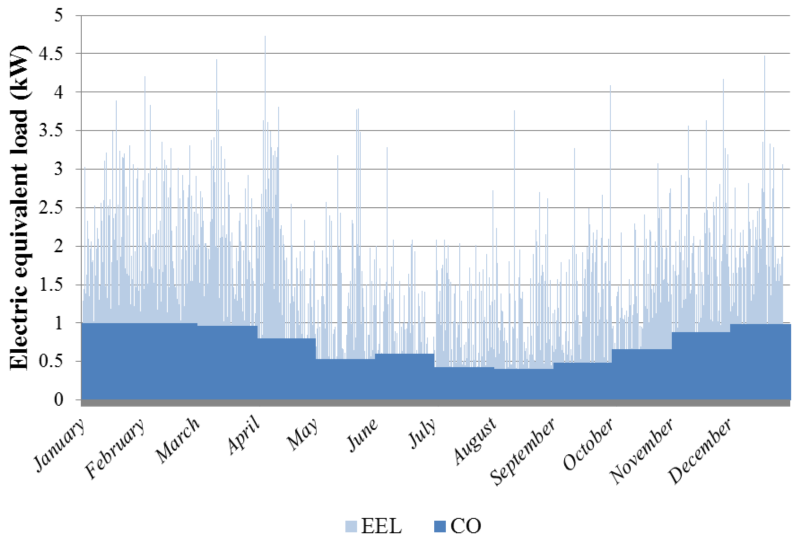

Figure 6. Electric equivalent load with continuous operation (CO) strategy, annual overview. CO follows a monthly average of EEL (the darker color).

The size of the fuel cell, heat pump and water tank for different operation strategies is shown in Table 2. The size of the heat pump for ELF 2 kW is approximately 11% smaller than the heat pump for the other two strategies (ELF 1 kW and CO 1 kW), while the size of the water tank for the CO 1-kW strategy must be approximately 43% larger than the other two ELF strategies.

Table 2. Size of the system components with different operation strategies.

Component / Strategy	**ELF 2 KW**	**ELF 1 KW**	**ELF CO**
SOFC	2 kW	1 kW	1 kW
GSHP	8 kW	9 kW	9 kW
Water Tank	70 liter	70 liter	100 liter

RESULTS AND DISCUSSIONS

As mentioned above, three different cases are analyzed here: the CO strategy with a 1-kW maximum electrical power, ELF with a 1-kW maximum power of the SOFC and ELF with 2 kW. To analyze the system, thermodynamic benchmarks are used: i) overall efficiency of the fuel cell; ii) primary energy saving (PES) of the entire system (fuel cell and heat pump); iii) production and consumption of different types of energy (electricity and heat) divided for each component of the system. To provide the same quantities of energy, PES is related to the fuel consumption of the fuel cell, energy consumption of the system (electricity and heat) and also to the efficiency that a traditional system with separated production of heat and electricity has. PES is defined according to the study of a trigeneration system in (Kavvadias et al., 2010) as

$$\%PES = 1 - \frac{F_{SOFC} + \dfrac{E_{Grid}}{\eta_{el}}}{\dfrac{H_{Demand}}{\eta_{boiler}} + \dfrac{E_{Demand}}{\eta_{el}}} \tag{11}$$

F_{SOFC} is the fuel consumption of the system, E_{GRID} is the net electricity consumption from the grid (if the system has an exchange of electricity with the grid, then the difference between these two variables is considered), H_{DEMAND} is the heat demand from the user, and E_{DEMAND} is the electricity demand of the user. η_{boiler} is the efficiency of a traditional gas boiler used in a traditional system that covers heating and DHW demands. η_{el} is the efficiency of an electric energy consumer from the grid, considering both generation with a traditional power plant and grid efficiency. A traditional system covers the electricity demand only from the grid, while the innovative system proposed consumes electricity from the grid only when the SOFC produces less electricity than the demand from the user and/or heat pump. The overall efficiency of the fuel cell (η_{SOFC}) can be defined as

$$\eta_{SOFC} = \frac{E + H_{SOFC}}{F_{SOFC}} \tag{6}$$

where *E* is the net electricity produced by the SOFC (considering auxiliaries consumption and inverter efficiency), HSOFC is the heat available and FSOFC is the fuel consumption. Fig. 7 shows the PES and overall efficiency of the fuel cell for all of the different strategies discussed above (ELF 2 kW, ELF 1 kW and ELF CO). As seen, the overall efficiency is higher than 90% for all of the cases considered, while the PES is higher than 45%.

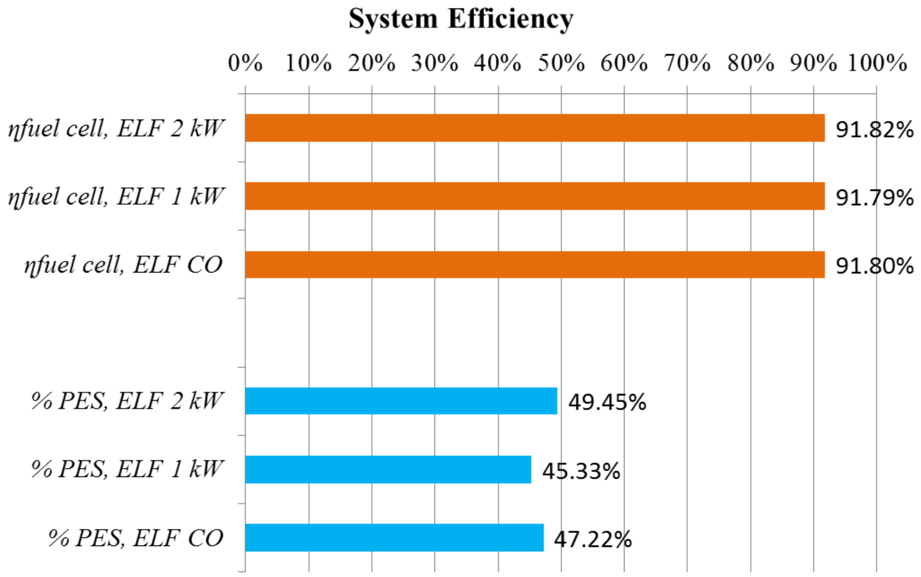

Figure 7. Fuel cell efficiency and %PES for all of the strategies.

ELF 2 kW

The ELF 2-kW case has the highest value of PES (49.45%) because of the size of the SOFC. A larger fuel cell is able to cover more electricity demand and GSHP consumption. It is also able to cover more waste heat so that the heat required by the heat pump is lower. Under this operation strategy, the electricity required to the grid is low. Fig. 8 shows that only 212 kWh of electricity is consumed from the grid during the periods of high request, and 198 kWh is provided to the grid when the consumption is lower than the request.

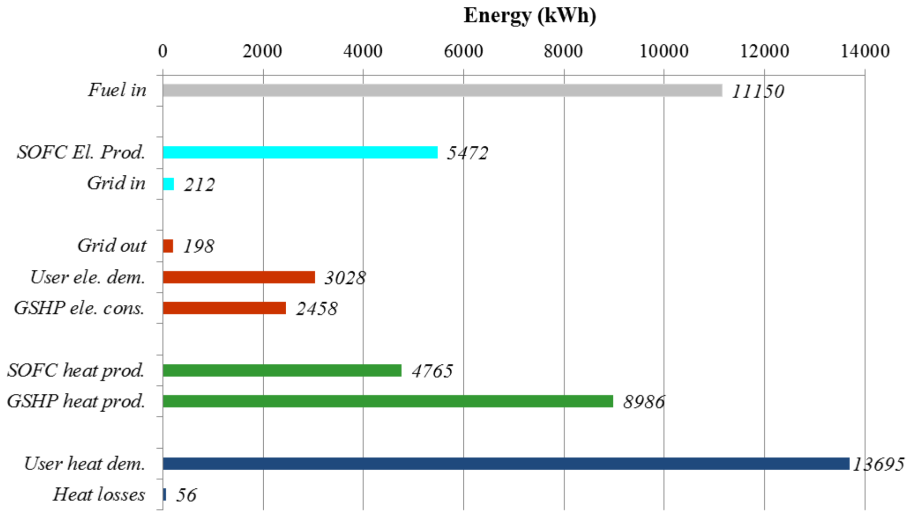

Figure 8. Energy flux for the ELF 2-kW operation strategy.

ELF 1 kW

The system working under ELF 1 kW has a smaller fuel cell (nominal power of 1 kW instead of 2 kW); therefore, both the electricity and heat demand covered by the fuel cell is lower compared with the previous case, see Fig. 9. Consequently, the PES decreases to 45.33% as displayed in Fig. 7. Fig. 9 shows that the heat recovery is 3854 kWh (28.15% of the user heat demand which is 13695 kWh) while under ELF 2 kW, the heat recovery is 4765 kWh (34.8% of the user heat demand). The electricity consumption from the grid is thus higher because of lower electricity production (4340 kWh in ELF 1 kW instead of 5472 kWh in ELF 2 kW), and also because the heat pump consumes more electricity than the ELF 2-kW case, (it is related to the lower waste heat available). Higher electricity consumptions from the grid explain why the PES decreases in this case compared to the previous case.
The exchanged electricity with the grid is also increased in this case compared to the previous case. Further, fuel consumption is decreased by about 20% due to smaller fuel cell system. Moreover, heat production from the heat pump is increased by about 10% to compensate the lower heat production from the fuel cell and satisfy the heat demand by the user.

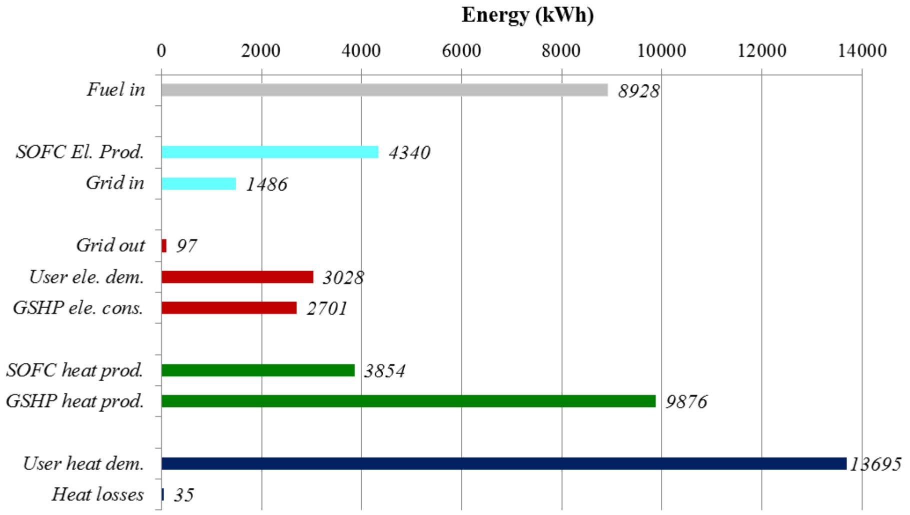

Figure 9. Energy flux for the ELF 1-kW operation strategy.

ELF CO

The system working under the ELF CO strategy has a fuel cell with constant electricity and heat production during the day. This constant value is the average of the electricity required during the considered period. Fig. 10 displays this operation strategy has a high exchange of electricity with the grid. Electricity from the grid of 1802 kWh is consumed when the consumption is higher than the demand, while 2025 kWh is given to the grid when the consumption is lower than the demand. This is related to mismatching between the production and consumption of electricity. Because of this mismatching, the heat losses are the highest of all of the cases analyzed here (199 kWh). Fuel consumption is highest in this case but also electricity production is highest. Further, heat production is highest in this case compared to the previous cases, which in turn results in lower heat production by the heat pump to satisfy the heat demand. On the other hand electricity consumption by the heat pump is the lowest one.

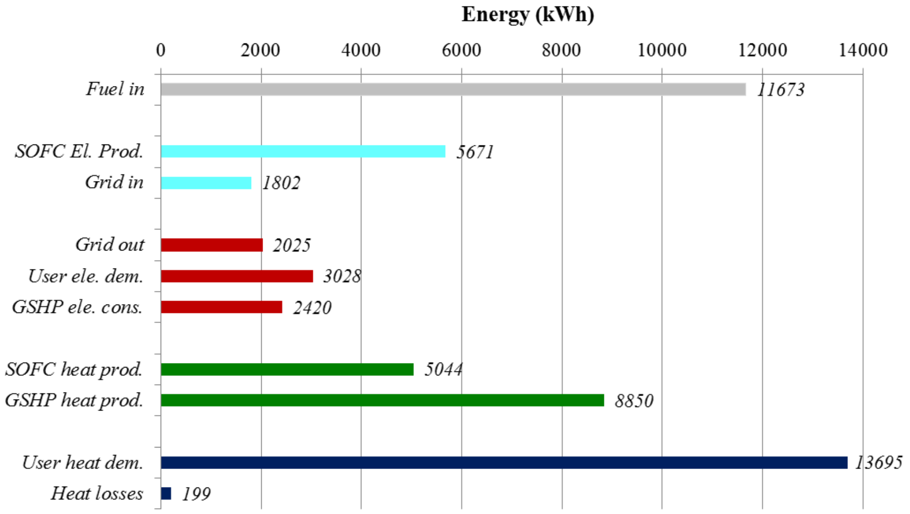

Figure 10. Energy flux for the ELF CO strategy.

CONCLUSIONS

An innovative cogeneration system based on the SOFC and GSHP is proposed for a resort located in a northern European country (Denmark). Additionally, an innovative parameter (electric equivalent load) is used to accomplish both the electricity and heat demand of the user and also define three different operation strategies, including ELF 2 kW, ELF 1 kW and ELF CO.

The ELF 2-kW operation strategy confirms that the system proposed could be independent from the grid when the system is allowed to exchange electricity with the grid and when there is mismatching between the electricity production and request. Eventually, other electrical storage could be interesting to study to make the system stand-alone and independent to the grid. Both the ELF 2 kW and ELF 1 kW strategies requires a small water tank because they have the capacity of following the heat demand from the user.

The ELF CO operation strategy also gives high primary energy saving even though the fuel cell works at constant load and does not follow the user demand. In this strategy, high thermal stress because of frequent start and shutdown is avoided. Mismatching between the electricity production and consumption is high, and the economic analysis of this strategy could only be performed once the net metering subsidy is available.

NOMENCLATURE

COP	coefficient of performance, –
CP	cathode preheater, –
CO	continuous operation, –
E	electricity, W
ELF	equivalent electric load following, –
F	fuel consumption, J/s
FP	fuel preheater, –
GSHP	ground source heat pump, –
H	heat, W
H / P	heat to power ratio, –
HP	heat pump
PES	primary energy saving, –
PP	prereformer preheater, –
RP	reformer preheater, –

Greek Letters

η	efficiency, –

Subscripts

aux	auxiliary
el	electricity
ex	exergy
inv	invertor
grd	ground
nom	nominal
req	required
trans	transmitted
w	water

REFERENCES

Annex 42. The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (COGEN-SIM). IEA Energy Conservation in Buildings & Community Systems. http://www.ecbcs.org/annexes/annex42.htm. Accessed on February 2014.

Bompard E., Napoli R., Wan B. and Orsello G. 2008. Economics evaluation of a 5kW SOFC power system for residential use. *Hydrogen Energy* 33:3243–47.

Busato F., Lazzarin R. and Noro M. 2012. Energy and economic analysis of different heat pump systems for space heating. *Low-Carbon Technologies* 7:104-112.

Cooper S.J.G., Hammond G.P., McManus M.C., Ramallo-Gonzlez A., and Rogers J.G. 2014. Effect of operating conditions on performance of domestic heating systems with heat pumps and fuel cell micro-cogeneration. *Energy and Buildings* 70:52–60.

Elmegaard B, Houbak N. 2005. DNA - A general energy system simulation tool. Proceeding of SIMS 2005, Trondheim, Norway.

EN 14825:2008. Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors, for space heating and cooling - Testing and rating at part load conditions and calculation of seasonal performance. European Committee for Standardisation.

Farhad S., Hamdullahpur F. and Yoo Y. 2010. Performance evaluation of different configurations of biogas-fuelled SOFC micro-CHP systems for residential applications. *Hydrogen Energy* 35:3758–68.

Kavvadias K.C., Tosios A.P. and Maroulis Z.B. 2010. Design of a combined heating, cooling and power system: Sizing, operation strategy selection and parametric analysis. *Energy Conversion and Management* 51(4): 833–45.

Lamas J., Shimizu H., Matsumura E. and Senda J. 2013. Fuel consumption analysis of a residential cogeneration system using a solid oxide fuel cell with regulation of heat to power ratio. *Hydrogen Energy* 38:16338–43.

Lee K.H. and Strand R.K.. 2009. SOFC cogeneration system for building applications, part 2: System configuration and operating condition design. *Renewable Energy* 34(12):2839–46.

Liso V., Brandon N., Zhao Y., Nielsen M.P. and Koer S.K. 2011. Analysis of the impact of heat-to-power ratio for a SOFC-based mCHP system for residential application under different climate regions in Europe. *Hydrogen Energy* 36:13715–26.

Petersen TF, Houbak N, Elmegaard B. 2006. A zero-dimensional model of a 2nd generation planar SOFC with calibrated parameters. *Int J Thermodyn* 9(4):161-9.

Riensche E, Achenbach E, Froning D, Haines MR, Heidug WK, Lokurlu A and Adrian S. 2000. Clean combined-cycle SOFC power plant–cell modeling and process analysis. *Power Sources* 86(1–2):404–10.

Rokni M. 2010. Plant characteristics of an integrated solid oxide fuel cell cycle and a steam cycle. *Energy* 35: 4691–99.

Rokni M. 2013. Thermodynamic analysis of SOFC (solid oxide fuel cell) – Stirling hybrid plants using alternative fuels. *Energy* 61:87–97.

Rokni, M. 2014. Biomass Gasification Integrated with a Solid Oxide Fuel Cell and Stirling Engine. *Energy* 77:6–18.

Sanchez D., Chacartegui R., Torres M. and Sanchez T. 2008. Stirling based fuel cell hybrid systems: an alternative for molten carbonate fuel cells. *Power Sources* 192:84–93.

“Typisk varmeforbrug”, Varde Forsyning A/S. In Danish. http://vardeforsyning.dk/Varme/Typisk-varmeforbrug.aspx. Accessed on February 2014.

UNI/TS 11300-4:2010. Renewable energy and other generation systems for space heating and domestic hot water production” (Italian), Ente Nazionale Italiano di Unificazione.