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Evaluation of the environmental sustainability of SOFC-based cogeneration systems in commercial buildings

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Abstract

In order to achieve the European Union (EU)'s climate targets, efficient and sustainable solutions must be developed. In this context, the building sector has a key role to play in the transition to a decarbonized society. Cogeneration is considered an efficient solution that enables better use of fuel energy to supply buildings with heat and electricity. In particular, fuel cell-based cogeneration systems have shown promising performance, thus attracting considerable attention in recent years. The main goal of this study is to analyze the environmental impact of Solid Oxide Fuel Cell (SOFC) cogeneration systems, focusing on commercial buildings. The analysis was performed in the framework of the H2020 Comsos project, whose aim is to investigate the techno-economic and environmental feasibility of SOFC-based systems in non-residential buildings. An MILP-based optimization framework was developed to address the optimal design and operation of energy systems with the inclusion of SOFC-based cogeneration solutions. Electrical and thermal efficiency curves, derived from real SOFC operation, were used to improve the accuracy of the SOFC performance simulation. A sensitivity analysis on the carbon intensity of electricity was carried out to explore the role of the SOFC technology under different levels of electrical grid decarbonization. It was found that natural gas-fed SOFC systems become environmentally advantageous (in terms of CO_2 emissions) when the carbon intensity of electricity is higher than $\sim$ 300 gCO_2/kWh.
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Keywords: Fuel cell; SOFC; Cogeneration; Carbon intensity; Environmental impact

1. Introduction

According to the International Energy Agency [1], energy demand in the building sector has grown by an average of 1% per year over the past decade. Non-residential buildings account for about 35%–40% of total CO_2 emissions of the building sector. Over their entire life cycle, buildings are responsible (directly and indirectly) for about 37% of global energy-related CO_2 emissions. Therefore, environmentally sustainable and efficient solutions are needed to reduce the energy demand of buildings and the associated CO_2 emissions.

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Solid Oxide Fuel Cells (SOFCs) are high-temperature electrochemical systems that can efficiently generate electricity and heat due to the direct conversion of chemical energy into electrical energy. Moreover, SOFCs can run on various fuels (natural gas, hydrogen, biogas, etc.) and produce almost no pollutant emissions (NO_x, SO_x, particulate matter), which is especially important in urban areas.

Arsalis [2] provided an overview of fuel cell-based Combined Heat and Power (CHP) solutions and reported that SOFCs are one of the most promising technologies for CHP applications. Indeed, SOFCs are characterized by high efficiency at partial loads, fast response to load variations, and low carbon emissions. Adam et al. [3] reviewed fuel cell-based CHP systems for residential applications, with a focus on heat integration, which is of particular interest for SOFCs due to their high operating temperature. Moreover, SOFCs are well suited for commercial buildings, as they typically have a constant electrical base load. This feature fits perfectly with the need for the SOFC to operate almost continuously throughout the year with a reduced number of on/off cycles.

This work was carried out in the framework of the Comsos project [4,5] and investigates the use of the SOFC CHP technology in commercial buildings, focusing on the supermarket sector. The main objective is to analyze the environmental sustainability (in terms of CO_2 emissions) of the proposed SOFC-based CHP solution.

2. Modeling of the energy system

A general layout of the energy system under study is shown in Fig. 1. The electrical demand of the building is met by electricity produced by the SOFC and/or imported from the grid. The thermal demand is instead satisfied by a gas boiler and/or the SOFC, which operates in CHP mode. Both the SOFC and the gas boiler are supplied with natural gas from the gas grid.

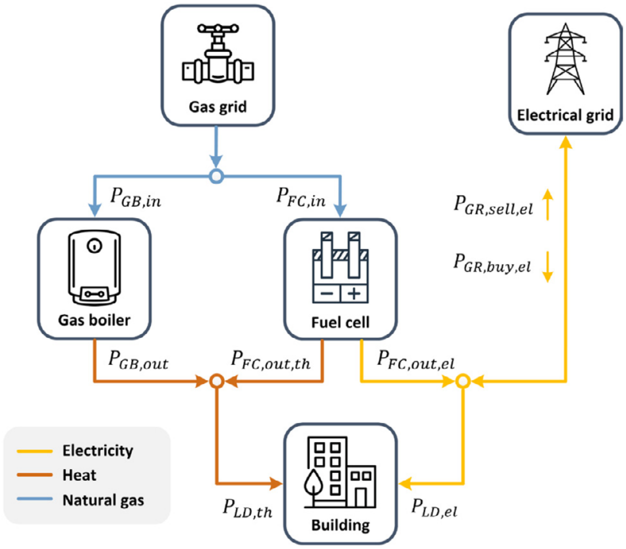

Fig. 1. Layout of the SOFC-based multi-energy system.

The optimal sizing and operation of the energy system were addressed by means of an MILP-based methodology. Simulations were performed over a one-year time horizon with hourly resolution. The decision variables of the optimization problem are: (1) the sizes of the gas boiler and the SOFC, and (2) the power exchanges between the different components for each hour during the year.

2.1. Energy simulation

Eq. (1) reports the electrical power balance (in kW) that must be satisfied in each time interval (t) of the simulation:

$$P_{FC,out,el}(t) + P_{GR,buy,el}(t) = P_{GR,sell,el}(t) + P_{LD,el}(t) \tag{1}$$

where $P_{FC,out,el}$ is the outlet electrical power of the SOFC, $P_{GR,buy,el}$ is the electrical power imported from the grid, $P_{GR,sell,el}$ is the electrical power exported to the grid, and $P_{LD,el}$ is the electrical demand of the building that must be met.

The thermal power balance (in kW) was instead computed as follows:

$$P_{FC,out,th}(t) + P_{GB,out}(t) = P_{LD,th}(t) \tag{2}$$

where $P_{FC,out,th}$ is the outlet thermal power of the SOFC, $P_{GB,out}$ is the outlet thermal power of the gas boiler and $P_{LD,th}$ is the thermal demand of the building that must be met.

The electrical and thermal efficiency curves of the SOFC were derived from real experimental data of a kW-size SOFC system [6,7], which are also in accordance with operating results from the Comsos project. A Piecewise Affine (PWA) approximation was then used to describe the SOFC conversion efficiency, which was implemented within the MILP-based framework according to the process described in [8].

2.2. Energy system sizing

The main objective of the optimization problem is to find a cost-optimal solution that minimizes the CO_2 emissions. Specifically, the following two steps were performed to derive the design of the energy system:

1. A minimum-emissions optimization is conducted to evaluate the minimum value of CO_2 emissions, regardless of the costs.
2. A minimum-cost optimization is then conducted, imposing a constraint on the maximum value of emitted CO_2 equal to the value obtained in step 1. This is done to ensure that the minimum level of CO_2 emissions is achieved at the lowest cost (e.g., to avoid unnecessary oversizing of technologies). In step 2, the Net Present Cost (NPC) of the system was considered as the objective function of the optimization problem.

The CO_2 emissions were evaluated according to the following relationship:

$$m_{CO_2,tot} = \sum_{t=1}^{8760} \left(m_{CO_2,GR}(t) + m_{CO_2,FC}(t) + m_{CO_2,GB}(t) \right) \tag{3}$$

where $m_{CO_2,tot}$ (in t/y) is the annual amount of CO_2 released by the system operation, while $m_{CO_2,GR}$, $m_{CO_2,FC}$ and $m_{CO_2,GB}$ (in t/h) are the CO_2 emissions related to the electrical grid, fuel cell and gas boiler, respectively. The $m_{CO_2,GR}$ term was computed based on the electrical power imported from the grid ($P_{GR,buy,el}$) and the value of the Electricity Carbon Intensity (ECI). The $m_{CO_2,FC}$ term is due to the gas consumption in the SOFC and was assessed assuming that the molar ratio between the CH_4 consumed and the CO_2 generated is 1:1. The $m_{CO_2,GB}$ term, which is caused by the gas consumption in the gas boiler, was computed in the same way as for $m_{CO_2,FC}$.

The NPC of the energy system (in €) was derived as:

$$NPC = C_{inv,0} + \sum_{i=1}^{n} \left[\frac{C_{OM,i}}{(1+d)^i} + \frac{C_{RP,i}}{(1+d)^i} \right] \tag{4}$$

where $C_{inv,0}$ is the investment cost at the beginning of the analysis period (i.e., capital expenditures for the purchase of the fuel cell and the gas boiler), $C_{OM,i}$ is the Operating and Maintenance (OM) cost of the system in the i-th year, $C_{RP,i}$ is the total replacement cost (sum of the contributions of all the components) in the i-th year, d is the real discount rate, and n is the lifetime of the project (20 years). The $C_{OM,i}$ term includes the OM costs of the gas boiler and the SOFC (expressed as a percentage of their capital expenditure), the cost due to the electricity purchased from the electrical grid, the profit from the sale of electricity to the grid, and the cost due to the natural gas purchased from the gas grid (to supply the gas boiler and the SOFC).

3. Results and discussion

The MILP-based method was applied to the case study of a supermarket in northern Italy, in the city of Milan. The hourly load profiles of the supermarket (both electrical and thermal) were taken from [9]. The electrical and thermal demand of the building are 2402 MWh and 692 MWh per year, respectively. The supermarket has an electrical base load of about 85 kW, which is mainly due to refrigeration. The peak electrical demand is 572 kW and occurs in the summer because of cooling needs. A detailed list of all the techno-economic data used for the optimal design of the energy system can be found in [9]. Two different cases were analyzed:

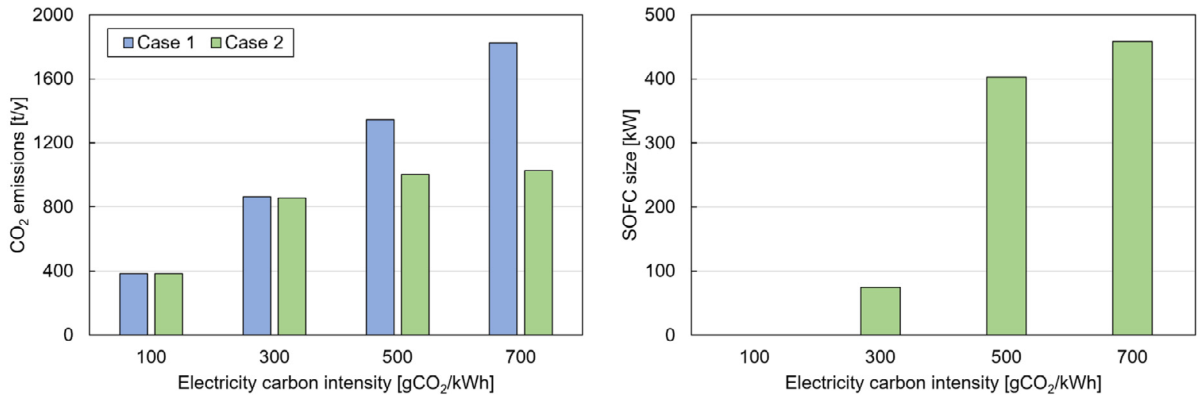

Fig. 2. On the left: CO_2 emissions as a function of the electricity carbon intensity for Case 1 and Case 2. On the right: SOFC size as a function of the electricity carbon intensity for Case 2.

- Case 1. The size of the SOFC is set to zero. This corresponds to the reference case with no SOFC.
- Case 2. There are no constraints on the size of the SOFC, which can be installed in the energy system if this results in a configuration with minimal CO_2 emissions.

The sizing process for Case 1 and Case 2 was performed according to the two-step methodology described in Section 2.2. A sensitivity analysis on the ECI factor was also conducted to investigate the role of SOFC systems under different levels of electrical grid decarbonization (from 100 to 700 gCO_2/kWh, which covers the values of most European countries).

Fig. 2(left) shows the CO_2 emissions for Case 1 and Case 2 as a function of the carbon intensity of grid electricity. It can be noted that CO_2 emissions of Case 2 become lower than those of Case 1 when the ECI value is above 300 gCO_2/kWh. This means that, from an environmental perspective (in terms of CO_2), natural gas-fed SOFC systems are preferable to energy systems without SOFC (i.e., electricity from the grid and heat from a gas boiler) if the electricity carbon intensity is higher than about 300 gCO_2/kWh. At 100 gCO_2/kWh, the CO_2 emissions of Case 1 and Case 2 are the same since the CO_2-optimal configuration of the energy system is the same in both cases, i.e., without SOFC.

The optimal SOFC size as a function of the electricity carbon intensity is displayed in Fig. 2(right). At 300 gCO_2/kWh, the fuel cell size is 75 kW, which is close to the electrical base load of the building (supermarket). By increasing the ECI factor to 500–700 gCO_2/kWh, the SOFC size increases to 400–460 kW. Considering these sizes (i.e., 400–460 kW), the SOFC can meet the electrical load of the building throughout the year, with the sole exception of part of the summer peak demand. For example, at 700 gCO_2/kWh, the SOFC size (460 kW) is smaller than the peak electrical demand (572 kW) because the grid is responsible for peak coverage in summer. Indeed, the use of the grid (whose share is less than 1% of the annual electrical load) avoids oversizing the SOFC system, which can thus operate in its optimal efficiency range.

The cost-effectiveness of the SOFC-based solution is shown in Fig. 3, where the NPC values of the Case 1 and Case 2 configurations are reported. As for Case 2, a sensitivity analysis was performed on the SOFC CAPEX (the SOFC size is the same regardless of the SOFC cost and is shown in Fig. 2 on the right). Specifically, the investment cost of the SOFC technology was reduced from 12.0 k€/kW (reference COMSOS cost at the beginning of the project) to 1.2 k€/kW (90% cost reduction). Indeed, it is expected to reach SOFC costs of about 1 k€/kW with growing production volumes and additional R&D activities [10]. Fig. 3 shows that, for an SOFC CAPEX of 12.0 k€/kW, the SOFC-based solutions (i.e., Case 2 with an ECI factor of 300 to 700 gCO_2/kWh) are always more expensive than system configurations without SOFC (Case 1). However, when considering an SOFC cost of 1.2 k€/kW, the SOFC installation becomes advantageous from both an economic and environmental perspective in the ECI range of 300 to 700 gCO_2/kWh. It is noteworthy that the cost of SOFC systems has fallen significantly in recent years and is currently in the range of 4–8 k€/kW.

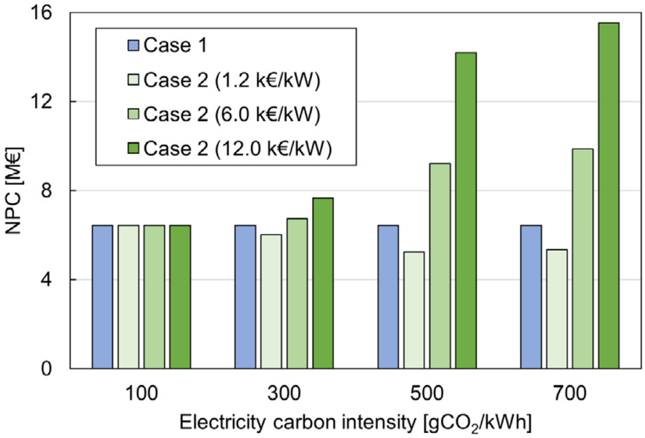

Fig. 3. NPC as a function of the electricity carbon intensity for Case 1 and Case 2. Different SOFC CAPEX are shown for Case 2.

4. Conclusions

The environmental impact of SOFC-based energy systems has been assessed, focusing on non-residential applications. The goal was to identify cost-optimal system configurations that minimize the release of CO_2 emissions. A sensitivity analysis on the electricity carbon intensity was also conducted to investigate the environmental performance of natural gas-fed SOFC systems under different levels of electrical grid decarbonization.

It was found that the environmental impact of SOFC CHP systems is strongly influenced by the value of the electricity carbon intensity. The CO_2 emissions of the SOFC-based solution become lower than those of the reference configuration (i.e., electricity supplied from the grid and heat produced by the gas boiler) when the ECI value is above 300 gCO_2/kWh. An SOFC investment cost of 1.2 k€/kW (which can be expected with increased R&D funding and production scale-up) makes SOFCs convenient also from an economic perspective. Moreover, another argument in favor of SOFC systems is that pollutant emissions (e.g., NO_x, SO_x, particulate matter) are almost zero, thus further improving the environmental competitiveness of SOFC-based solutions (particularly in an urban context).

In conclusion, considering that several countries still have very high ECI levels, natural gas-fed SOFC systems can represent an environmentally sustainable solution – in the short-medium term – in the transition towards scenarios with high penetration of renewable energy sources. Future steps will address the analysis of the sustainability of SOFC CHP systems including a progressive decarbonization of the gas grid by means of biofuels (biomethane) and hydrogen, which will further increase the attractiveness of the SOFC technology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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