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Residental Systems Based on Solid Oxide Fuel Cells for Skandinivian Climate

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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.

Keywords: SOFC; heat pump; operating strategy; hybrid 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 [1], [2]. 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 [3]. Numerous studies have been investigated in the literature on SOFC-based hybrid systems that suggest high thermal efficiencies. However, studies on combined SOFC-heat pumps are very rare, e.g., [4] 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. [5] 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 [6], while the impact of heat-to-power ratio for a SOFC based micro CHP for residential application in European climate was elaborated in [7]. Variation of the heat to power output ratio to match the electric and hot water demands of a Japanese residence can be found in [8].

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.

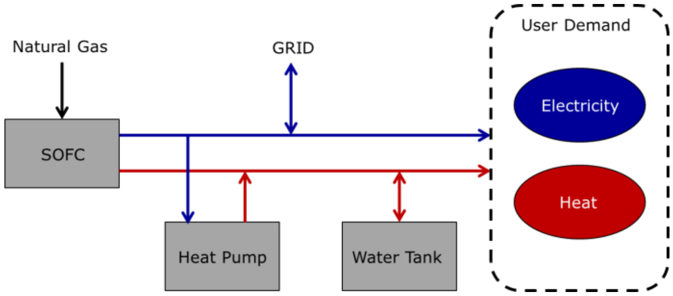

Figure 1. General scheme of the system proposed here with the main component and energy flows: fuel (black), electricity (blue) and heat (red).

SOFC SYSTEM

An SOFC system fuelled by natural gas is simulated using the in-house program DNA. It is made with these components (Fig. 2):

- air compressors to compress the air necessary for the fuel cell system;
- a catalytic partial oxidation (CPO) to convert the heavier hydrocarbons into CH4, H2 and CO;
- a desulfurizer to remove the sulfur from the fuel and avoid fuel cell poisoning;
-heat exchangers to increase plant efficiency, preheating fuel and air using the off-fuel and off-air, respectively (CP, RP, FP, AP), and to heat water for space heating and domestic hot water (DHW) using the wasted off-gases (HEAT RECOVERY);
- a burner to burn the unused fuel out of the fuel cell;
- SOFC stacks with performances similar to the type developed at DTU Risø National Laboratory.

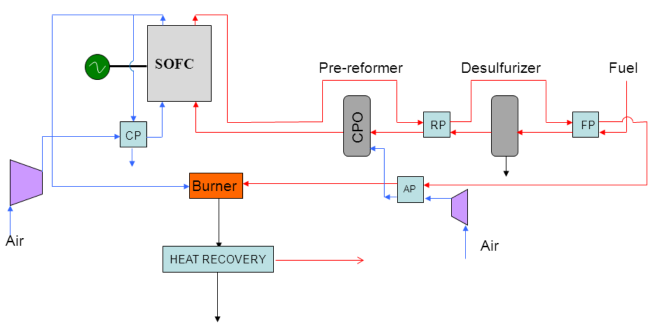

Figure 2. Representation of the SOFC system. CP = cathode preheater, FP = fuel preheater, AP = air preheater, RP = reformer preheater.

The SOFC system has electricity consumption because of auxiliary components (air compressors) and DC/AC conversion (inverter). Results from the study of [2] show 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,

$$\eta_{trans} = \eta_{aux}\eta_{inv} \quad (1)$$

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 (ηthermal) and electrical efficiency (ηSOFC) of the SOFC plant are defined as

$$\eta_{thermal,SOFC} = \frac{H_{SOFC}}{F_{SOFC}} \quad (2)$$

$$\eta_{eletrical,SOFC} = \frac{E_{SOFC}}{F_{SOFC}} \quad (3)$$

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 [9];
- EN 14825 to consider the partial load of the heat pump in heating mode based on [10].

In this study, a calculation method based on the model of [11] is developed to consider the UNI-TS 11300-4 standard.

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 [11] 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. To calculate the partial load, the EN 14825 calculation method is also used in this study. If the degradation factor is unknown or undetermined, EN 14825 suggests the value of 0.25.

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. More details can be found in [15].

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

To simulate the energy consumption for a normal house in Denmark, data from the domestic hot water and electrical energy profile must be collected.

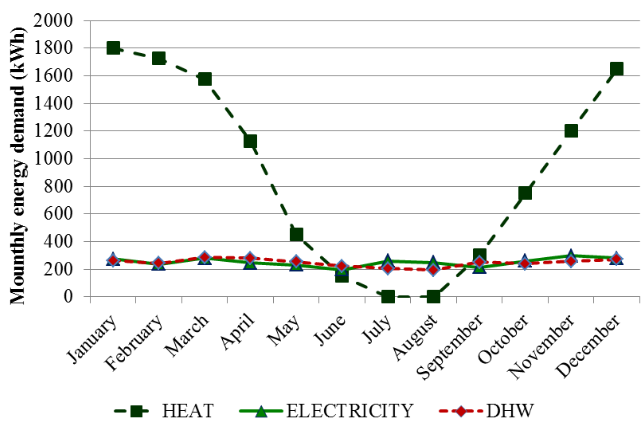

Figure 3. Average monthly demand on electricity, heat and domestic hot water (DHW) for a resort located in Denmark.

Data for electricity consumption are taken from a study of heat and power cogeneration [12], 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 [13] in which it is assumed that the useful surface of the house is approximately 150 m^2 and is located in the Copenhagen area. Fig. 3 shows the hourly annual demand for space heating, DHW and electricity. 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.

OPERATION 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 [14]. An innovative operation strategy defined and analyzed in [14] 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 (EUSER) and heating (HUSER) user demand;
- heat-to-power ratio (H/P) and auxiliaries consumption (ηtrans) of the SOFC;
- heat pump efficiency (COP).

The detailed can be found in [15]. EEL is finally defined as

$$EEL = \frac{1}{\eta_{trans}} \times \frac{E_{USER} + \dfrac{H_{USER}}{COP}}{1 + \dfrac{H/P}{COP * \eta_{trans}}} \tag{4}$$

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.

RESULTS AND DISCUSSION

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 [14] as

$$\%PES = 1 - \frac{F_{SOFC} + \frac{E_{Grid}}{\eta_{el}}}{\frac{H_{Demand}}{\eta_{boiler}} + \frac{E_{Demand}}{\eta_{el}}} \quad (5)$$

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. The overall efficiency of the fuel cell (η_{SOFC}) can be defined as

$$\eta_{SOFC} = \frac{E + H_{SOFC}}{F_{SOFC}} \quad (6)$$

where E is the net electricity produced by the SOFC (considering auxiliaries consumption and inverter efficiency), H_{SOFC} is the heat available and F_{SOFC} is the fuel consumption. Fig. 4 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%.

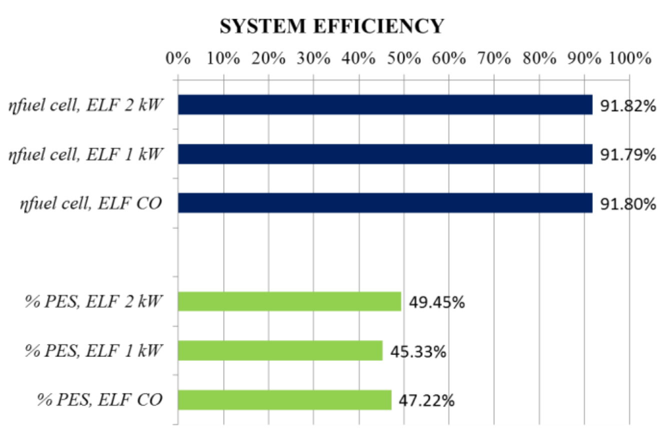

Figure 4. Fuel cell efficiency and %PES for all of the strategies.

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 of the grid when the system is allowed to exchange electricity with the grid and when there is mismatching between the electricity production and request.

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