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Energy and environmental performance from field operation of commercial-scale SOFC systems

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A R T I C L E I N F O

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A B S T R A C T

Solid Oxide Fuel Cells (SOFCs) are capable of generating electrical and thermal power with very high conversion efficiency and almost no pollutant emissions into the atmosphere. Despite extensive literature on SOFC-based energy system models and experimental testing at the cell and short-stack level, there is currently a lack of performance data for SOFC modules under actual field conditions. To fill this gap, the present work investigates the energy and environmental performance of six SOFC modules, ranging in size from 10 to 60 kW, over thousands of hours of operation. These systems, supplied by the three leading SOFC manufacturers in Europe, have been installed and operated in different non-residential buildings worldwide, as part of the European Comsos project. The aim of this study is to establish a comprehensive set of field operation data to characterise commercial-scale SOFC systems. Specifically, raw data are processed to derived electrical and thermal efficiency maps, degradation rates and pollutant emissions, including particulate matter (PM), nitrogen oxides (NO_x) and carbon monoxide (CO). A comparison with competing technologies is also provided to better highlight the potential benefits of adopting SOFC-based cogeneration systems. Values in the range of 51–61% were found for the system-level electrical efficiency under rated conditions. The electrical efficiency also remained consistently high across a wide modulation range (between 50% and 100% of rated power), with peak values reaching 65%. In addition, promising results were obtained for the average percentage loss in electrical efficiency, with a minimum value of 0.7%/1000 h. Regarding the environmental analysis, NO_x and CO emissions were analysed at both constant and variable power output, proving to be impressively low across the entire modulation range. The same applies to PM concentrations, which were below ambient level. Overall, SOFCs demonstrated to be one of the best cogeneration solutions for commercial-scale systems (tens to hundreds of kW in size), from both an energy and environmental perspective. However, further reductions in costs and dedicated financial schemes are necessary for a widespread market penetration.

1. Introduction

The building sector has made significant progress in enhancing energy efficiency over the past decade. The Energy Performance of Buildings Directive, released in 2021 as part of the Fit For 55 Package, seeks to accelerate building renovation rates, reduce greenhouse gas (GHG) emissions and energy consumption, and promote the uptake of renewable energy in buildings [1].

1.1. Fuel cells for the building sector

The International Energy Agency (IEA) [2] suggests that hydrogen and fuel cells (FCs) could serve as a viable solution within the buildings sector, especially in areas where natural gas infrastructure is already established and where energy consumption is hard to decarbonise, such as regions facing cold climates or within old city centres. In addition, FC-based combined heat and power (CHP) systems have the potential to support the electricity grid by enabling flexible modulation of power output. As a results, they can help balance electricity supply and demand, particularly during peak periods of domestic energy consumption.

As far as the building sector is concerned, fuel cells – both solid oxide fuel cells (SOFCs) and proton exchange membrane fuel cells (PEMFCs) – have primarily been investigated for residential applications in Europe,

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Japan, Korea and the United States. Japan has been the leading country for the use of micro-CHP systems in buildings through the Ene-Farm project. Under this framework, 430,000 FC units were in operation in Japan by the end of 2021 [2,3]. FC-based CHP solutions have also been explored in the European residential sector through the Ene.Field and PACE projects [4,5]: the former installed 1000 FC units between 2012 and 2017, while the latter is in the process of completing the installation of over 2500 FC units with rated power ranging from 0.5 to 1 kW. From the Ene.Field experience, the average SOFC electrical efficiency was found to be about 42% under optimal conditions during laboratory tests and 37% (with peaks up to 47%) based on real-life data from field trails (2017 data, from Ref. [4]). According to the Ene.Field reports, FC competitiveness in terms of life cycle cost (for small systems with a capacity of about 0.7 kW) can be attained when a cumulative production capacity of 5000–10,000 units per manufacturer is reached. The primary limitation of fuel cells in residential applications (as in the Ene-farm and Ene.Field initiatives) is their small system size (<1 kW). This can lead to high specific investment costs (as an example, the Panasonic CHP system installed in the Ene-Farm initiative recently reached a cost of about 13, 500 €/kW for the integrated SOFC-boiler unit [6]) and, as observed in the Ene.Field experience, to limited electrical efficiency at the system level.

1.2. Literature review on SOFC–CHP systems

The performance of SOFC systems has also been investigated in the scientific literature. Tan et al. [7] presented a detailed review of SOFC-based energy systems for building applications. The authors revised a high number of scientific works focusing on SOFC installations in residential and commercial buildings. Their analysis revealed that the electrical efficiency of atmospheric SOFC–CHP systems falls in the range of 40–50%, reaching 60–70% in hybrid pressurised configurations (SOFC-GT). Hybrid SOFC-GT systems are typically earmarked for industrial-scale applications, primarily due to the higher investment costs and increased system complexity [8]. In contrast, commercially available SOFC–CHP solutions (working at atmospheric pressure) are well-suited for deployment in the building sector for distributed heat and power generation. Narayanan et al. [9] evaluated the integration of an SOFC–CHP system in both older and more contemporary buildings in Germany, integrated with photovoltaics (PV) and batteries. The SOFC mainly operated during winter and on cloudy days, demonstrating its effectiveness, especially for the older buildings, in covering the thermal demand. In another study [10], a 30-kW SOFC–CHP unit was modelled and validated considering the use of different fuels (such as methane and methanol) and system layouts. Marocco et al. [11] investigated the role of SOFC–CHP systems in the context of commercial buildings. Specifically, they assessed the impact of various parameters, e.g. the investment cost of the SOFC technology and the spark spread (i.e. relative difference between electricity and natural gas prices), to uncover the conditions that make the SOFC technology economically profitable. Their findings indicated that an investment cost of 6 k€/kW is sufficient for the SOFC to be chosen in the cost-optimal configuration when the spark spread is about 0.1 €/kWh. The same authors also explored the environmental sustainability of such systems at different carbon intensity levels of the electricity grid [12]. De Masi et al. [13] discussed preliminary experimental testing of a 1-kW SOFC CHP unit powered by hydrogen, installed in a nearly zero energy house. Additionally, they developed a dynamic numerical model using TRNSYS software, which was subsequently validated with real operating data.

When integrated with an electrolyser, solid oxide fuel cells can also provide energy storage services. Mottaghizadeh et al. [14] proposed a solid oxide cell-based energy storage for an islanded building and explored the potential for thermal integration between the fuel cell and electrolyser units. Specifically, through the implementation of a network of heat exchangers, the SOFC can effectively supply heat to the electrolyser during its endothermic and standby modes. An in-depth life cycle assessment (LCA) of SOFC systems for a single-family house was conducted in a study by Di Florio et al. [15]. The authors compared an SOFC system fuelled by natural gas (NG) and a reversible solid oxide cell (r-SOC) fed by hydrogen. The outcomes of this investigation showed that the NG-powered SOFC is currently the environmentally preferred choice, while r-SOC systems (which rely heavily on power supply from the electrical grid) will only become advantageous in future scenarios with a higher penetration of renewable energy sources (i.e. lower carbon intensity of the electrical grid). In the literature review conducted by Lamagna et al. [16], a growing interest in the r-SOC technology was highlighted, although this solution is still in a pre-industrialisation stage with few real applications in the building sector.

Finally, solid oxide fuel cells powered by biogas have demonstrated high electrical efficiency values, reaching up to 55% [17]. Biogas-fed SOFC modules have been identified as ideal CHP technology in the market segment corresponding to a few tens of kW in size [18]. In addition, when considering target investment costs for the SOFC technology, interesting economic benefits were shown through the operation of biogas-based SOFC cogeneration systems compared to traditional solutions [19].

1.3. SOFC–CHP systems: producers and ongoing project

Despite the limitations of small-size residential applications, interest in SOFC technology continues to grow. The inherent benefits, such as fuel flexibility, high operating efficiency and near-zero pollutant

Table 1
List of EU-funded projects focused on stationary SOFC–CHP (at system level) from 2013 onwards (Source: Clean Hydrogen Initiative).

Project acronym	Project title	Time	Description
CH2P	Cogeneration of Hydrogen and Power using solid oxide based system fed by methane rich gas	2017–2022	Building a transition technology for early infrastructure deployment (natural gas or bio-methane to produce hydrogen and power with SOFCs)
Comsos	Commercial-scale SOFC systems	2018–2023	Strengthening the European SOFC industry's world-leading position for SOFC products in the range of 10–60 kW, installing totally 450 kWe
D2Service	Design of 2 Technologies and Applications to Service	2015–2020	Simplifying both residential and commercial fuel cell systems for easy, fast and save system service and maintenance
DEMOSOFC	Demonstration of large SOFC system fed with biogas from WWTP	2015–2020	Design and installation of an industrial size 175 kWe SOFC plant running on sewage biogas
DIAMOND	Diagnosis-aided control for SOFC power systems	2014–2017	Improving the performance of SOFCs for CHP applications by implementing innovative strategies for on-board diagnosis and control
INNO–SOFC	Development of innovative 50 kW SOFC system and related value chain	2015–2019	Development, manufacturing and validation of the next generation 50 kW SOFC system
PACE	Pathway to a Competitive European FC mCHP market	2016–2023	Major initiative aimed at ensuring the European mCHP sector makes the next move to mass market commercialisation
RoRePower	Robust and Remote Power Supply	2019–2023	SOFC systems for off-grid power generation in certain markets
SO-FREE	Solid oxide fuel cell combined heat and power: Future-ready Energy	2021–2024	Development of a fully future-ready SOFC-based system for CHP generation

Table 2

Producers of SOFC modules (complete system) and specifications for the available products.

Producer	Commercial Product	Rated power [kW]	Electrical efficiency [% LHV]	Fuel	Source
Bloom Energy	Bloom Energy Server 5.5	330 kW	65-53%	NG, biogas	[20]
Bloom Energy	Hydrogen fuel cell	300 kW	52%	H_2	[21]
Bosch	SOFC	10 kW	60%	NG, H_2, biomethane	[22]
Convion	C60	60 kW	60%	NG, biogas	[23]
FuelCell Energy	SOFC	250 kW	62–65%	NG, H_2	[24]
Mitsubishi Heavy Industries	MEGAMIE Hybrid SOFC-GT	250 kW	53%	NG	[25,26]
SolydEra	Bluegen BG-15	1.5 kW[a]	57%	NG (with up to 20% H_2), SNG, biomethane	[27]
Sunfire	PowerPlus	20 kW	>50%	NG, H_2	[28,29]

[a] Larger modules are also available by combining the single 1.5 kW modules.

emissions make this solution extremely attractive for power and heat generation in medium-to large-scale applications. In addition, the investment cost for SOFCs has significantly decreased in recent years, now ranging between 4 and 8 k€/kW [12]. A list of European projects dealing with SOFC–CHP systems for stationary applications since 2013 is provided in Table 1. On a global level, seven major SOFC manufacturers have been identified and are listed in Table 2, which also includes specifications of their available commercial products (note that stack-only producers are not included).

1.4. Contribution to existing literature

There are limited studies in the literature that provide power-efficiency curves of SOFC modules derived from real field operation [17,30]. Moreover, the existing literature lacks a comprehensive overview of SOFC systems, encompassing real-world performance and environmental measurements. Previous projects and initiatives have highlighted discrepancies between nominal data on the datasheet and actual field performance, underlining the need for in-depth analysis of data collected from real installations sites. These data are crucial for improving the accuracy and robustness of the eco-technoeconomic assessments of SOFC-based energy systems.

The present work aims to fill this gap by providing performance data and emissions measurements gathered from the long-term operation (thousands of hours) of various commercial-scale SOFC modules (ranging in size from about 10 to 60 kW) fuelled by natural gas in non-residential buildings. The field operation is conducted as part of the Comsos project [31,32], which involves the three main European solid oxide cell producers: SolydEra, Sunfire and Convion. The novel dataset includes measurements of electrical and thermal efficiency, degradation rate as well as emissions (NO_x, CO, PM). Energy and environmental indicators are also presented as a function of the loading rate, allowing for an assessment of SOFC technology performance under both rated power and part-load conditions.

This work is structured as follows: Section 2 provides a description of the SOFC–CHP layout and the installations within the Comsos project. Section 3 details the methodology used for evaluating the energy and environmental performance. Finally, the results are presented in Section 4 and conclusions are drawn in Section 5.

2. SOFC–CHP system definition

2.1. SOFC–CHP layout

The typical configuration of an SOFC–CHP system is illustrated in Fig. 1. The fuel (natural gas in this analysis) is supplied to the anode side (green lines), while air (orange lines) is directed to the cathode side. Preheated natural gas undergoes partial or complete reforming (based on the system design) to produce H_2 and CO before entering the anode [33]. In smaller systems, the steam reforming process might use external

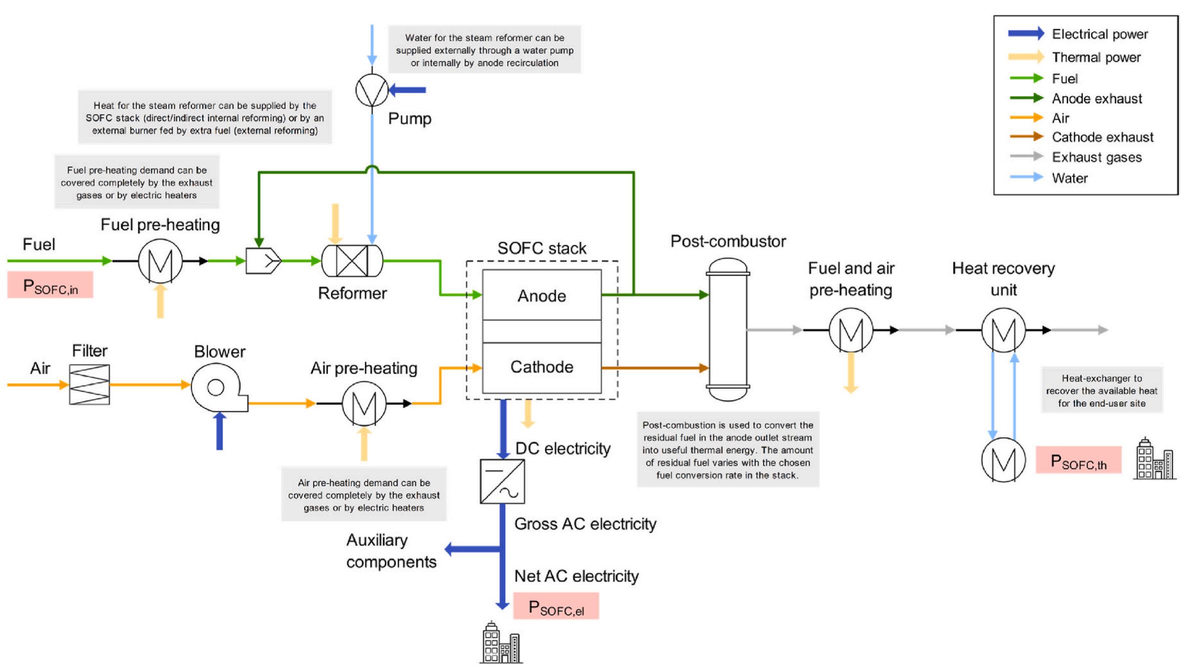

Fig. 1. Typical layout of an SOFC–CHP system.

Country	SOFC units installed	Total power installed
Italy	1	9 kW
Germany	2	18 kW
Austria	1	25 kW
Estonia	1	60 kW
China	6	185 kW
US	1	24 kW

Fig. 2. Comsos installations by July 2023.

water, whereas large systems employ internal anode recirculation to avoid water consumption. The air is initially filtered, then directed to a blower and pre-heater before reaching the cathode side. Even if not depicted in the figure, air recirculation may be used to enhance system efficiency, despite the increased system complexity associated with high-temperature recirculation loops [34].

The SOFC stack operates at a temperature of approximately 800–850 °C and generates DC electrical power, which is then converted to AC power by an inverter. A fraction of the as-produced electrical power is supplied to the auxiliary components such as blowers and pumps. Additionally, due to the exothermic nature of the SOFC reaction, the generated thermal power can be used to cover the thermal need of the steam reformer. Alternatively, excess thermal power can be exported via the air flow, which is supplied in excess compared to the stoichiometric value. In smaller systems, the necessary heat for the steam reformer can also be provided by an external burner, fuelled by additional natural gas.

The residual unreacted fuel (H_2, CO) in the anode exhaust gases undergoes combustion with the cathode exhaust in a catalytic post-combustor. The resulting high-temperature gas stream is used to pre-heat the incoming fuel and air, later serving as a source of heat production at the end-user site. Exhaust gases are typically available to the end-user at a temperature ranging between 150 and 250 °C. It is worth noting that all the abovementioned auxiliaries are integrated into the commercial SOFC modules available in the market.

The SOFC–CHP systems under investigation in this study exhibit various internal configurations, influenced by the size and layout choices made by the manufacturers. Due to confidentiality constraints regarding the internal system layout, specific details are not provided. The systems are treated as a unified black box, analysed from the perspective of the end-user.

2.2. SOFC–CHP installations in the COMSOS project

The Comsos project (Commercial-scale SOFC systems, 2018–2023) is an EU-funded initiative aimed at enhancing the European SOFC industry's global leadership in the production of SOFC systems within the 10–60 kW power range. The primary goal of the project is to achieve a cumulative installed power capacity exceeding 300 kW. The core of the consortium consists of the following three SOFC system manufacturers: Convion (60-kW SOFC unit), Solydera (9-kW SOFC unit) and Sunfire (25-kW SOFC unit). Collaborating partners include VTT (coordinator and responsible for data analysis), Politecnico di Torino (involved in data analysis and exploitation activities) and BlueTerra (focused on market and business models).

A geographical representation of the Comsos SOFC installations, along with data on installed capacity up to July 2023, can be found in Fig. 2. More than 445 MWh of electrical energy have been generated by the nine SOFC units installed in China, Austria, Estonia and Italy, spanning more than 16,800 operating hours.

The present work provides results on six distinct SOFC modules (two per manufacturer) installed in different regions around the world. For confidentiality reasons, the analysed SOFC modules will not be associated with any producer, and the results will be referenced with generic identifiers for the SOFC modules (1A, 1B, 2A, 2B, 3A, 3B).

3. Methods

3.1. Performance analysis

This section describes the methodology used to evaluate the energy performance of the SOFC units.

3.1.1. Electrical and thermal efficiency

The efficiency evaluation was conducted – where data were available – in accordance with the international standard IEC 62282-3-200 for stationary fuel cell power systems [35]. The values of electrical efficiency (η_{el}, in %) and thermal efficiency (η_{th}, in %) were provided by the SOFC manufacturers through monthly reports [36]. Specifically, at each time step (t), they were defined as follows:

$$\eta_{el}(t) = \frac{P_{SOFC,el}(t)}{P_{SOFC,in}(t)} \tag{1}$$

$$\eta_{th}(t) = \frac{P_{SOFC,th}(t)}{P_{SOFC,in}(t)} \tag{2}$$

where $P_{SOFC,el}$ (in kW) and $P_{SOFC,th}$ (in kW) are, respectively, the electrical and thermal power generated by the SOFC system, and $P_{SOFC,in}$ (in kW) is the inlet power. The term $P_{SOFC,el}$ was assessed as the net AC electrical power generated by the SOFC module (as illustrated in Fig. 1). It was evaluated after the balance-of-plant (BOP) of the SOFC module (i.e. blowers, electric heaters, pumps, electronics, DC/AC inverter, etc.). The electrical efficiency η_{el} thus represents the net efficiency of the entire SOFC module, from the inlet fuel (natural gas from the grid) to AC power (delivered to the end-users or to the grid).

The term $P_{SOFC,th}$ was quantified as thermal power available for the end-user, generally measured on the water side of the exhaust gas-water heat exchanger, as depicted in Fig. 1. Finally, $P_{SOFC,in}$ was computed based on the mass flow rate and the lower heating value (LHV) of the inlet fuel (i.e. natural gas from the gas network in the present work).

The total efficiency of the SOFC module (η_{tot}, in %) was evaluated as the sum of the electrical and thermal efficiencies, as typically done for the assessment of CHP systems:

$$\eta_{tot}(t) = \frac{P_{SOFC,el}(t) + P_{SOFC,th}(t)}{P_{SOFC,in}(t)} \tag{3}$$

In order to avoid a direct connection between the SOFC performance and its manufacturer, the efficiency curves are shown as a function of the normalised electrical power ($y_{SOFC,el}$, in %), which stands for the electrical power ($P_{SOFC,el}$) normalised with respect to the rated electrical power of the SOFC module ($P_{SOFC,rated}$):

$$y_{SOFC,el}(t) = \frac{P_{SOFC,el}(t)}{P_{SOFC,rated}} \tag{4}$$

The parameter $y_{SOFC,el}$ ranges from 0%, when the SOFC is off or in stand-by mode (open circuit voltage), to 100%, when the SOFC operates at its rated power output.

The time step (denoted as t) of the available data is 1, 15 or 60 min, depending on the SOFC module and the datalogging setup. Based on the data supplied by the manufacturers, efficiency values in three key operating points were then extracted:

- Efficiency at rated power ($\eta_{el,rated}$ and $\eta_{th,rated}$, in %), defined as the average efficiency value for all the data with $y_{SOFC,el} > 99.5\%$.
- Efficiency at 50% of rated power ($\eta_{el,50\%}$ and $\eta_{th,50\%}$, in %), defined as the average efficiency value for all the data with $49.5\% < y_{SOFC,el} < 50.5\%$.
- Maximum electrical efficiency ($\eta_{el,max}$, in %), defined as the highest electrical efficiency value among the available data. Once this point was identified, the corresponding operating point ($y_{SOFC,el}$) and thermal efficiency (η_{th}) were retrieved.

3.1.2. *Degradation rate*

In this study, the degradation of the electrical efficiency of the SOFC systems was also investigated. The goal was to analyse the SOFC modules from the perspective of the end-user, thus collecting data at the system boundaries. Consequently, the degradation rate was determined as the percentage decline in the SOFC electrical efficiency over time.

The degradation rate ($d_{el,k}$, in %/1000 h) was analysed for sequential time periods, each spanning 1000 h. The number of time periods (N) varies depending on the hours of operation of each SOFC module. For a given time period (k), the degradation rate stands for the reduction of the average AC electrical efficiency with respect to the previous time period ($k-1$). It was computed as follows ($k = \{2, \ldots, N\}$):

$$d_{el,k} = \frac{(\eta_{el,k} - \eta_{el,k-1})}{\eta_{el,k-1}} \tag{5}$$

where $\eta_{el,k}$ is the average AC electrical efficiency in the time period k, and $\eta_{el,k-1}$ is the average AC electrical efficiency in the time period $k-1$. The degradation rate is thus expressed as an electrical efficiency loss between two subsequent time periods. This analysis can be applied to different regions of the efficiency curve (i.e. by setting a minimum and maximum value of $y_{SOFC,el}$).

3.2. *Emissions analysis*

The emissions measurements (field measurements) were conducted by means of a laboratory-in-a-van approach. All measuring equipment, computers, calibration gases, and related instrumentation were installed into a van, which was then transported to the installation sites [36]. A simplified representation of the measurement setup is depicted in Fig. 3 [30]. It can be seen that a heated sampling line is positioned inside the exhaust chimney. Extracted gas is then conveyed, through two distinct sampling lines, to the FTIR (Fourier-transform infrared spectroscopy) for measuring gaseous species and to the ELPI (electrical low-pressure impactor) for measurement of particulate matter (PM). Further details on the measurement setup can be found in Ref. [37].

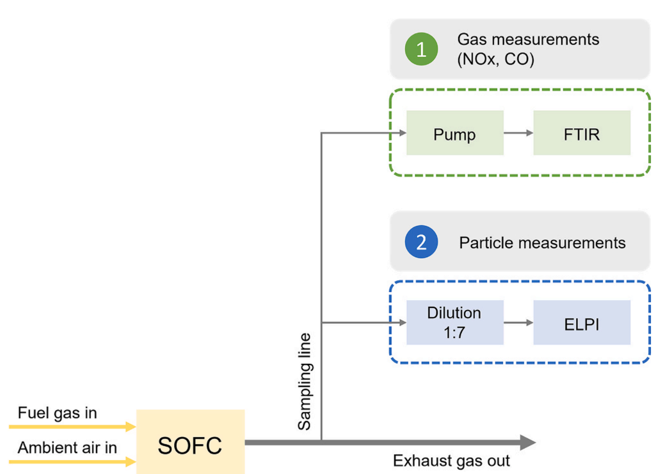

Fig. 3. Emissions measurement setup.

The FTIR analyser was employed to measure NO_x and CO concentrations, which were recorded on a volume basis ($y_{i,vol}$, in ppm_v, where $i = NO_x$ or CO) during the emissions measurement campaign. Generally, it is preferable for emissions data to be expressed in relation to the electrical power produced ($y_{i,el}$, in mg/kWh, where $i = NO_x$ or CO) to facilitate comparability with other power production technologies. The conversion from mass to energy basis was performed according to Eq. *(6)*, based on the mass flow rate of the exhaust gas stream ($\dot{m}_{ex}$, in kg/h). Alternatively, depending on the available data, the volume flow rate ($\dot{V}_{ex}$, in Nl/min) was also used for the estimation of $y_{i,el}$, as shown in Eq. *(7)*. The exhaust gas flow rate is usually not directly measured within the SOFC unit; it was thus estimated through a mass balance, calculated as the sum of the inlet air and fuel mass streams.

$$y_{i,el}(t) = y_{i,vol}(t) \cdot \frac{\dot{m}_{ex} \cdot MW_i}{MW_{ex} \cdot P_{SOFC,el}(t)} \tag{6}$$

$$y_{i,el}(t) = y_{i,vol}(t) \cdot \frac{\dot{V}_{ex} \cdot 60 \cdot MW_i}{10^3 \cdot 22.4 \cdot P_{SOFC,el}(t)} \tag{7}$$

where MW_i (in g/mol) is the molecular weight of the i-th component (NO_x and CO) and MW_{ex} (in g/mol) is the molecular weight of the exhaust gas stream. Due to the high dilution rate, the latter was assumed equal to the molecular weight of air. NO_x was considered as $NO_{2,eq}$.

The ELPI device was instead used to measure the PM concentration in the exhaust gas stream. The main components of the ELPI are the charger and the low-pressure impactor: the particles are charged within the charger, whereas the aerodynamic size classification is done inside the impactor. ELPI is able to measure (in real-time) size distribution and concentration of particles in the size range from 8 nm to 10 µm. Prior to analysis with the ELPI, the sampling flow from the exhaust pipe was diluted to approximately 1:7 with purified compressed air. Background levels (zero) were measured as a reference by using High Efficiency Particulate Air (HEPA)-filtered air. Particulates concentration was provided as number of particles per cubic centimetres and results were analysed without any conversion.

4. Results and discussion

This section includes an analysis of the performance of the SOFC modules, focusing on efficiency figures (electrical, thermal, total) and degradation rates. Additionally, measurements of pollutant emissions (NO_x, CO, PM) are presented.

4.1. *Performance analysis*

4.1.1. *Electrical and thermal efficiency*

The present work focuses on the analysis of six SOFC modules fuelled by natural gas, selected from the full set of installations within the Comsos project. Specifically, two modules (A and B) were chosen for each of the three manufacturers (1, 2 and 3), selecting the systems with the highest number of operating hours within the project. Results in terms of rated electrical and thermal efficiencies ($\eta_{el,rated}$ and $\eta_{th,rated}$) are shown in Fig. 4 and Table 3. Table 3 also shows the cumulative operating hours to which the data available in this work refer. The values of rated electrical and thermal efficiency were calculated as described in Section 3.1.1.

The electrical efficiency (net electrical efficiency, from natural gas input to AC power output) in rated conditions is in the range 51–61%, while the rated thermal efficiency ranges from 18 to 28%. The latter mostly depends on the thermal management on the end-user side and varied greatly across the tested SOFC modules. Data on thermal

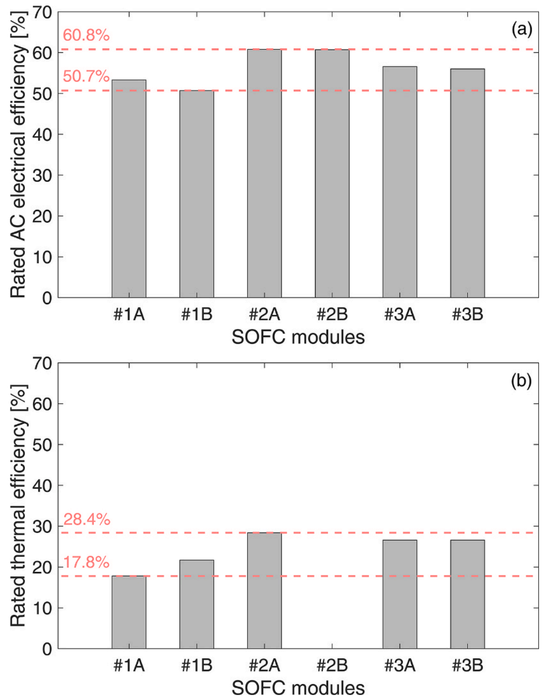

Fig. 4. Electrical and thermal efficiency (at rated power) of the six SOFC modules involved in the analysis. Rated electrical and thermal efficiency are calculated as described in Section 3.1.1.

Table 3
Operating hours, electrical, thermal and total efficiency (at rated power) for the six SOFC modules involved in the analysis. Rated electrical and thermal efficiency are calculated as described in Section 3.1.1.

SOFC unit	Operating hours [h]	AC electrical efficiency [%]	Thermal efficiency [%]	Total efficiency [%]
#1A	5016	53.3%	17.8%	71.1%
#1B	9354	50.7%	21.7%	72.4%
#2A	4129	60.8%	28.4%	89.2%
#2B	3122	60.7%	n.a.[b]	n.a.[b]
#3A	46[a]	56.6%	26.6%	83.2%
#3B	4195	56.0%	26.6%	82.6%

[a] The results of SOFC #3A are provided in terms of FAT test (this is the reason for the reduced number of operating hours).
[b] The data on thermal recovery were not available for SOFC module #2B. As a consequence, thermal and total efficiency were not evaluated.

efficiency for SOFC module #2B are not available because it was operated without heat recovery during the analysed period (decision from the site owner).

For all six modules, details regarding the efficiency curves and electrical efficiency at rated power, at reduced power (50% of the rated power) and at the maximum efficiency point are available in the Appendix. The performance of one module for each manufacturer is investigated below. In particular, SOFC modules #1A, #2A and #3A are considered.

Fig. 5 shows the electrical efficiency map (electrical efficiency as a function of the normalised electrical power) for the three selected SOFC modules (#1A, #2A and #3A). A very high electrical efficiency (between 45% and 65%, with most of the data above 50%) was found for the 50–100% modulation range. The SOFC modules were thus able to operate in a wide modulation range (up to 50% of the rated power) while maintaining stable performance in terms of electrical power generation. It is noteworthy that SOFC #1A (blue dots) and SOFC #2A (red dots) also operated at lower partial loads, up to 20–30% of the rated power, with a limited reduction in electrical efficiency (which was about 40% at a normalised AC electrical power of 30%).

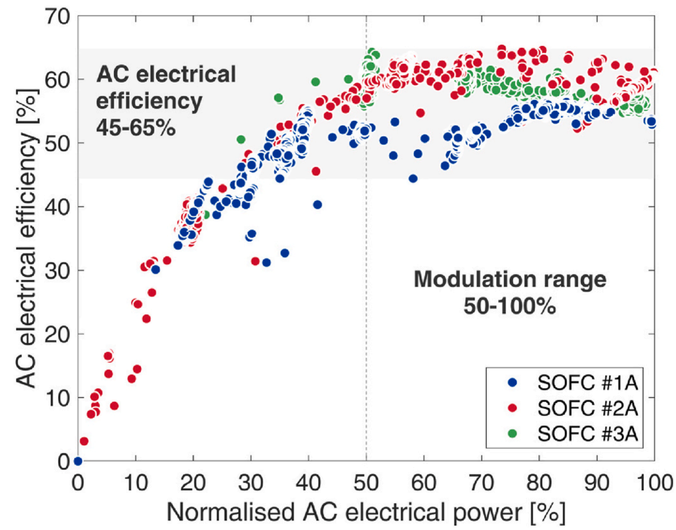

Fig. 5. AC electrical efficiency map for 3 different SOFC modules (#1A, #2A and #3A).

Fig. 6 illustrates the thermal efficiency map for SOFC #1A and SOFC #2A (as no operational data from the field were available for SOFC #3A). The thermal efficiency tends to increase as the produced electrical power decreases. This phenomenon occurs because, when decreasing the electrical power production, the stack is operated in different operating conditions (e.g. fuel utilisation) that lead to a higher rate of heat production at the system level. Lower electrical efficiency is thus compensated with increase in thermal efficiency. In the modulation range of 50–100%, thermal efficiency varies greatly between 15% and 45%. These values then increase up to approximately 55% for lower loads (20% normalised electrical power).

The high variability observed in thermal efficiency values can be ascribed to two main factors. Firstly, it results from the limited precision of the commercially available heat measurement sensors in the heat recovery circuit. Secondly, it is influenced by the thermal recovery strategy which depends on the specific requirements of the end-user. In the investigated sites, the heat generated within the SOFC modules is commonly employed for heating and domestic hot water purposes, operating within a temperature range of 40–80 °C on the water side.

The key operating points (i.e. rated electrical power, 50% normalised electrical power, and maximum efficiency point) were also extracted

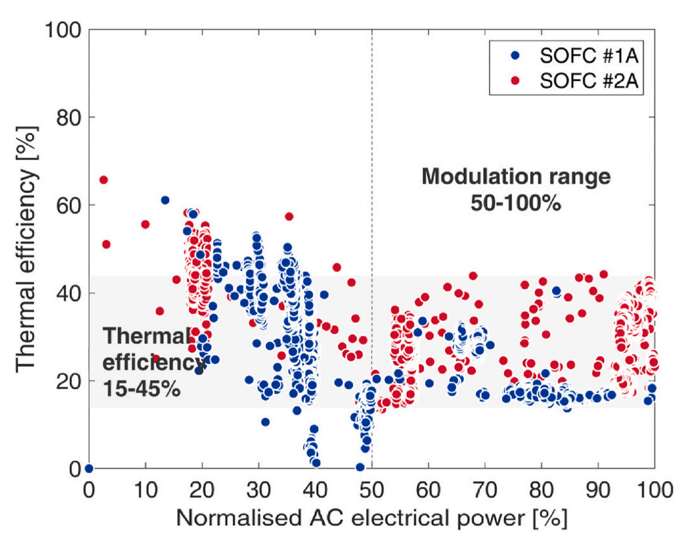

Fig. 6. Thermal efficiency map for SOFC modules #1A and #2A.

Table 4
AC electrical and thermal efficiency of the SOFC modules in the key operating points (derived as explained in Section 3.1.1): rated power, 50% of rated power and maximum efficiency point.

Normalised AC electrical power [% $P_{SOFC,\ rated}$]	AC electrical efficiency [%]	Thermal efficiency [%]
SOFC #1A		
100% (rated)	53.3%	17.8%
50%	51.7%	15.6%
84.9% (max. electrical efficiency)	56.6 %	17.0%
SOFC #2A		
100% (rated)	60.8%	28.4%
50%	59.1%	14.5%
73.5% (max. electrical efficiency)	64.8%	24.6%
SOFC #3A		
100% (rated)	56.6%	26.6%
50%	59.3%	22.1%
51% (max. electrical efficiency)	64.3%	22.1%

Table 5
Performance comparison between the Comsos SOFC units and conventional cogeneration systems in the commercial-scale range (tens to hundreds of kW), except for the power plants (combined cycles). Data refer to NG-fed systems.

Technology	Rated AC electrical efficiency [%]	Ref.
SOFC	53–61	This work
MCFC	45–50	[38]
PEMFC	35–45	[39]
ICE	35–40	[33]
Gas turbines	15–20	[38]
Power plants (combined cycles)	50–65 (only large-scale systems)	[40,41]

from the efficiency maps and are provided in Table 4. Points with maximum AC electrical efficiency above 60% are detected: 64.8% for SOFC #2A and 64.3% for SOFC #3A. As already mentioned, the electrical performance remains stable even during partial load operation: AC electrical efficiency is between 52% and 59% for a normalised AC electrical power of 50%.

The performance of the six investigated SOFC modules at rated power aligns with the values declared by the manufacturers in their datasheet and with the performance of commercial SOFC systems available in the market. The electrical and thermal efficiency values under rated conditions for these commercial products are provided in the Supplementary Material (Table S1).

The values for the rated AC electrical efficiency determined in the Comsos project were also compared with the rated values of alternative technologies for electricity generation, as shown in Table 5. Alternative technologies for decentralised commercial-scale power production, such as PEMFCs, molten carbonate fuel cells (MCFCs) and internal combustion engines (ICEs), are characterised by lower performance compared to SOFCs. Low-temperature fuel cells (e.g. PEMFCs) and ICEs show efficiency values in the range 35%–45%, whereas higher figures are associated with MCFCs (up to 50%). Small-scale gas turbines are the worst solution in terms of efficiency, with values below 20%. On the contrary, large-size power plants, such as traditional gas turbine combined cycles, can achieve higher efficiencies (above 60%), but only for MW- to GW-scale plants.

If the end user can guarantee relatively continuous operation (i.e. limited number of on-off cycles), SOFCs – which show a rated electrical efficiency of over 50% – are the best-in-class solution for decentralised power generation in the commercial-scale sector (tens to hundreds of kW in size). Moreover, they can effectively vary the electrical power in the modulation range from 50% to 100% (percentage of the rated value), while ensuring stable and good performance.

4.1.2. *Degradation rate*

The degradation rate was estimated for the six SOFC modules as defined in Section 3.1.2. As an example, Fig. 7 shows the effect of degradation on the AC electrical efficiency of SOFC #2A. As visible from the zoom on the right side of Fig. 7, focused on the rated power area, the efficiency gradually decreases when moving from the green (0–1000 h) to the light blue (1000–2000 h) to the yellow (2000–3000 h) dots. The normalised electrical power decreases from 100% to approximately 93–95% during the first 3000 h of operation. Primarily, this can be attributed to stack degradation affecting the performance of the entire system.

The degradation rate was also evaluated, for all the six SOFC modules, in the 70–100% modulation range and results are shown in Table 6. The analysis focused on this region (close to the rated power) since most

Table 6
Average degradation rate for the six analysed SOFC modules in the 70–100% modulation range (percentage of the rated power).

SOFC	Degradation rate [%/1000h]
#1A	n.a.
#1B	0.7
#2A	1.3
#2B	3.2
#3A	n.a.
#3B	0.7

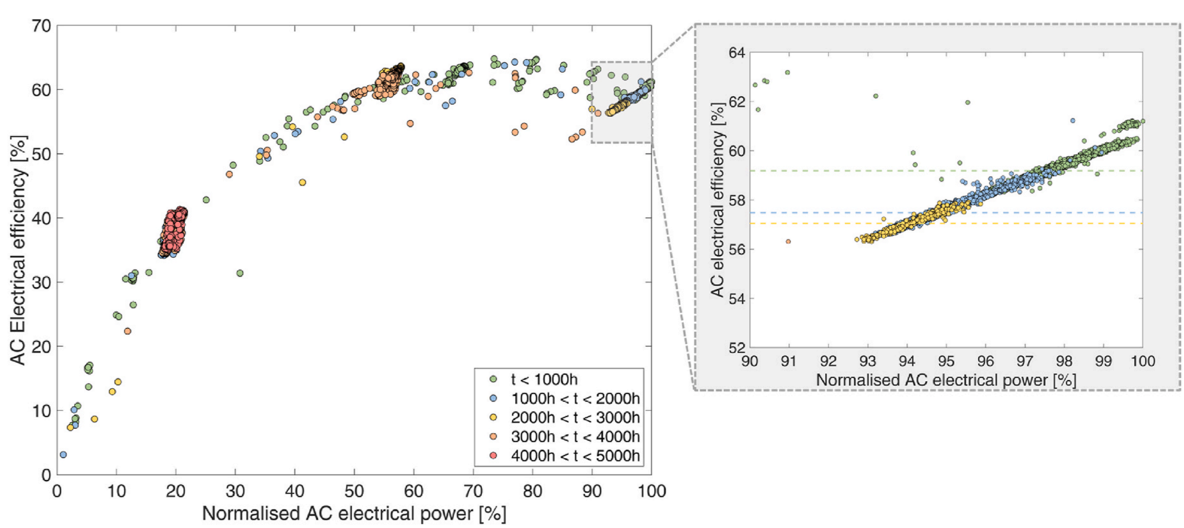

Fig. 7. Impact of degradation phenomena on SOFC #2A (operated for 4129 h).

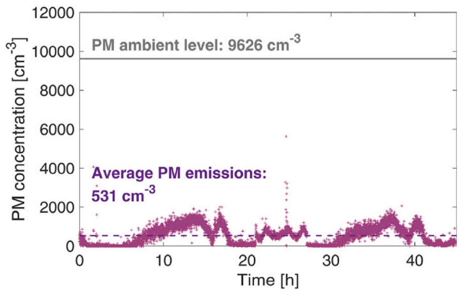

Fig. 8. PM emissions measurements from SOFC #1 (at constant power output equal to the rated power, i.e. normalised AC electrical power equal to 100%).

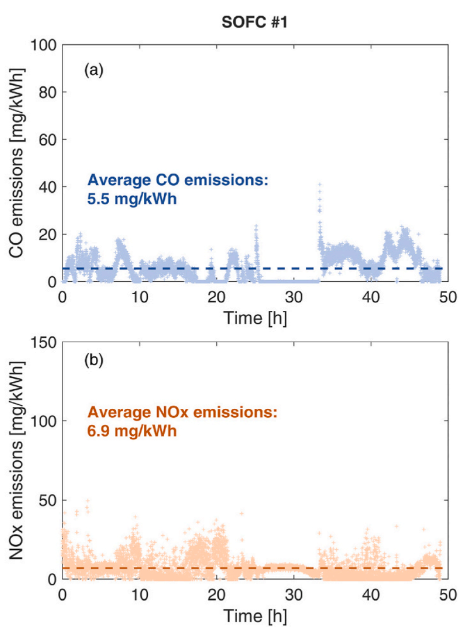

Fig. 9. CO (a) and NO_x (b) measurements from SOFC #1 (at constant power output equal to the rated power, i.e. normalised AC electrical power equal to 100%).

of the SOFCs operated in this area during the analysed period. The limited number of data available for other regions of the efficiency map (<70%) were not sufficient to retrieve reliable degradation rate values.

The results presented in Table 6 are given as average degradation rates over the entire operating period (obtained by averaging the degradation rates of all the 1000-h intervals, computed according to Eq. *(5)*). No data are provided for SOFC #1A and SOFC #3A because no clear degradation trend was discernible (SOFC #1A) and the number of available hours was not sufficient for the analysis (SOFC #3A). The degradation rate for the other four SOFC modules was found to be between 0.7 and 3.2%/1000 h. Despite the wide range discovered, three out of four modules showed degradation rates below 1.3%/1000 h, with two of them achieving 0.7%/1000 h.

The reasons behind the degradation of SOFC systems are complex and multifaceted. Degradation phenomena in SOFCs are typically investigated at the cell and stack levels in the literature [42]. Firstly, the cell structure (electrolyte-supported, electrode-supported or metal-supported) can influence the performance (such as open circuit voltage and ohmic losses) from the beginning of life [43]. Secondly, various degradation mechanisms can occur during SOFC operation. In the cathode, issues such as poisoning, microstructural deformation and chemical and thermal strains can arise. In the electrolyte, phase transition, impurities diffusion, dopant diffusion and mechanical failures are possible. The anode can experience microstructural changes, coking, poisoning and delamination. The interconnector may suffer from corrosion, chromium vaporization and mechanical failures. Finally, as demonstrated in the works by Lai et al. [44,45], degradation can be influenced by the operating point (current density), the working temperature and fuel utilisation. A review of degradation rates (expressed as voltage reduction per thousand hours) is provided in the Supplementary Material (Table S2). For the same current density and operating conditions, voltage degradation can be related to electrical efficiency degradation. Results using reformate natural gas as fuel (as in the present study) show degradation rates in the range 0.2–2 %/1000h. This range aligns with the findings of the present research, which are slightly higher due to the expected increased degradation in real-world operation compared to laboratory conditions (e.g. variable load operation and thermal cycles).

4.2. Emissions analysis

This section deals with the analysis of the emissions measurements, specifically PM, NO_x and CO emissions under both steady and variable power output conditions. Typically, the majority of fuel supplied to an SOFC system undergoes electrochemical reactions within the stack, resulting in 0 PM and NO_x emissions. Downstream the stack, a catalytic post-combustor is employed to convert the unreacted fuel (H_2 and CO) from the anode. The combustion reaction occurring in the post-combustor could lead to a small generation of PM and NO_x, and to some unreacted CO. Furthermore, other residual PM could also be found in the inlet air after the filtering process. In contrast to previous literature [30] – where higher detection limits led to the impossibility of estimating the actual pollutants level – the current analysis employed more accurate systems, allowing for a quantitative evaluation of pollutants at the SOFC outlet.

Fig. 8 shows the PM level (in number of particles per cm^3, in the size range of 8 nm–10 μm) at the SOFC outlet (purple dots) and in the surrounding environment (grey line). The analysis was performed at constant power output and refers to an SOFC module from manufacturer #1 (defined here as SOFC #1). The average PM emissions during the 45 h of analysis amounted to 531 particles per cm^3, while the average ambient concentration was recorded at 9626 particles per cm^3. As discussed above, when the SOFC system operates, the incoming air is filtered (thus removing particulate matter) and no particulates are generated within the SOFC stack. The minimal PM level detected at the outlet of the SOFC system can be attributed to both the catalytic post-combustor and to some residual particulates in the airflow after the inlet filtration. Consequently, PM concentration in the exhaust gases was lower than that in the surrounding environment.

For the same SOFC module (SOFC #1), CO and NO_x emissions were also measured in the same test campaign at constant power output. The results for CO and NO_x emissions are shown in Fig. 9a and b, respectively. It can be seen that the average CO emissions stand at 5.5 mg/kWh, while the average NO_x emissions amount to 6.9 mg/kWh.

As shown in Fig. 10, the level of CO and NO_x emissions was also assessed for SOFC modules of the other two manufacturers (denoted here as SOFC #2 and SOFC #3). In this case, the results were analysed under conditions of variable power output, within the modulation range of 50–100%. The differences in emissions values among the investigated SOFC modules may be ascribed to the different system layouts, such as different fuel conversion rates within the stack and different post-combustion operating conditions (i.e. air-fuel ratio) as discussed in Fig. 1. SOFC #2 shows an average CO emissions level of 32.1 mg/kWh, while NO_x emissions amount to 51.8 mg/kWh. Slightly lower values are observed for SOFC #3: the average CO and NO_x emissions are 19.2 mg/kWh and 39.6 mg/kWh, respectively. The results reveal that pollutants

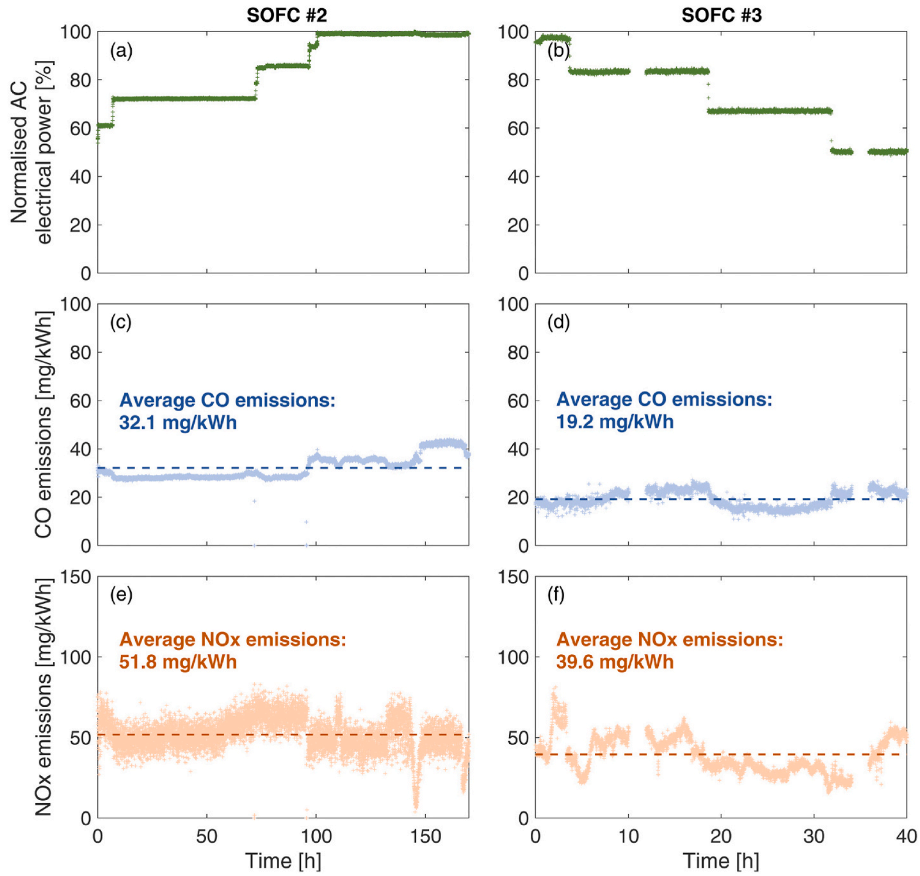

Fig. 10. CO (c, d) and NOx (e, f) measurements from SOFC #2 and SOFC #3 under variable power output (a, b).

values remain relatively stable across the selected modulation range and are not adversely impacted by part-load operation. This independence of pollutant emissions from the power output of the cogeneration system constitutes a significant advantage of SOFC systems when compared to conventional combustion-based technologies (where part-load operation often results in increased emission levels because of the off-design operation of the combustion section) [46].

The average data for CO and NO_x emissions from the three investigated SOFC modules are summarised in Fig. 11: they are in the range 6–32 mg/kWh (CO) and 7–52 mg/kWh (NO_x).

A comparison of pollutant emissions with alternative power generation technologies is presented in Table 7. The data from this study (for the SOFC technology) are provided in both mg/kWh and in mg/Nm^3 to facilitate the comparison with available data in the literature. The emissions from SOFCs during field operation are very low and align with the reported emissions values for other fuel cell technologies (MCFC and PEMFC). Emissions from internal combustion engines, which are widely employed for CHP applications, are in the range of approximately 280–520 mg/kWh for NO_x and around 620 mg/kWh for CO. These values can be achieved through an appropriate combustion system layout. Indeed, it should be noted that the formation of NO_x and CO occurs under opposite combustion conditions: NO_x emissions are reduced in low-dilution combustion zones, whereas CO formation is inhibited in high-dilution combustion zones. Achieving an exhaust stream with low NO_x and low CO levels thus necessitates a proper combustion set-up and, typically, a post-combustion unit to cope with the existing normative. Even when expressed in terms of power produced (mg/kWh), emissions from ICEs are about 1-2 order of magnitude higher than those from fuel cell-based systems.

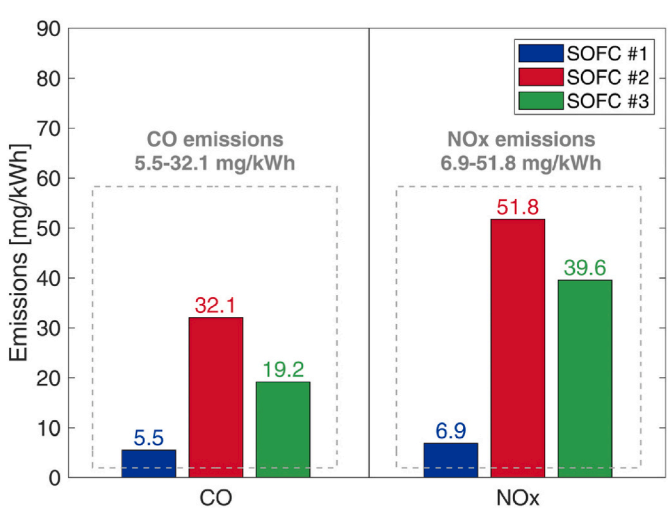

Fig. 11. Average CO and NO_x emissions from the Comsos SOFC modules.

Table 7
Emissions comparison between the SOFC solution and other technologies for power production. Data refer to NG-fed systems.

Technology	NO_x emissions	CO emissions	Ref.
SOFC	6.9–32.1 mg/kWh 1.2–6.1 mg/Nm^3	5.54–51.8 mg/kWh 0.8–6.0 mg/Nm^3	This work
MCFC	4.5 mg/kWh	n.a.	[47–49]
PEMFC	6.9 mg/kWh	7.11 mg/kWh	[50]
ICE	282–517 mg/kWh <250 or < 500 mg/Nm^3	618 mg/kWh 650 mg/Nm^3	[51–55]
Power plants (combined cycles)	208–243 mg/kWh 80–100 mg/Nm^3	6–11 mg/Nm^3	[54,56,57]

5. Conclusions

This study provides performance figures and emissions measurements obtained from the long-term operation (thousands of hours) of various commercial-scale SOFC modules installed in non-residential buildings. The assessment was performed as part of the Comsos project, focusing on six SOFC modules (namely SOFC #1A, #1B, #2A, #2B, #3A and #3B) supplied by the three main SOFC manufacturers at European level. Electrical and thermal efficiency values, degradation rates and pollutant emissions were presented and discussed. In addition, a comparison with competing cogeneration technologies was carried out.

The main results of the analysis can be wrapped up as follows.

- The system-level electrical efficiency (measured from natural gas input to AC electricity output) ranged from 51% to 61% under rated conditions, whereas the rated thermal efficiency was between 18% and 28%. Notably, a very high electrical efficiency spanning from 45% to 65% (with most data exceeding 50%) was found for the 50–100% modulation range (expressed as percentage of the rated power). The SOFC modules are thus able to operate across a broad modulation range while maintaining stable performance in terms of electricity generation. Moreover, maximum electrical efficiency values higher than 60% were observed (64.8% for SOFC #2A and 64.3% for SOFC #3A).
- The degradation rate was investigated for four SOFC modules and was found to be in the range 0.7–3.2 %/1000 h (expressed as a reduction in the electrical efficiency). Despite this wide range identified, the degradation rate was less than 1.3%/1000 h for three modules (and equal to 0.7 %/1000 h for two of them).
- In terms of PM emissions, the SOFC systems operated by filtering the inlet air (thus removing particulates) and producing almost no particulate matter. For this reason, the SOFC exhaust gases resulted in lower PM emissions (531 cm^{-3}) compared to the surrounding environment (9626 cm^{-3}). Additionally, CO and NO_x emissions were assessed, with results in the range of 6–32 mg/kWh and 7–52 mg/kWh, respectively. It is noteworthy that emissions levels remained relatively constant across the modulation range and were not affected by part-load operation.

Overall, if the end user can guarantee near-continuous operation (with limited number of on/off cycles), SOFCs are the best-in-class solution for decentralised power generation among commercial-scale systems (range from tens to hundreds of kW). Future work will involve continuing the analysis of the long-term operating data to delve deeper into the degradation phenomena, and to evaluate the SOFC performance under different fuel feedings (including biogas and hydrogen).

CRediT authorship contribution statement

Marta Gandiglio: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft, Writing – review & editing. **Paolo Marocco:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **Aki Nieminen:** Data curation, Formal analysis, Investigation, Resources. **Massimo Santarelli:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Jari Kiviaho:** Funding acquisition, Project administration, Supervision.

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.

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Acronyms

AC	Alternating current
BOP	Balance of plant
CHP	Combined heat and power
DC	Direct current
ELPI	Electrical low-pressure impactor
EU	European Union
FAT	Factory acceptance test
FC	Fuel cell
FTIR	Fourier transform infrared spectroscopy
GHG	Greenhouse gas
GT	Gas turbine
HEPA	High efficiency particulate air filter
HV	High voltage
ICE	Internal combustion engine
LCA	Life cycle assessment
LHV	Lower heating value
MCFC	Molten carbonate fuel cell
NG	Natural gas
PEMFC	Proton exchange membrane fuel cell
PM	Particulate matter
PV	Photovoltaics
r-SOC	Reversible solid oxide cell
SNG	Synthetic natural gas
SOC	Solid oxide cell
SOFC	Solid oxide fuel cell
WWTP	Wastewater treatment plant

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.08.332.

Appendix B

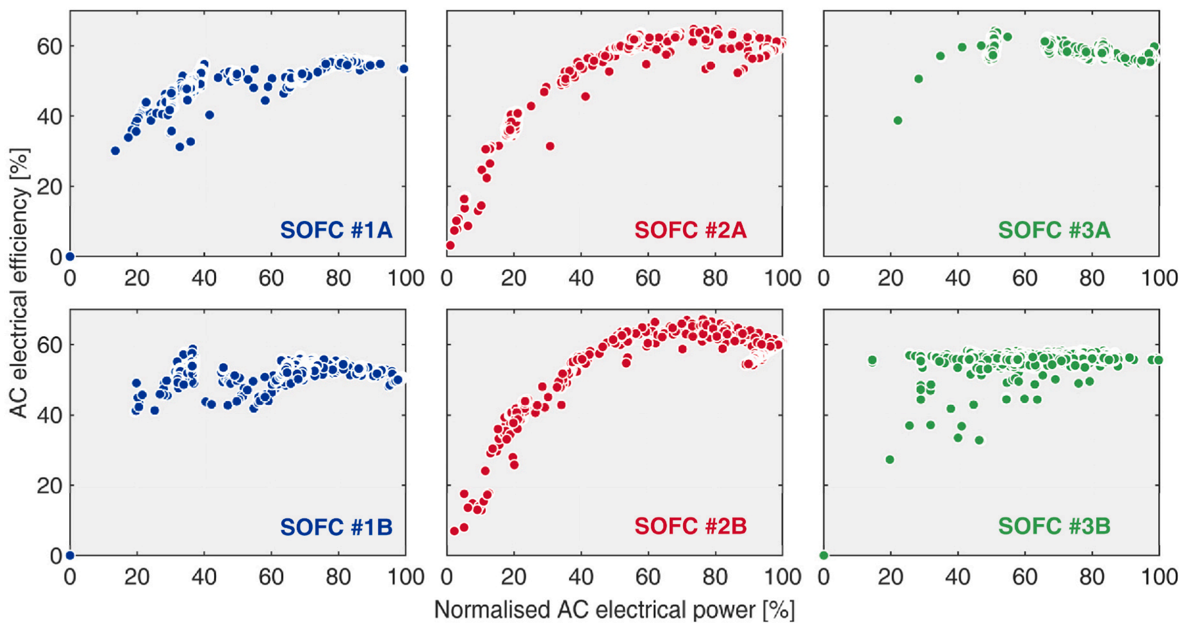

Fig. B1. AC electrical efficiency for 6 different SOFC modules.

Table B1
AC electrical and thermal efficiency of the SOFC modules in the key operating points: rated power, 50% of rated power, and maximum efficiency point.

Normalised AC electrical power [% $P_{SOFC,\ rated}$]	AC electrical efficiency [%]	Thermal efficiency [%]
SOFC #1A		
100% (rated)	53.3%	17.8%
50%	51.7%	15.6%
84.9% (max electrical efficiency)	56.6 %	17.0%
SOFC #1B		
100% (rated)	50.7%	21.7%
50%	46.0%	23.0%
36.6% (max electrical efficiency)	58.8%	32.9%
SOFC #2A		
100% (rated)	60.8%	28.4%
50%	59.1%	14.5%
73.5% (max electrical efficiency)	64.8%	24.6%
SOFC #2B		
100% (rated)	60.7%	n.a.*
50%	61.0%	n.a.*
76.5% (max electrical efficiency)	67.3%	n.a.*
SOFC #3A		
100% (rated)	56.6%	26.6%
50%	59.3%	22.1%
51% (max electrical efficiency)	64.3%	22.1%
SOFC #3B		
100% (rated)	56.0%	26.6%
50%	54.5%	27.8%
76.7% (max electrical efficiency)	58.4%	22.1%

* The data on thermal recovery were not available for SOFC module #2B. As a consequence, thermal and total efficiency were not evaluated.

References

[1] European Parliament. Revision of the energy performance of buildings directive: Fit for 55 package. Think Tank 2022. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)698901. [Accessed 19 April 2023].

[2] Chen O, Delmastro C. IEA Buildings 2022:1–284. https://www.iea.org/reports/buildings. [Accessed 19 April 2023].

[3] Simader G, Vidovic P. Success factors for demonstration projects of small-scale stationary fuel cells in residential buildings. E3S Web Conf 2022;334:1–7. https://doi.org/10.1051/e3sconf/202233404007.

[4] Nielsen ER, Brorson C. Learning points from demonstration of 1000 fuel cell based micro-CHP units Summary of analyses from the ene.field project Work package leader: learning points from demonstration of 1000 fuel cell based micro-CHP units - summary of analyses from the Ene. field project; 2017. https://enefield.eu/news/reports/learning-points-from-demonstration-of-1000-fuel-cell-based-micro-chp-units-2/.

[5] Pace EU. Project (ga No. 700339. https://pace-energy.eu/. [Accessed 19 April 2023].

[6] Owano N. Panasonic trims Ene-Farm fuel cell size and price. PhysOrg 2023. https://phys.org/news/2013-01-panasonic-trims-ene-farm-fuel-cell.html. [Accessed 19 April 2023].

[7] Tan L, Dong X, Chen C, Gong Z, Wang M. Diverse system layouts promising fine performance demonstration: a comprehensive review on present designs of SOFC-based energy systems for building applications. Energy Convers Manag 2021;245: 114539. https://doi.org/10.1016/J.ENCONMAN.2021.114539.

[8] He V, Gaffuri M, Van herle J, Schiffmann J. Readiness evaluation of SOFC-MGT hybrid systems with carbon capture for distributed combined heat and power. Energy Convers Manag 2023;278. https://doi.org/10.1016/J.ENCONMAN.2023.116728.

[9] Narayanan M, Mengedoht G, Commerell W. Evaluation of SOFC-CHP's ability to integrate thermal and electrical energy system decentrally in a single-family house with model predictive controller. Sustain Energy Technol Assessments 2021;48. https://doi.org/10.1016/J.SETA.2021.101643.

[10] Zhou J, Wang Z, Han M, Sun Z, Sun K. Optimization of a 30 kW SOFC combined heat and power system with different cycles and hydrocarbon fuels. Int J Hydrogen Energy 2022;47:4109–19. https://doi.org/10.1016/J.IJHYDENE.2021.11.049.

[11] Marocco P, Gandiglio M, Santarelli M. When SOFC-based cogeneration systems become convenient? A cost-optimal analysis. Energy Rep 2022;8:8709–21. https://doi.org/10.1016/j.egyr.2022.06.015.

[12] Marocco P, Gandiglio M, Santarelli M. Evaluation of the environmental sustainability of SOFC-based cogeneration systems in commercial buildings. Energy Rep 2023;9:433–8. https://doi.org/10.1016/J.EGYR.2023.09.032.

[13] De Masi RF, Festa V, Penchini D, Ruggiero S, Tariello F, Vanoli GP, et al. State of art of hydrogen utilization for building sector and set-up with preliminary experimental results of 1 kWel solid oxide fuel cell installed in a nearly zero energy house. Energy 2024;302:131810. https://doi.org/10.1016/j.energy.2024.131810.

[14] Mottaghizadeh P, Fardadi M, Jabbari F, Brouwer J. Dynamics and control of a thermally self-sustaining energy storage system using integrated solid oxide cells for an islanded building. Int J Hydrogen Energy 2021;46:24891–908. https://doi.org/10.1016/j.ijhydene.2021.03.136.

[15] Di Florio G, Macchi EG, Mongibello L, Baratto MC, Basosi R, Busi E, et al. Comparative life cycle assessment of two different SOFC-based cogeneration systems with thermal energy storage integrated into a single-family house nanogrid. Appl Energy 2021;285. https://doi.org/10.1016/J.APENERGY.2020.116378.

[16] Lamagna M, Groppi D, Nastasi B. Reversible solid oxide cells applications to the building sector. Int J Hydrogen Energy 2023;48:27033–58. https://doi.org/10.1016/j.ijhydene.2023.03.387.

[17] Langnickel H, Rautanen M, Gandiglio M, Santarelli M, Hakala T, Acri M, et al. Efficiency analysis of 50 kWe SOFC systems fueled with biogas from waste water. J Power Sources Adv 2020;2:100009. https://doi.org/10.1016/J.POWERA.2020.100009.

[18] Baldinelli A, Barelli L, Bidini G, Cinti G. Micro-cogeneration based on solid oxide fuel cells: market opportunities in the agriculture/livestock sector. Int J Hydrogen Energy 2021;46:10036–48. https://doi.org/10.1016/J.IJHYDENE.2020.04.226.

[19] Gandiglio M, Drago D, Santarelli M. Techno-economic analysis of a solid oxide fuel cell installation in a biogas plant fed by agricultural residues and comparison with alternative biogas exploitation paths. Energy Proc 2016;101:1002–9. https://doi.org/10.1016/j.egypro.2016.11.127.

[20] Bloom Energy. Bloom energy server 2023. https://www.bloomenergy.com/resource/bloom-energy-server/. [Accessed 28 March 2023].

[21] Bloom Energy. Hydrogen data sheet 2023. https://www.bloomenergy.com/resource/hydrogen-spec-sheet/. [Accessed 28 March 2023].

[22] Bosch. Shaping the energy transition with SOFC 2023. www.bosch-sofc.com. [Accessed 28 March 2023].

[23] Oy Convion. Convion fuel cell systems 2023. https://convion.fi/. [Accessed 28 March 2023].

[24] FuelCell Energy. Solid oxide fuel cell. 2023. https://www.fuelcellenergy.com/platform/solid-oxide-fuel-cell-platforms. [Accessed 28 March 2023].

[25] Mitsubishi Power. Hybrid system of solid oxide fuel cells (SOFC) and micro gas turbines (MGT). https://power.mhi.com/products/sofc. [Accessed 28 March 2023].

[26] Ando Y, Oozawa H, Mihara M, Irie H, Urashita Y, Ikegami T. Demonstration of SOFC-micro gas turbine (MGT) hybrid systems for commercialization. Mitsubishi Heavy Ind Tech Rev 2015;52. https://www.mhi.co.jp/technology/review/pdf/e524/e524047.pdf.

[27] Solydera. Bluegen BG-15 2023. https://bluegen.eu/en/(accessed March 28, 2023).

[28] Sunfire GmbH. Sunfire supplies ThyssenKrupp marine systems with 50 kW SOFC - Sunfire. 2015. https://www.sunfire.de/en/news/detail/sunfire-supplies-thyssenkrupp-marine-systems-with-50-kw-sofc-20.

[29] Gandiglio M, Santarelli M, Münch M, Modena S, Varkaraki E, Hakala T, et al. Deliverable 5.2: techno-economic models of the considered SOFC-based CHP systems - ComSos "Commercial-scale SOFC systems. 2018. https://www.comsos.eu/comsos-results/techno-economic-models-of-the-considered-sofc-based-chp-systems-2/.

[30] Gandiglio M, Lanzini A, Santarelli M, Acri M, Hakala T, Rautanen M. Results from an industrial size biogas-fed SOFC plant (the DEMOSOFC project). Int J Hydrogen Energy 2020;45:5449–64. https://doi.org/10.1016/J.IJHYDENE.2019.08.022.

[31] Comsos Project. Official website eu project (ga 779481). https://www.comsos.eu/. [Accessed 20 April 2023].

[32] Accurso F, Gandiglio M, Santarelli M, Buunk J, Hakala T, Kiviaho J, et al. Installation of fuel cell-based cogeneration systems in the commercial and retail sector: assessment in the framework of the COMSOS project. Energy Convers Manag 2021;239. https://doi.org/10.1016/J.ENCONMAN.2021.114202.

[33] Tjaden B, Gandiglio M, Lanzini A, Santarelli M, Järvinen M, Jarvinen M. Small-scale biogas-SOFC plant: technical analysis and assessment of different fuel reforming options. Energy Fuel 2014;28:4216–32. https://doi.org/10.1021/ef500212j.

[34] Curletti F, Gandiglio M, Lanzini A, Santarelli M, Maréchal F. Large size biogas-fed Solid Oxide Fuel Cell power plants with carbon dioxide management: technical and economic optimization. J Power Sources 2015;294:669–90. https://doi.org/10.1016/j.jpowsour.2015.06.091.

[35] International Electrotechnical Commission (IEC). Iec 62282-3-200:2015 - fuel cell technologies - Part 3-200: stationary fuel cell power systems - performance test methods. 2015. https://webstore.iec.ch/publication/23736. [Accessed 28 March 2023].

[36] Gandiglio M, Santarelli M, Münch M, Modena S, Varkaraki E, Hakala T, et al. Deliverable D4.4 - verification plan of the installed systems. 2019. https://www.comsos.eu/comsos-results/verification-plan-of-the-installed-systems/.

[37] Rautanen M, Vesala H, Kajolinna T, Pellikka T. DEMOSOFC project - deliverable number 4.3-a Analysis of the emissions from the DEMO. 2018. http://www.demosofc.eu/?attachment_id=1027.

[38] Lanzini A, Madi H, Chiodo V, Papurello D, Maisano S, Santarelli M, et al. Dealing with fuel contaminants in biogas-fed solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) plants: degradation of catalytic and electro-catalytic active surfaces and related gas purification methods. Prog Energy Combust Sci 2017;61:150–88. https://doi.org/10.1016/j.pecs.2017.04.002.

[39] Cigolotti V, Genovese M, Fragiacomo P. Comprehensive review on fuel cell technology for stationary applications as sustainable and efficient poly-generation energy systems. Energies 2021;14:4963. https://doi.org/10.3390/EN14164963. 2021;14:4963.

[40] Smith RW. Steam turbine cycles and cycle design optimization: combined cycle power plants. Adv. Steam turbines mod. Power plants. Woodhead Publishing; 2022. p. 61–102. https://doi.org/10.1016/B978-0-12-824359-6.00001-9. Woodhead Publishing Series in Energy.

[41] Shiozaki S, Fujii T, Takenaga K, Ozawa M, Yamada A. Gas turbine combined cycle (Ed.). In: JSME Series in Thermal and Nuclear Power Generation, Adv. Power Boil., 2. Elsevier; 2021. p. 305–44. https://doi.org/10.1016/B978-0-12-820360-6.00006-0.

[42] Zarabi Golkhatmi S, Asghar MI, Lund PD. A review on solid oxide fuel cell durability: latest progress, mechanisms, and study tools. Renew Sustain Energy Rev 2022;161:112339. https://doi.org/10.1016/J.RSER.2022.112339.

[43] Kim Y-D, Lee J-I, Saqib M, Park K-Y, Hong J, Yoon KJ, et al. Degradation of anode-supported solid oxide fuel cells under load trip and cycle conditions and their degradation prevention operating logic. J Electrochem Soc 2018;165:F728–35. https://doi.org/10.1149/2.1391809jes.

[44] Lai H, Harun NF, Tucker D, Adams TA. Design and eco-technoeconomic analyses of SOFC/GT hybrid systems accounting for long-term degradation effects. Int J Hydrogen Energy 2021;46:5612–29. https://doi.org/10.1016/J.IJHYDENE.2020.11.032.

[45] Lai H, Adams TA. Eco-technoeconomic analyses of natural gas-powered SOFC/GT hybrid plants accounting for long-term degradation effects via pseudo-steady-state model simulations. J Electrochem Energy Convers Storage 2024;21. https://doi.org/10.1115/1.4062711.

[46] Gonzalez-Salazar MA, Kirsten T, Prchlik L. Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. Renew Sustain Energy Rev 2018;82:1497–513. https://doi.org/10.1016/J.RSER.2017.05.278.

[47] Mehmeti A, Pedro Pérez-Trujillo J, Elizalde-Blancas F, Angelis-Dimakis A, McPhail SJ. Exergetic, environmental and economic sustainability assessment of stationary Molten Carbonate Fuel Cells. Energy Convers Manag 2018;168:276–87. https://doi.org/10.1016/j.enconman.2018.04.095.

[48] Bove R, Moreno R. International status of molten carbonate fuel cells technology 2015 (EUR 23363 EN - 2008). 2008. https://publications.jrc.ec.europa.eu/repository/handle/JRC44203.

[49] Maru HC, Farooque M. Molten carbonate fuel cell: product design improvement. 2005. https://www.osti.gov/servlets/purl/895626.

[50] Soltanimehr S, Rezaei F, Rahimpour MR. Impact assessment of exhaust gas emissions from cogeneration PEMFC systems. Curr Trends Futur Dev Membr Cogener Syst Membr Technol 2020:49–64. https://doi.org/10.1016/B978-0-12-817807-2.00003-4.

[51] Jenbacher. Gas engines - type 2. 2023. https://www.jenbacher.com/en/gas-engines/type-2/j208.
[52] Caterpillar. Emission reduction for CHP. 2023. https://www.cat.com/en_US/by-industry/electric-power/Articles/White-papers/emission-reduction-for-chp.html#multimedia-glgeEaeqKlvGlbM-poster.
[53] Web Testo Italia. Combined heat and power plant – CHP. 2023. https://static-int.testo.com/media/b9/60/3d20e1cbe010/Knowledge-Basic-testo-350-Application-CHP-EN.pdf.
[54] Torchio MF. Comparison of district heating CHP and distributed generation CHP with energy, environmental and economic criteria for Northern Italy. Energy Convers Manag 2015;92:114–28. https://doi.org/10.1016/J.ENCONMAN.2014.12.052.
[55] Kristensen PG, Jensen JK, Nielsen M, Illerup JB. Emission factors for gas fired CHP units< 25 MW. Novemb: IGRC; 2004. https://www2.dmu.dk/1_viden/2_Miljoe-tilstand/3_luft/4_adaei/doc/EmissionfactorsforgasfiredCHPunits.pdf.
[56] Gouw JA de, Parrish DD, Frost GJ, Trainer M. Reduced emissions of CO2, NOx, and SO2 from U.S. power plants owing to switch from coal to natural gas with combined cycle technology. Earth's Future 2014;2:75–82. https://doi.org/10.1002/2013EF000196.
[57] Wood DA. Long-term atmospheric pollutant emissions from a combined cycle gas turbine: trend monitoring and prediction applying machine learning. Fuel 2023;343:127722. https://doi.org/10.1016/J.FUEL.2023.127722.