Energy 310 (2024) 133145

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Technoeconomic and environmental performance assessment of solid oxide fuel cell-based cogeneration system configurations

Dibyendu Roy *, Samiran Samanta, Sumit Roy, Andrew Smallbone, Anthony Paul Roskilly

Department of Engineering, Durham University, Durham, DH1 3LE, UK

ARTICLE INFO

Handling editor: G Chicco

Keywords:
Hydrogen energy
Solid oxide fuel cell
CHP
Technoeconomic analysis
Decarbonisation

ABSTRACT

In this study, an innovative energy solution to fulfil the electricity and heating needs of a mixed community, including residences, a commercial building, and a small brewery has been investigated. The primary objective is to comprehensively analyse the technoeconomic, and environmental aspects of a UK-based solid oxide fuel cell (SOFC) energy hub designed for local-scale electricity and heating demands. This present study investigates two different configurations: (a) SOFC-based cogeneration and (b) SOFC-heat pump cogeneration configuration. These configurations are modelled to provide year-round electricity and heating for a local scale application and are evaluated using hydrogen and natural gas as fuels. A thorough environmental assessment is also conducted for SOFC and SOFC-heat pump system configurations fuelled by natural gas. The hydrogen fuelled SOFC-heat pump configuration outperforms other system configuration with energy efficiency of 96 %. Meanwhile, the hydrogen-fuelled SOFC cogeneration system yields maximum exergy efficiency at 61.51 %. The natural gas-powered SOFC-heat pump cogeneration system yields the lowest levelized cost of energy (LCOE) at 0.1603 £/kWh, in comparison to the higher LCOE of 0.213 £/kWh for the alkaline hydrogen-fuelled system. The natural gas-fuelled SOFC system emits 0.3352 kg/kWh of CO_2, with even lower emissions of 0.275 kg/kWh for the SOFC-heat pump system configuration.

1. Introduction

1.1. Motivation and background

With increasing energy demand, growing concerns on environmental challenges associated with traditional fossils fuels and the consequences of climate change becoming more apparent, it is critical to move towards cleaner and sustainable energy sources. Hydrogen is a clean fuel, and it is expected to play a major role in achieving decarbonisation targets. It is projected that hydrogen demand in the UK expected to grow in the early 2030s and installed production capacity requirement could reach up to 20 GW by the year 2035 [1]. Large scale deployment of low carbon fuels and zero carbon fuels such as green hydrogen is required in the United Kingdom, as it is committed to achieve net zero target by the year 2050 [2].

In the UK, natural gas boilers or electric heating are the predominant heating options for most residential homes and commercial office buildings. Very few homes and buildings use heat pumps for heating, and hydrogen for heating homes is in the phase of a pilot project trial [3]. It will be a challenging task to completely replace natural gas boilers with hydrogen boilers in a short period of time. Presently some new gas boiler supports up to 20 % hydrogen blending with natural gas [4]. Furthermore, the cost of green hydrogen varies geographically; for example in the USA, the cost is lower, while green hydrogen remains slightly more expensive in the UK [5]. Presently the UK government intends to build up to 5 GW low-carbon hydrogen production capacity, which could help reduce the cost of green hydrogen [2]. Interestingly, hydrogen could be a more effective solution to use it as a fuel in fuel cells to generate both electricity and heat. Fuel cells are devices that convert chemical energy into electrical energy through an electrochemical reaction. Among fuel cells, solid oxide fuel cell (SOFC) offer high energy efficiency, fuel flexibility, quiet operation, low environmental impact, and reduced corrosion issues. Furthermore, SOFC also produces useful waste heat, which can be used in cogeneration and tri-generation applications.

Combined heat and power (CHP) systems is one type of cogeneration which produce simultaneous heat and power and have high energy efficiency. The CHP systems can be classified as follows [6]: a) prime

* Corresponding author.
E-mail address: dibyendu.roy@durham.ac.uk (D. Roy).

https://doi.org/10.1016/j.energy.2024.133145
Received 9 October 2023; Received in revised form 12 August 2024; Accepted 8 September 2024
Available online 16 September 2024

movers, such as steam turbines, gas turbines, internal combustion engine, Stirling engines, fuel cells, and organic Rankine cycles; b) energy sequences, such as topping cycles and bottoming cycles; and c) plant size. It is important to note that the effectiveness of CHP systems is dependent on the technology employed and its design [7]. Also, the efficiency of fuel cell-based CHP systems ranges from 60 to 90 % [8]. Onsite production of electricity, CHP systems could avoid transmission and distribution losses, and it can operate independently of the grid, enhancing resilience and reliability [9].

The energy landscape is rapidly changing and becoming increasingly complex, making it crucial to take a comprehensive and interdisciplinary approach when evaluating the feasibility and viability of new energy solutions. One such solution is the application of SOFC, which has the potential to play a pivotal role in decarbonising energy systems. SOFCs, which function at high temperatures within the range of 650 °C–950 °C [10], are capable of directly converting chemical energy in fuels into electrical energy through electrochemical reactions. Efficiency of SOFC is not limited by the Carnot efficiency and yield higher efficiency, high flexibility and low emissions [11]. In this context, the realization of SOFC-based energy hubs presents an alternative approach for decarbonisation, addressing both electricity and heating demands within the United Kingdom.

1.2. Literature review

Several researchers have investigated integrated systems utilising SOFCs. For example, Zheng et al. [12] conducted energy and exergy analyses on a system that integrated SOFC with an electrolyser, chiller, and heat storage system under varying seasonal environments. They reported energy efficiencies of 82.61 %, 79.36 %, and 87.30 % for summer, transitional seasons, and winter, respectively, along with corresponding exergy efficiencies of 43.85 %, 44.47 %, and 45.58 %. In a separate study, Wang et al. [13] proposed utilising SOFCs in conjunction with a gas turbine (GT) and an organic Rankine cycle (ORC) for a marine ship. They reported that the investment cost of the heat exchanger accounted for the highest proportion (22.62 %) and suggested focusing on minimizing the heat exchange process. In another study, Ran et al. [14] investigated the thermodynamic performance of an integrated system involving SOFC, micro-GT, supercritical CO_2 (s-CO_2), and an absorption refrigerator. They reported energy and electrical efficiencies of 70.49 % and 60.59 %, respectively. Obara [15] investigated a combined system that integrates SOFCs with carbon dioxide capture, utilisation, and storage (CCUS) and reported a levelised unit cost of electricity (LCOE) of 0.36 $/kWh. In another study, Veldhuizen et al. [16] investigated the performance of a marinized SOFC system using methane, methanol, diesel, ammonia, and hydrogen as fuels, and reported that the electrical efficiency was highest for methane (58.1 %), followed by diesel (57.6 %) and ammonia (55.1 %). Alnaqi et al. [17] investigated two different combinations of biomass SOFC-Vanadium-Chlorine cycle integrated systems using biomass as a fuel, and reported exergy efficiencies of 58.96 % and 60.79 %, respectively. In another study, Zhao et al. [18] explored the integration of a proton exchange membrane electrolyser (PEME) hydrogen production facility with an SOFC-GT system, ORC, and s-CO_2 cycle. The results demonstrated high round-trip thermal and exergy efficiencies of 54.29 % and 50.34 %, with an energy storage density of 367.92 $kWh \cdot m^{-3}$. Roy [19] presented a proposal for the integration of a rice husk gasification facility with an SOFC stack, externally fired gas turbine (EFGT), and water heating system. The study reported an impressive maximum exergy efficiency of 41.15 % and the integration achieved the lowest levelised unit cost of energy, amounting to 0.044 $/kWh. In their study, Ding et al. [20] conducted a thermodynamic analysis of integrating SOFC with a graphene-collector thermionic energy converter (GTEC) to enhance electricity production. The findings revealed that the hybrid system achieved a remarkable maximum power density of 0.774 W/cm^2 at 1073 K. This value is 1.20 times higher than the power density achieved by the standalone SOFC. In their research, Narayanan et al. [21] conducted a study on energy management for a single house utilising SOFC-based CHP facility. The study focused on integrating this system into a decentralised residential energy system, which included solar thermal collectors, photovoltaics, sensible heat storage, lithium-ion batteries, and grid electricity.

Molten carbonate fuel cell (MCFC) is another promising high-temperature fuel cell. However, recent research shows that the levelised cost of electricity (LCOE) of MCFC systems is higher than that of SOFC-based systems. For example, Pérez-Trujillo et al. [22] compared the performance of SOFC-GT system with MCFC-GT system and reported that the SOFC-GT system had a lower LCOE, yielding 0.339 $/kWh, while the MCFC-GT system yielded 0.875 $/kWh. A recent study by Zhao et al. [23] shows that SOFC-based systems can be effectively employed in cogeneration systems to generate both electricity and high-quality steam for industrial applications. The study reported a net efficiency of 56.9 % and a cogeneration efficiency of 86.8 %. Ahmadi et al. [24] investigate different combinations of SOFC and absorption power cycle to provide power and domestic hot water for residential or industrial applications, and report that exergy efficiency can reach up to 50 %.

For heating applications, there is currently a major focus on heat pump technologies. This technology is mature and offers a cost-effective energy efficiency option. Heat pumps can be efficiently integrated with SOFCs or other types of fuel cells for cogeneration applications. For example, Li et al. [25] integrated a ground-source heat pump with an SOFC for the utilisation of agricultural waste in a rural area in China. They reported that an energy efficiency of 67.3 % and an exergy efficiency of 29.2 % can be achieved. In another study, Mei et al. [26] investigated a cogeneration system that integrated SOFC, a thermoelectric generator, and an absorption heat pump, and reported the electrical efficiency of 44.53 %. Capuano et al. [27] examined the design and analysis of a proton exchange membrane fuel cell (PEMFC) integrated with an air source heat pump for residential space heating. The study revealed that this configuration achieved a coefficient of performance (COP) exceeding 1.5, resulting in reduced primary energy requirements and up to 60 % lower operating costs compared to traditional boilers. Jin et al. [28] conducted a study on a small-scale residential application, examining the integration of PEMFC and heat pump cogeneration system. The results demonstrated an impressive overall COP improvement of 7.6 % compared to conventional independent heating methods. In our previous study [29], we assessed the feasibility of SOFC and heat pump (HP)-based cogeneration solely for residential houses using technoeconomic analysis in two distinct case studies, and reported minimal LCOE of 0.2984£/kWh with hydrogen as fuel for SOFC-HP system.

1.3. Novelty and contribution

Based on the literature review, it is evident that there are existing studies on integrated energy systems based on different fuel cells as prime movers. However, most of the previous fuel cell based integrated energy system studies were mainly concentrated on energy, exergy and economic analysis. Previous studies on focused on the influence of important parameters on the system level performances of SOFC based systems. Surprisingly, there seems to be a notable gap in the literature regarding the exploration of the concept of SOFC integrated energy hub specifically designed to meet the real-world electricity and heating demands of community-scale applications. There is a lack of research on onsite SOFC based CHP systems based on local energy demand and the appropriate sizing of the systems based on actual demand.

This study investigates the viability of using hydrogen and natural gas in a solid oxide fuel cell based energy hub to meet the local scale electricity and heating demands in the United Kingdom. The proposed SOFC-based energy hub is capable of providing electricity and heating to a residential community of 36 homes, a commercial building, and a small brewing and beverage industry based in the UK. The study considered two distinct configurations: (a) SOFC-based cogeneration system and (b) SOFC-heat pump-based cogeneration system. Both configurations were evaluated using both hydrogen and natural gas as fuels. A comprehensive comparison of the technical and economic performance of both configurations was performed. Furthermore, the study provides a comprehensive evaluation of the environmental assessment of SOFC, and SOFC-heat pump systems fuelled by natural gas. The objective of this study is also consistent with United Nations Sustainable Development Goal (SDG) No. 7, which aims to achieve "Affordable and Clean Energy". This study offers a comprehensive analysis of the technical, economic, and environmental aspects of an energy hub based on solid oxide fuel cells to meet the local scale electricity and heating demands in the United Kingdom. In this study, we have broadened the scope by including the energy demands of a commercial building, a small brewing and beverage industry, and residential houses. To the best of the authors' knowledge, this is the first study of its kind that is based on the actual electricity and heating demands of residential homes, a commercial building, and a small industry in the UK. This study provides a valuable insight into the potential of hydrogen as a clean energy source for CHP applications and provides a comparison with natural gas-fuelled CHP systems. The study also aims to offer invaluable insights for policymakers and stakeholders in the energy sector, with a particular focus on the context of the UK's net-zero 2050 strategy. The major contributions of the study are listed below:

- Conceptualization, design and modelling of SOFC-based energy hub to meet the local-scale electricity and heating demands of a residential community, a commercial building, and a small industry based in the United Kingdom.
- Feasibility assessment of SOFC based zero carbon cogeneration configurations with green hydrogen as fuel has been performed.
- Performance comparison of the proposed systems when operated with green hydrogen and natural gas.
- Investigation of energy and exergy analyses of the conceptualized systems.
- Economic analysis has been performed to estimate the levelized cost of energy(LCOE).
- Sensitivity analysis of the cost of green hydrogen from PEM and ALK electrolysers has been conducted to estimate LCOE.
- Environmental analysis has been conducted to estimate the levelized CO_2 emissions.
- Comparison of the performance of the proposed configurations with previous SOFC-based systems.

2. Material and methods

The framework of this study is presented in Fig. 1. SOFC-based energy hubs were designed and sized based on the electricity and heating demands of a cluster that integrates a commercial building, a small brewing and beverage industry, and residential houses. The systems were analysed in detail using energy, exergy, economic, and environmental analyses.

2.1. Energy demand

The electricity and heating demand of a residential hub with 36 number of houses, a commercial building of 800 m^2 and a small Brewing & Beverage industry were chosen. Fig. 2 shows the residential, commercial, and industrial heating and electricity demands throughout the year. The systems were modelled in such way that it can supply the required heating and electrical requirements throughout the year. The electrical and heating demands of the residential and commercial buildings are taken from report by the Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, United Kingdom [30], and are scaled accordingly. The heating and electrical demands of the brewery are taken from Ref. [31].

2.2. System description

The study investigated two distinct configurations: (1) SOFC-based Combined Heat and Power (CHP) system and (2) SOFC-Heat Pump-

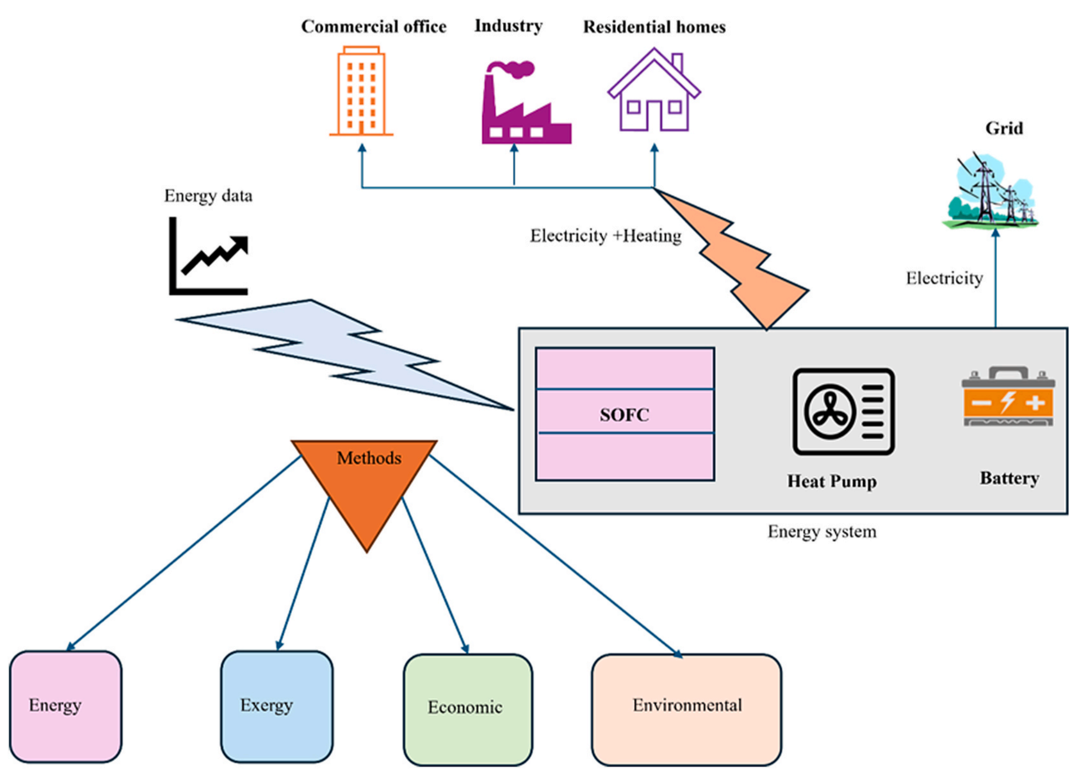

Fig. 1. Framework of the study.

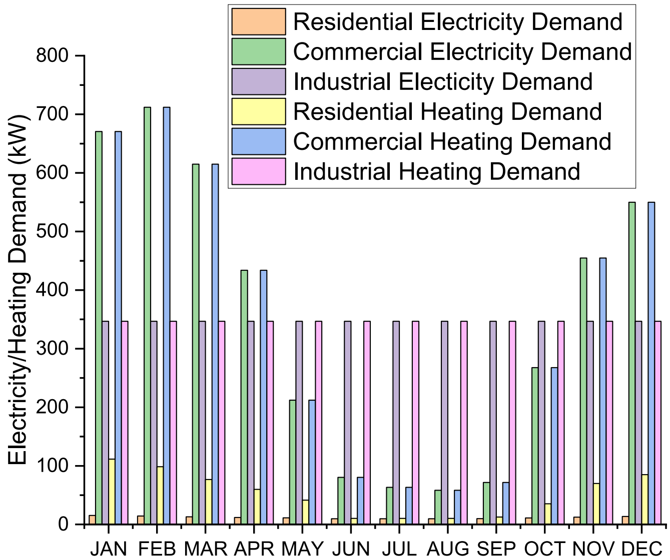

Fig. 2. Monthly electricity and heat demand of the cluster.

based CHP system. MATLAB software environment was used for the technical, economic as well as the environmental analysis of the systems. Both configurations were analysed utilising green hydrogen and natural gas (NG) as fuels. The configurations, when operated using green hydrogen, are realised as zero-carbon CHP systems. The schematic diagrams for these proposed systems are shown in Figs. 3 and 4, respectively. The unutilised fuel from the SOFC was completely burned in the afterburner which has an outlet temperature of 960 °C. This waste heat was recovered and was used for preheating the fuel and air to 800 °C for the SOFC. Furthermore, the waste was used for producing the hot water for residential applications and generation of steam for industrial processes. The SOFC-CHP system configuration fuelled by NG, depicted in Fig. 3a, is an integration of an SOFC, a heat recovery steam generator (HRSG), and a hot water production unit. The required electricity for the cluster is generated by the SOFC, and the waste heat from the SOFC stack is recovered by the HRSG and water heater unit. The steam produced from the HRSG unit is supplied to the mixer unit, where it is mixed with the natural gas. In addition, steam at 100 °C is also provided to a small industry for process heating applications. Hot water tanks were assumed as "Heat Storage" in this study. The hot water from the heat storage tank is then supplied to residential homes and office buildings, maintaining a supply temperature of 80 °C and a return temperature of 25 °C. The hydrogen-fuelled SOFC CHP configuration is shown in Fig. 3b, combining SOFC stack to supply electricity to the cluster, HRSG to supply steam at 100 °C to the industry, and a water heater to supply hot water to commercial buildings and residential houses. The systems have been meticulously designed to fulfil the required heat demand of the cluster efficiently. The primary focus lies in meeting the specific heat requirements of the cluster while minimizing any excess electricity generation. Some excess electricity is stored in batteries, keeping 15 % of the surplus for the cluster's needs. The remaining surplus power is supplied to the grid, thereby strengthening the overall reliability of the system.

The SOFC-HP CHP system configuration fuelled by NG, depicted in Fig. 4a, is identical to Fig. 3a. Only a heat pump is added to the system configuration as shown in Fig. 4a. It is considered that the heat pumps are installed in the commercial buildings and residential homes with the electricity for the heat pumps supplied by the fuel cell stack. The floor heating requirement for the commercial buildings and residential homes is managed by the heat pumps. Waste heat is recovered from the fuel cell stack by the water heater unit, which then provides hot water to residential homes and office buildings. Moreover, steam at 100 °C is also supplied from the HRSG unit to the small industry for process heating purposes. The hydrogen-fuelled SOFC-HP based CHP configuration is shown in Fig. 4b. Similar to Fig. 4a, this CHP system also considered heat pumps installed to provide space heating in commercial buildings and residential homes, with the electricity for the heat pumps supplied by the fuel cell stack. Additionally, steam is provided to the industry by the HRSG, and hot water is supplied to the buildings and residential homes by the water heater.

2.3. Solid oxide fuel cell

A solid oxide fuel cell is a high temperature device that functions within the range of 650–950 °C. It can utilise a diverse range of fuels, including methane, syngas, biogas, ammonia, methanol etc. This investigation evaluates a specific type of SOFC, known as the internal reforming model. This unique design takes into account several chemical reactions that occur internally. Following reactions were considered in the SOFC model [32].

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \Delta H = +206.0 \text{ kJ/mol} \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta H = -41 \text{ kJ/mol} \tag{2}$$

$$H_2 + 0.5O_2 \rightarrow H_2O \qquad \Delta H = -242.0 \text{ kJ/mol} \tag{3}$$

The total current flow through the SOFC is evaluated by the equation number (4) [33]:

$$I_{FC} = \frac{\dot{m}_{a,in} \times \left(y_{H_2} + y_{CO} + y_{CH_4}\right) \times 2 \times F}{M_{mol,a}} \tag{4}$$

where, $y_{H_2}, y_{CO}, y_{CH_4}$ indicate the concentrations of H_2, CO and CH_4 at the anode inlet, respectively. F stands for Faraday constant; $M_{mol,a}$ refers to the molar mass of fuel entering the anode channel and $\dot{m}_{a,in}$ refers to the mass flow rate of the fuel entering the anode.

It is considered in the model that only a portion of the fuel undergoes transformation at the SOFC unit. The equation number (5) is employed to estimate the fuel utilisation factor (UF).

$$UF = \frac{I}{I_{FC}} \tag{5}$$

where, I represents the actual current flow.

The cell voltage for the SOFC is estimated by the equation number (6) [33,34]:

$$V_{SOFC} = \frac{\Delta G}{2F} + \frac{RT_{SOFC}}{2F} ln\left(\frac{y_{O_2}^{0.5} \times y_{H_2}}{y_{H_2O}} \times P_{SOFC}^{0.5}\right) - j \times R_{SOFC} \tag{6}$$

where, R_{SOFC} denotes the area specific resistance for fuel cell; ΔG is the standard Gibbs free energy; T_{SOFC} is the operating temperature of SOFC; j represents the current density; P_{SOFC} stands for the pressure; y_{H_2O} is the mole fraction of H_2O; y_{O_2} denotes the mole fraction of O_2, and R denotes the universal gas constant.

The power output from the SOFC stack is determined by the equation number (7).

$$\dot{W}_{SOFC} = N_{SOFC} \times j \times A_{SOFC} \times V_{SOFC} \times \eta_{inv} \tag{7}$$

where, N_{SOFC} is the cell numbers; j denotes the current density; A_{SOFC} is the area of a cell; η_{inv} is the inverter efficiency.

Singhal et al.'s experimental findings [35] were utilised to confirm the accuracy of the current SOFC model. The fuel mixture used for validation consisted of 89 % hydrogen and 11 % H_2O, and the cell temperature was fixed at 1000 °C. As shown in Fig. 5, the results of the SOFC model match the experimental data with discrepancy of 3.7 %.

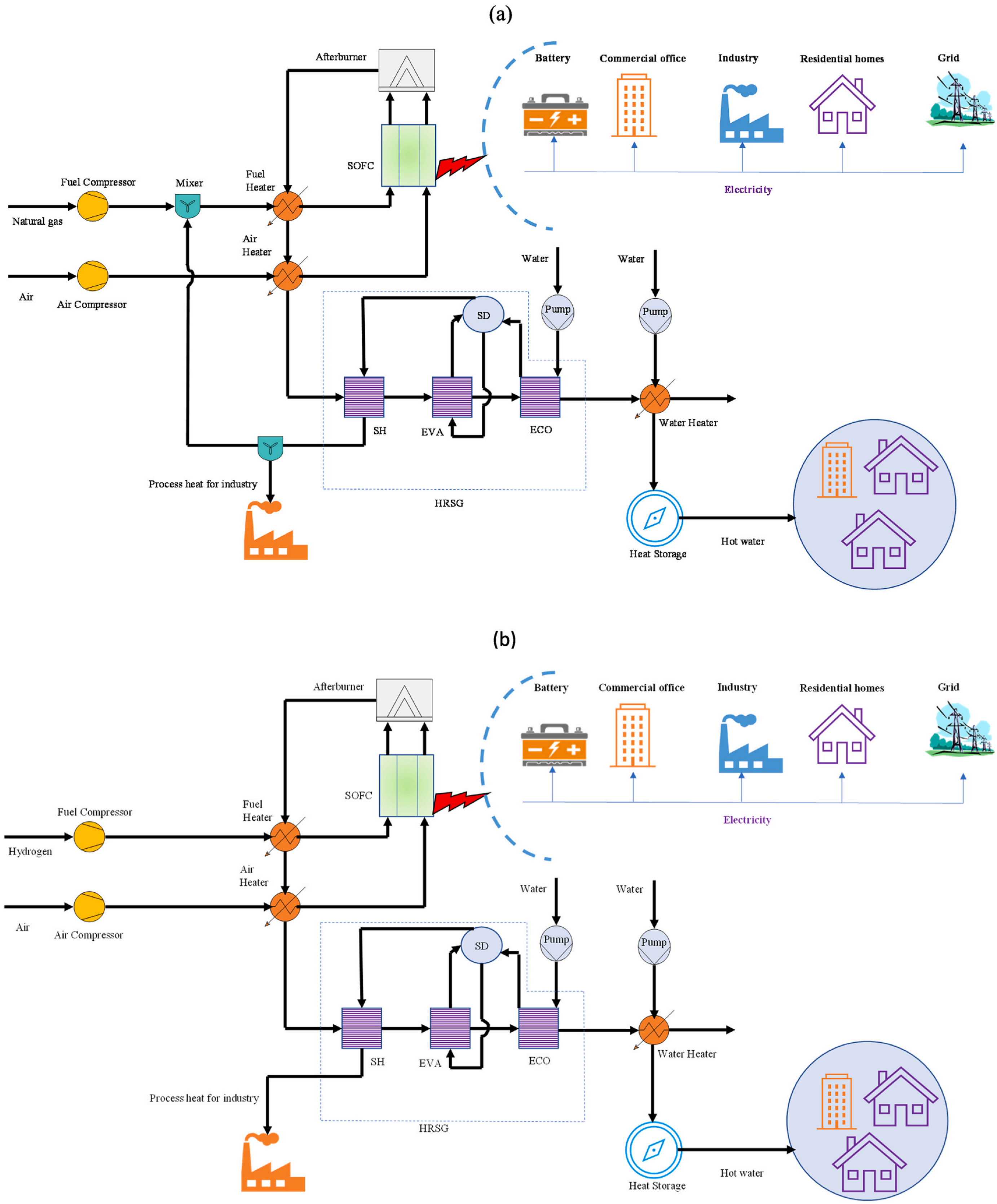

Fig. 3. Layout of SOFC based CHP system fuelled by (a) NG and (b) H_2.

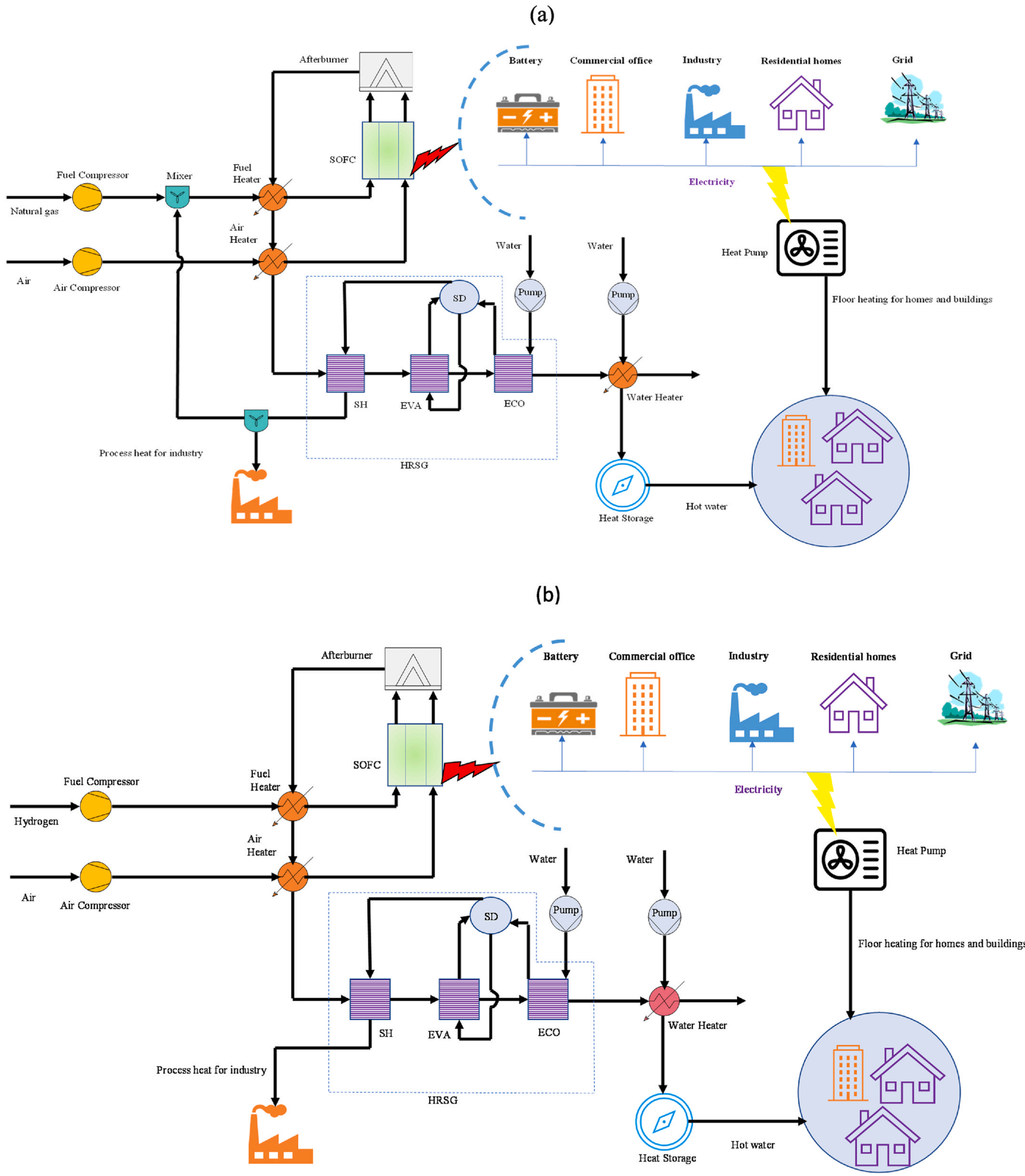

Fig. 4. Layout of SOFC-HP based CHP system fuelled by (a) NG and (b) H_2.

2.4. Exergy analysis

The exergy (Ex) value of each stream is the combination of its physical and chemical exergy as provided below

$$Ex = Ex_{PH} + Ex_{CH} \tag{8}$$

where physical exergy is denoted by Ex_{PH} and chemical exergy is denoted by Ex_{CH} . The equations, given below, can be used to estimate physical exergy and chemical exergy values [36,37].

$$Ex_{PH} = \dot{n}_k[(h - h_0) + T_0(s - s_0)] \tag{9}$$

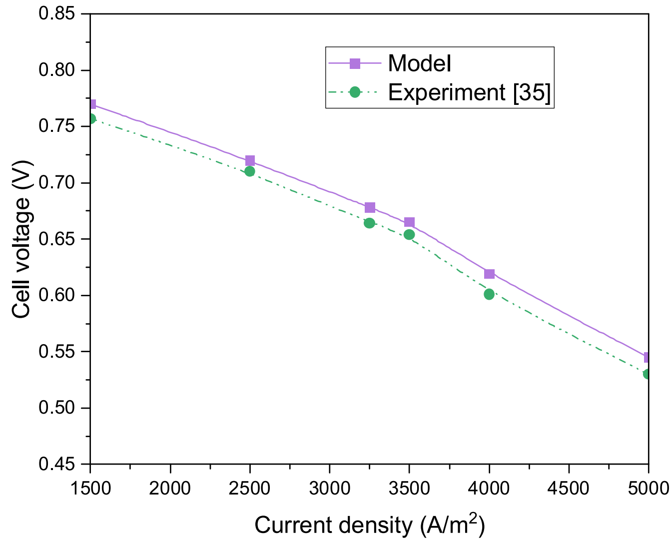

Fig. 5. SOFC model validation.

$$Ex_{CH} = \dot{n}_k \left(\sum_k y_k \overline{ex}^0_{CH} + RT_0 \sum_k y_k \ln y_k \right) \tag{10}$$

where, molar enthalpy is denoted by h, molar flow rate of kth stream is denoted by $\dot{n}_k$, universal gas constant is denoted by R, molar fraction of kth species is denoted by y_k, standard chemical exergy of species is denoted by $\overline{ex}^0_{CH}$ molar entropy is denoted by s, and the subscript 0 denotes atmospheric condition.

2.5. Economic analysis

In this sub-section methods employed for economic analysis are provided. The key input parameters required for the economic analysis is presented in Table 1.

The equation number (11) has been employed for estimating yearly expenditure (YE) for the proposed system.

$$YE = TACC + O\&M + YRC + ACF \tag{11}$$

where, TACC: total annual capital cost, O&M: operation and maintenance cost, and ACF: cost of fuel.

The total annual capital cost (TACC) is estimated by the following relation

$$TACC = NCAP \times (1 + MF_{PC}) \times (1 + MF_{TPC}) \times (1 + MF_{TOP}) \times CRF \tag{12}$$

where, MF_{TOC}: multiplication factor for total overnight cost; MF_{TPC}: multiplication factor for total plant cost; MF_{PC}: multiplication factor for procurement, construction, and engineering cost; NCAP: net capital cost; and CRF: capital recovery factor.

Table 1
The important input parameters.

Parameter	Value	Unit	Ref.
yr	30	years	[38]
H	8000	hours	[39]
UC_{CAP}	85	%	[40]
C_{NG}	7.21	p/kWh	[41]
$C_{hydrogen}$	6.79(PEM electrolyser) 6.45(Alkaline Electrolyser)	$/kg	[5]
i_n	3	%	[42]
MF_{TOP}:	20.20	%	[43]
MF_{TPC}	52.5	%	[43]
MF_{PC}	9	%	[43]
SOFC lifetime	5	years	

The net capital cost ($NCAP$) is calculated by summing the capital costs of all the proposed system's components, and is shown in equation number (13).

$$NCAP = \sum_i CAP_i \tag{13}$$

The capital recovery factor (CRF) has been defined by the equation number (14) [36].

$$CRF = \frac{i_n(1 + i_n)^{yr}}{(1 + i_n)^{yr} - 1} \tag{14}$$

where, i_n and yr are "annual interest rate" and "operational years".

The equipment cost functions employed in this analysis are presented in Table 2. As the cost functions are old, Chemical Engineering Plant Cost Index (CEPCI) values are employed to revise them. The revised equipment cost has been estimated by the equation number (15) [36,46].

$$CAP_{i,2022} = CAP_i \times \frac{CEPCI_{2022}}{CEPCI_{OY}} \tag{15}$$

where $CEPCI_{OY}$ value in the year at which the original cost function was derived, and $CEPCI_{2022}$ is value for the base year.

2.6. Performance indicators

The net energetic efficiency of the CHP system has been defined by the equation number (16) [48,49]:

$$\eta_{En} = \frac{\dot{W}_{net} + \dot{Q}_{net}}{\dot{m}_{fuel} \times LHV_{fuel}} \tag{16}$$

where mass flowrate of fuel is denoted by $\dot{m}_{fuel}$, lower heating value of the fuel is denoted by LHV_{fuel}, $\dot{Q}_{net}$ is the total heat output from the system and $\dot{W}_{net}$ denotes net power output from the system.

The electrical efficiency of the CHP system has been defined by the equation number (17).

$$\eta_{Elec} = \frac{\dot{W}_{net}}{\dot{m}_{fuel} \times LHV_{fuel}} \tag{17}$$

The heating efficiency of the overall system has been estimated by the equation number (18)

Table 2
Cost functions.

Equipment	Cost function	CEPCI (Year)	Reference
Solid oxide fuel cell	$CAP_{SOFC} = A_{SOFC}(2.96T_{cell} - 1907)$	395.6 (2002)	[44]
Inverter	$CAP_{inverter} = 10^5 \left(\frac{\dot{W}_{SOFC,DC}}{500}\right)^{0.7}$	395.6 (2002)	[44]
Afterburner	$CAP_{AB} = \frac{46.08 \times \dot{m}_{oxydant}}{0.995 - \frac{P_{out}}{P_{in}}}[1 + \exp(0.018 \times T_{out} - 26.4)]$	368.1 (1994)	[44]
AC	$CAP_{AC} = 1516.5 \times (W_{AC})^{0.67}$	402.3 (2003)	[45]
FC	$CAP_{FC} = 1516.5 \times (W_{FC})^{0.67}$	402.3 (2003)	[45]
HEX	$CAP_{HEX} = 3 \times 130 \times (A/0.093)^{0.78}$	468.2 (2005)	[44]
HRSG	$CAP_{HRSG} = 6570 \times \left(\frac{\dot{Q}}{LMTD}\right)^{0.8} + 21276 \times \dot{m}_{steam} + 1184.4 \times \dot{m}_{gas}^{1.2}$	376.8 (1996)	[46]
Pump	$CAP_{Pump} = 3 \times 422 \times 1.41 \times \left(\frac{\dot{W}_P}{1}\right)^{0.71} \times fn$ $fn = 1 + (0.2/(1 - \eta))$	394.1 (2000)	[47]

$$\eta_{Heat} = \frac{\dot{Q}_{net}}{\dot{m}_{fuel} \times LHV_{fuel}} \quad (18)$$

The CHP system's exergy efficiency has been estimated by the equation number (19) [49].

$$\eta_{Ex} = \frac{\dot{W}_{net} + Ex_{heat}}{\dot{m}_{fuel} \times LHV_{fuel}} \quad (19)$$

where Ex_{heat} denotes total exergy related to the heat output.

The levelised cost of energy(LCOE) of the CHP system has been defined by the equation number (20) [50].

$$LCOE = \frac{YE}{UC_{CAP} \times H \times (\dot{W}_{net} + \dot{Q}_{net})} \quad (20)$$

where H represents annual operating hours, and UC_{CAP} represents capital utilisation factor.

3. Results and discussion

3.1. SOFC based cogeneration system

In this subsection, the techno-economic results of the SOFC based CHP configurations are discussed. The net energy efficiency, electrical efficiency, exergy efficiency, and heating efficiency of the SOFC-based CHP system operating with natural gas were calculated monthly and are presented in Fig. 6. The results show that the maximum energy efficiency, exergy efficiency, electrical efficiency, and heating efficiency were 60.64 %, 45.09 %, 44.81 %, and 15.82 %, respectively, in the month of February. Upon closer examination, it becomes apparent that the energy efficiency demonstrated a downward trend during the months of June to September. This decline can be attributed to lower heating demands during these months, as reflected in the corresponding decrease in heating efficiency, as illustrated in Fig. 6. This observation highlights the influence of seasonal variations on the overall performance of the SOFC-based CHP system.

Similarly, the energy efficiency, exergy efficiency, electrical efficiency, and heating efficiency of the SOFC-based CHP system operating with hydrogen were estimated monthly and are presented in Fig. 7. The results indicate that the maximum energy efficiency, exergy efficiency, electrical efficiency, and heating efficiency were 82.54 %, 61.51 %, 57.58 %, and 24.96 %, respectively, in the month of February. Interestingly, a close comparison of the graphs for hydrogen fuel with those of natural gas fuel, as discussed earlier, exhibits similar patterns. The system's performance with hydrogen also demonstrates a dip in energy efficiency and heating efficiency during the months of June to September, aligning with the reduced heating demands during this period. This observation suggests a consistent trend of seasonal impact on the SOFC-based CHP system's efficiencies, regardless of the fuel source used.

The variation of capacity utilisation factor of the natural gas (NG) fuelled SOFC-CHP system is depicted in Fig. 8 on a monthly basis, reflecting the electrical and heating demands of the energy hub. As depicted in the figure, the peak demand for both electricity and heating occurs in February, with utilisation rates of 86.96 % for heating and 86.95 % for electricity. From June to September, the capacity utilisation decreases to its minimum level due to reduced electrical and heating demands during these months. This trend aligns with the observed

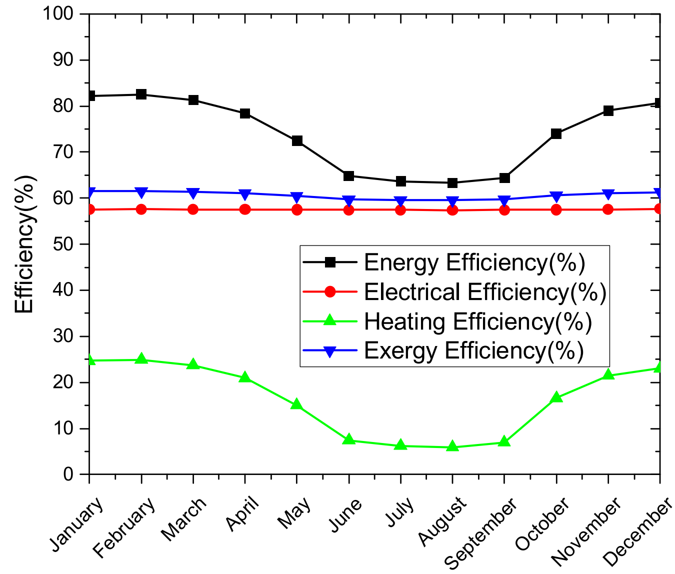

Fig. 7. Monthly efficiency variation of the hydrogen-based SOFC- CHP configuration.

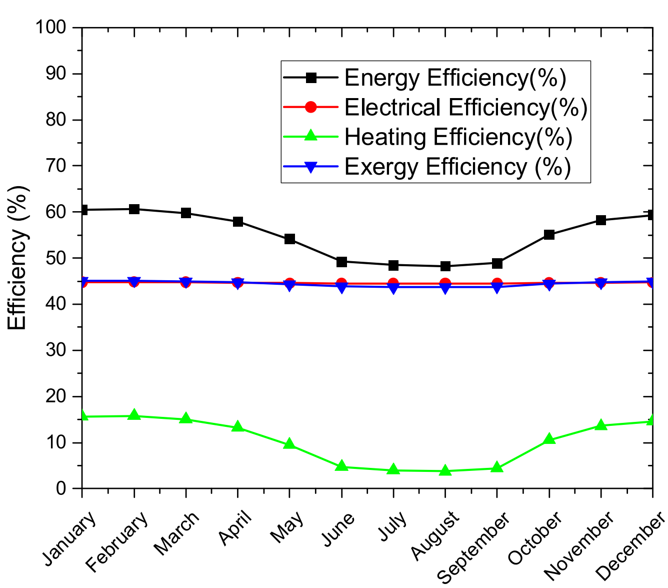

Fig. 6. Monthly efficiency variation of the natural gas-based SOFC- CHP configuration.

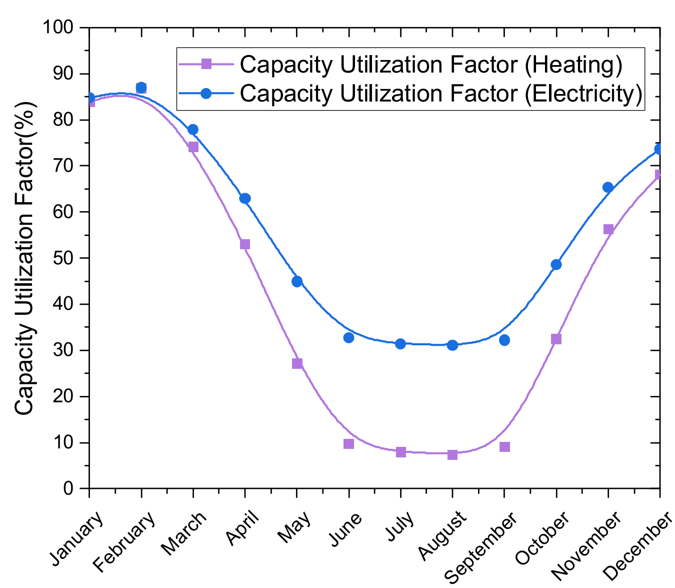

Fig. 8. Monthly capacity utilisation factor variation of the natural gas fuelled SOFC -CHP configuration.

seasonal variations. Moving on to the hydrogen-fuelled CHP system, Fig. 9 showcases the monthly capacity utilisation corresponding to the electrical and heating needs of the energy hub. Similar to the natural gas fuelled CHP configuration, the highest capacity utilisation is once again observed in February, with rates of 86.95 % for heating and 86.96 % for electricity. Furthermore, the utilisation rates during the months of June to September exhibit a decline, mirroring the pattern observed in the natural gas system. These findings highlight the influence of seasonal fluctuations on the capacity utilisation of both the natural gas and hydrogen-fuelled SOFC systems. It emphasises the importance of optimising system operation to meet the varying demands throughout the year while ensuring efficient utilisation of resources.

The size of the SOFC stack for the proposed energy hub has been estimated for both fuels based on the heating and electricity demand of the cluster. For the NG-fuelled SOFC-CHP configuration, the area required for the SOFC stack is determined to be 2196 m^2, as depicted in Fig. 10. The SOFC-CHP configuration utilises 100 % area of the SOFC stack in February, and SOFC area requirement varies throughout the year based on the energy requirement of the cluster. It is proposed that when the energy requirement in the cluster is lower, some cells will not be operational to reduce the total stack area. Fig. 10 depicts the operational size requirements of the SOFC stack throughout the year when fuelled by natural gas for the SOFC-CHP configuration. In the case of the NG system, the power-to-area ratio of the SOFC stacks is estimated to be 1.54 kW/m^2, and it remains constant throughout the year.

Conversely, for the hydrogen-fuelled SOFC-CHP configuration, the area required for the stack is calculated to be 1166.5 m^2, as depicted in Fig. 11. It is also found that the SOFC-CHP configuration with hydrogen as fuel utilises 100 % stack area in February. Similar to the NG fuelled configuration, the SOFC area requirement for the hydrogen-fuelled SOFC-CHP configuration varies throughout the year based on the energy requirement of the cluster. Interestingly, the power to stack area requirement is higher (2.13 kW/m^2) for hydrogen fuelled SOFC-CHP configuration compared to natural gas fuelled configuration. This suggests that with the same size of SOFC stack, the hydrogen fuelled SOFC-CHP configuration will produce higher power output compared to the natural gas based configuration.

The comparison of the LCOE for the SOFC-CHP configuration with natural gas, Proton exchange membrane (PEM) hydrogen, and Alkaline (ALK) hydrogen as fuels is displayed in Fig. 12. The LCOE for PEM hydrogen, ALK hydrogen and natural gas systems is estimated to be

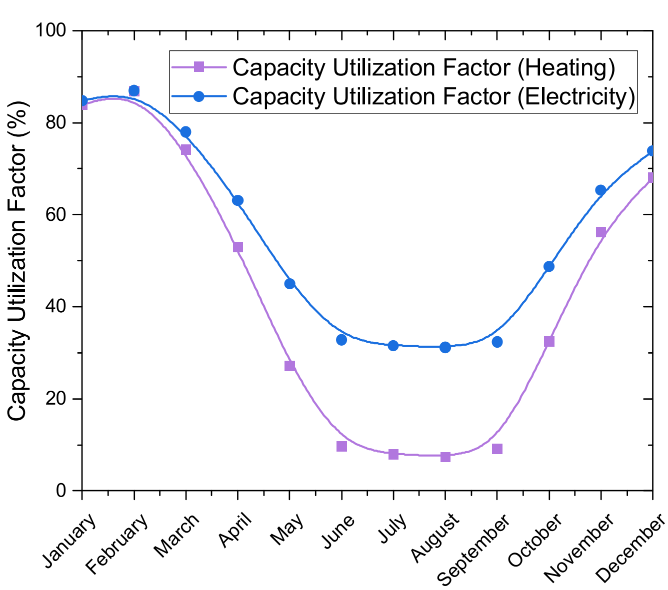

Fig. 9. Monthly capacity utilisation factor variation of the hydrogen fuelled SOFC -CHP configuration.

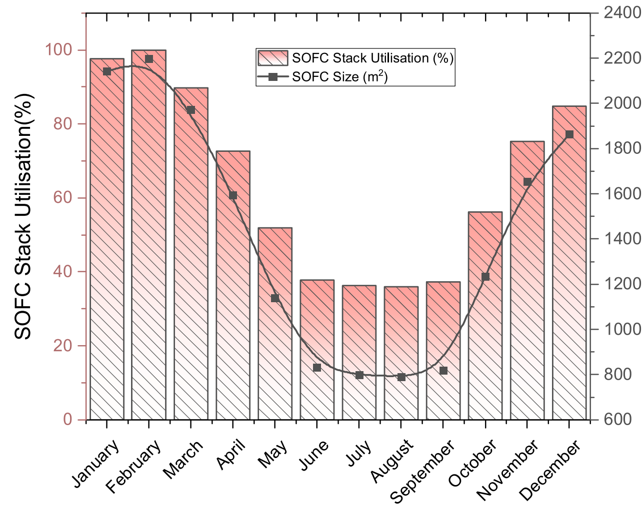

Fig. 10. Monthly variation of SOFC stack size and its utilisation for natural gas fuelled SOFC-CHP configuration.

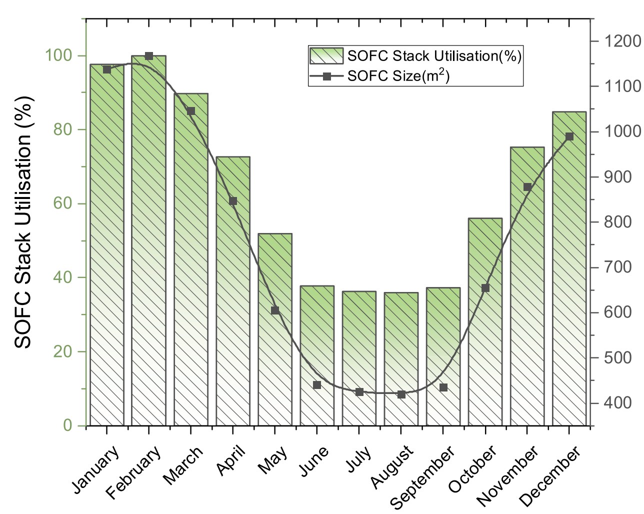

Fig. 11. Monthly variation of SOFC stack size and its utilisation for H_2 fuelled SOFC-CHP.

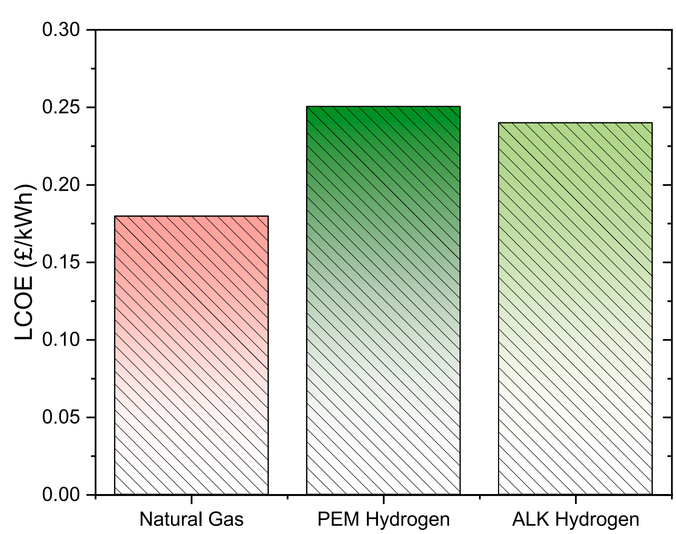

Fig. 12. LCOE of the SOFC-CHP system configuration fuelled by natural gas, PEM hydrogen and ALK hydrogen.

0.2505 £/kWh, 0.24$/kWh and 0.1791 £/kWh, respectively. It's noteworthy that the LCOE of the hydrogen system is higher than that of the natural gas system. The cost of green hydrogen varies based on several factors, including the price of electricity, production scale, and technical advancements. A sensitivity analysis was conducted to estimate the SOFC based system's LCOE, as shown in Fig. 13. The cost of green hydrogen from PEM and ALK electrolysers varied by ±40 %, and the LCOE has been estimated. With the large-scale deployment of green hydrogen production facilities, hydrogen is anticipated to play a major role in power and heating production.

3.2. SOFC -heat pump based cogeneration system

The energy efficiency, electrical efficiency, exergy efficiency, and heating efficiency of the SOFC-HP cogeneration system running on natural gas were estimated for each month of the year and are presented in Fig. 14. The maximum energy, electrical, exergy efficiency, and heating efficiencies were found to be 93.04 %, 44.48 %, 39.13 %, and 48.65 %, respectively, as shown in Fig. 14. Interestingly, the highest energy efficiency, electrical efficiency, and heating efficiency were all observed in the month of July, showcasing the system's outstanding performance during this period. Furthermore, the highest exergy efficiency was recorded in August, indicating another peak performance period for the system. These findings highlight the system's ability to achieve exceptional efficiency levels across different months of the year, emphasizing its reliability and adaptability in meeting varying energy demands. The results also suggest the potential for optimising system operation based on seasonal variations to further enhance its overall performance and contribute to a more sustainable and energy-efficient solution.

Similarly, the monthly estimations of energy efficiency, electrical efficiency, heating efficiency, and exergy efficiency were conducted for the SOFC integrated with a Heat Pump CHP system operating on hydrogen, and the results are presented in Fig. 15. Notably, the system demonstrated exceptional performance metrics, with the highest energy efficiency reaching 96 %, electrical efficiency reaching 52.43 %, exergy efficiency reaching 53.38 %, and heating efficiency reaching 43.89 %, as illustrated in Fig. 15. A significant observation is that the month of July consistently exhibited the highest efficiency across all the metrics measured. This indicates that the system's performance peaked during this period, suggesting the favourable influence of certain conditions or factors specific to that time of the year. These findings underscore the system's capability to achieve outstanding efficiencies when integrated with a Heat Pump CHP system running on hydrogen. Moreover, the

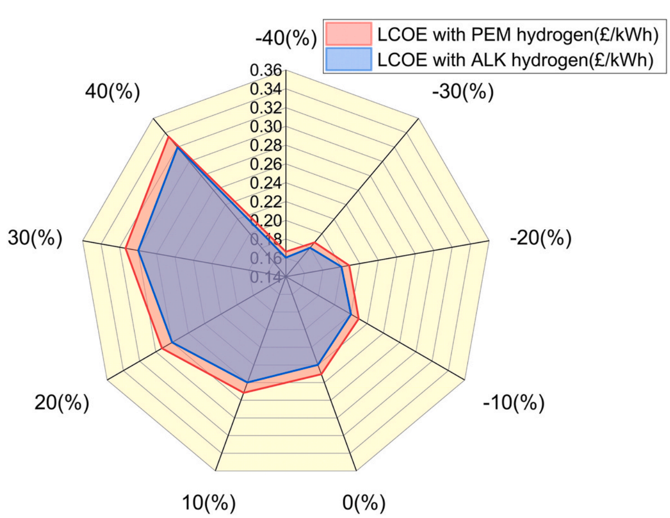

Fig. 13. Sensitivity analysis of LCOE of the SOFC- CHP configuration fuelled by green hydrogen.

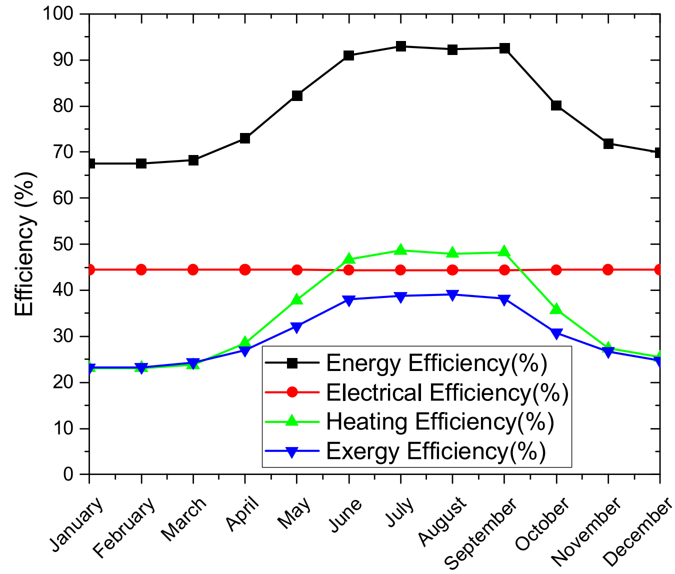

Fig. 14. Monthly efficiency variation of the natural gas-based SOFC-HP CHP configuration.

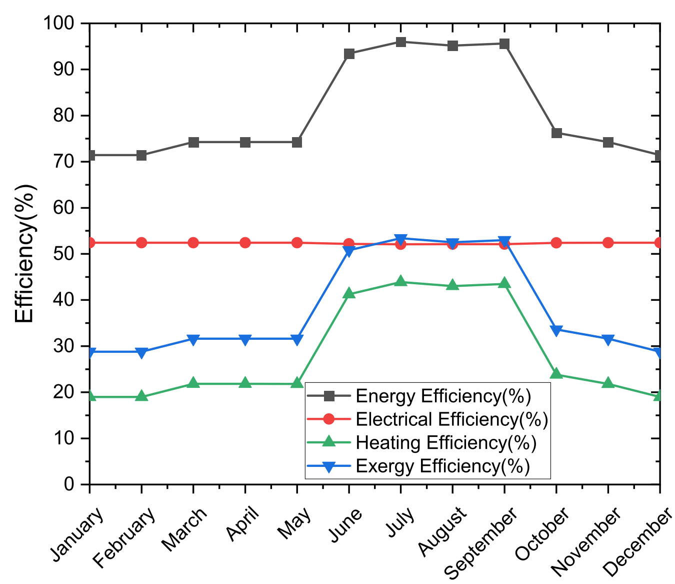

Fig. 15. Monthly efficiency variation of the hydrogen-fuelled SOFC-HP CHP configuration.

consistent prominence of July as the month with the highest efficiencies suggests the potential for optimising system operation and resource allocation during this period.

The monthly capacity utilisation factor of the SOFC- HP cogeneration system, which is fuelled by natural gas, is displayed in Fig. 16. The figure illustrates the capacity utilisation based on the electricity and heating needs of the energy hub. The maximum capacity utilisation factor for both electricity and heating is found to be around 86.96 % in the month of February. From June to September, the capacity utilisation is at its minimum due to a decrease in the demand for heating and electricity. Similarly, the variation in the capacity utilisation factor of the hydrogen-fuelled configuration for electrical and heating requirements is shown in Fig. 17. The capacity utilisation for both heating and electricity reaches its highest value of approximately 86.96 % in February. However, from June to August, the capacity utilisation factor drops to its minimum due to a reduction in the demand for heating and electricity.

According to the energy demands of the cluster, the sizing of the

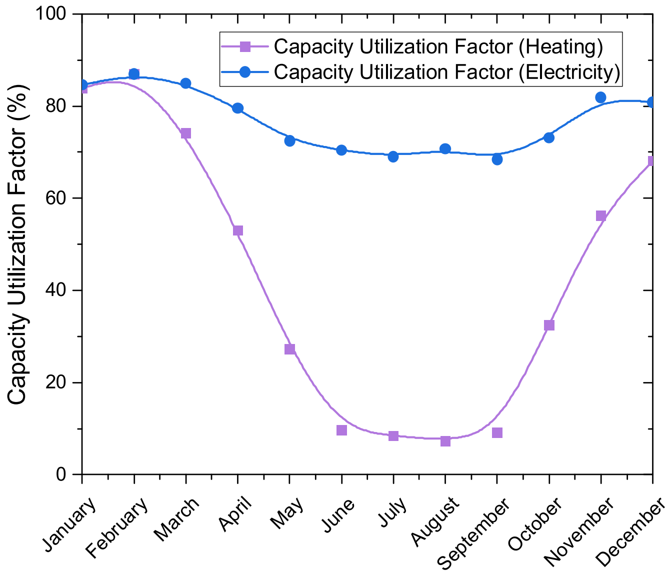

Fig. 16. Monthly capacity utilisation factor variation of the natural gas fuelled SOFC-HP CHP configuration.

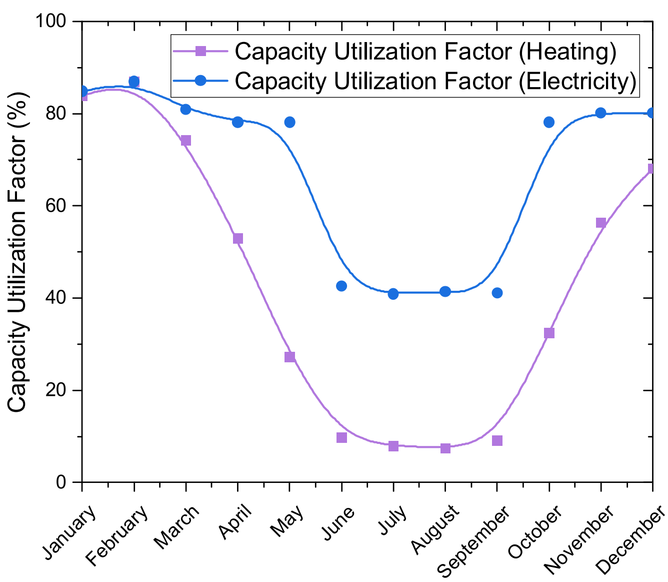

Fig. 17. Monthly capacity utilisation factor variation of the hydrogen fuelled SOFC-HP CHP configuration.

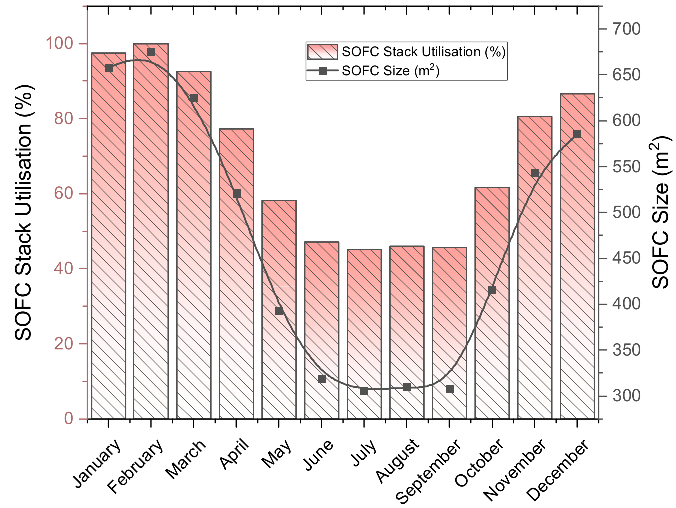

Fig. 18. Monthly variation of SOFC stack size and its utilisation for natural gas fuelled SOFC-HP CHP configuration.

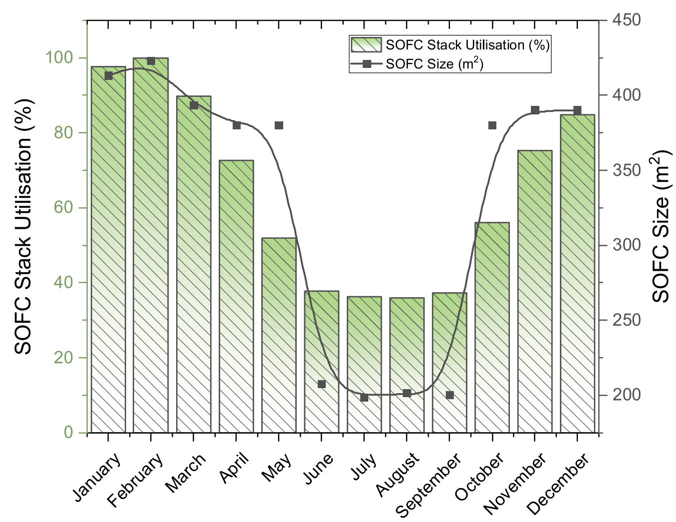

Fig. 19. Monthly variation of SOFC stack size and its utilisation for hydrogen fuelled SOFC-HP CHP configuration.

SOFC has been determined for both natural gas and H_2 fuelled configurations, coupled with a heat pump CHP configuration. In case of the NG fired system, the maximum SOFC stack area required to meet the highest demand (both electricity and heat) in February is 675 m^2. Fig. 18 shows that in February, the CHP configuration make complete use of the SOFC stack area, while in other months, the area requirement decreases based on the energy demands of the hub. It is considered in the modelling that some SOFC stacks will not be in operation to reduce its area. The sizing of the required SOFC in terms of stack area for all the months is depicted in Fig. 18. For the NG-fuelled configuration power to stack area ratio requirement remains at 1.54 kW/m^2, with only the stack area requirements varying based on the electricity and heating requirement of the different months. For the hydrogen-fuelled system, the area required for the SOFC stack to meet the highest demand in February is 423 m^2. Fig. 19 shows that in February, the system utilises full capacity of the SOFC stack area, while in other months, the area needed decreases based on the energy demands of the cluster. For hydrogen fuelled system the power to stack area requirement remains at 2.12 kW/m^2.

Fig. 20 compares the LCOE for the SOFC-Heat pump CHP system fuelled by natural gas and green hydrogen. The LCOE for the NG-powered system is calculated at 0.1603 £/kWh, while the LCOE for the proton exchange membrane (PEM) hydrogen-fuelled system is 0.2218 £/kWh, and the LCOE for the alkaline (ALK) hydrogen-powered system is 0.213 £/kWh. Green hydrogen costs fluctuate due to factors like electricity prices, production scale, and technological advancements. A sensitivity analysis was performed to estimate the LCOE of SOFC-HP based systems, illustrated in Fig. 21. The cost of green hydrogen from PEM and ALK electrolysers varied by ±40 %, and the LCOE has been estimated accordingly. It is projected that with the large-scale deployment of green hydrogen production facilities, the cost of green hydrogen will fall further, allowing for widespread usage of green hydrogen in power and heating generation in the near future.

3.3. Environmental analysis

In this sub-section, levelised CO_2 emission from the NG fired cogeneration systems has been estimated and further compared with standard NG fired systems. Fig. 22 presents a comparison of the levelised

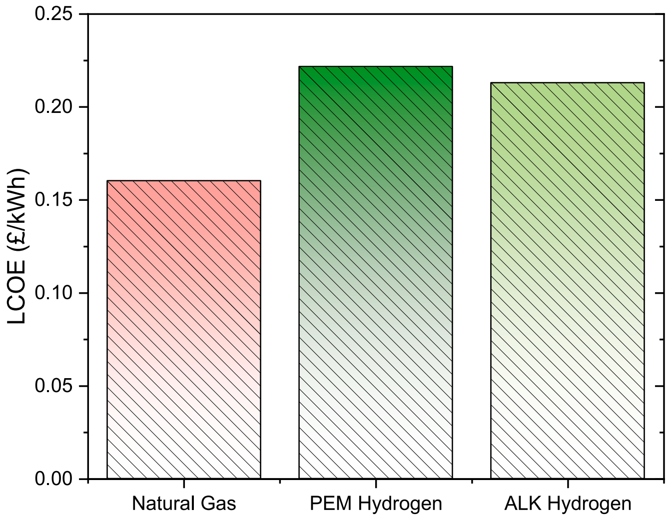

Fig. 20. LCOE of the SOFC-HP- CHP system configuration fuelled by natural gas, PEM hydrogen and ALK hydrogen.

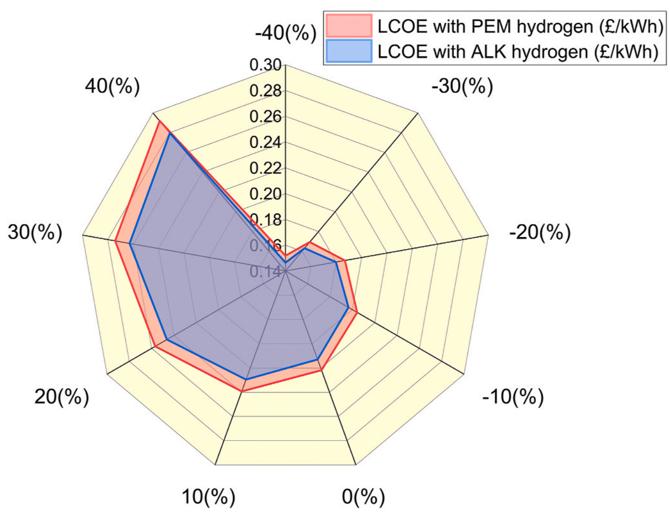

Fig. 21. Sensitivity analysis of LCOE of the SOFC-HP integrated CHP system fuelled by green hydrogen.

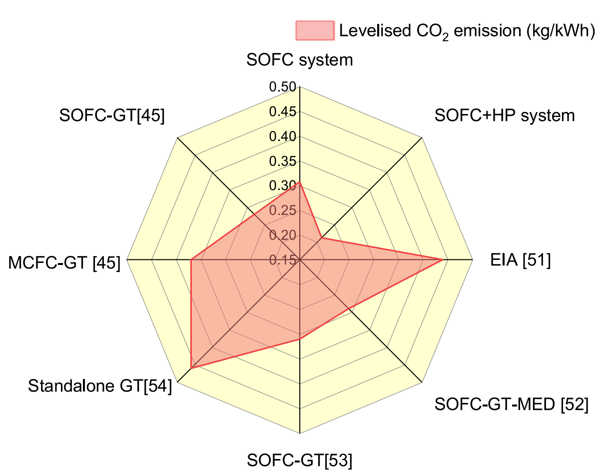

Fig. 22. Comparison of levelised CO_2 emission from proposed systems with a conventional system.

carbon dioxide emissions from SOFC-CHP, and SOFC-HP-CHP systems powered by natural gas to prior studies. According to the US Energy Information Administration (EIA), the CO_2 emissions produced from NG-generated electricity are 0.44 kg/kWh [51]. However, our analysis indicates that the levelised CO_2 emissions for a NG-fuelled SOFC based CHP system configurations are significantly lower at 0.3352 kg/kWh, and even lower for SOFC-HP cogeneration system at 0.275 kg/kWh. These results highlight the better emission levels of the natural gas systems in comparison to the EIA's reported values. The CO_2 emissions from the modelled SOFC based systems are also comparable with previous NG fuelled fuel cell systems. Vojdani et al. [52] reported CO_2 emissions from SOFC-GT and multi-effect desalination unit (MED) integrated system to be 0.29 kg/kWh. Eisavi et al. [53] reported CO_2 emissions from SOFC-GT hybrid system to be 0.31 kg/kWh. Hasanzadeh et al. [45] reported CO_2 emissions from stand-alone GT, the hybrid MCFC-GT, and the hybrid SOFC-GT systems were 0.46 kg/kWh, 0.37 kg/kWh, and 0.280 kg/kWh, respectively.

4. Comparison with other SOFC integrated systems

The performance of the proposed system configurations has been evaluated and compared against various SOFC integrated studies available in the literature. Performance comparison of proposed SOFC based systems with other systems are summarised in Table 3. The proposed SOFC-HP-CHP system configuration fuelled by hydrogen exhibits an overall energy efficiency of 96 %, which is the higher compared to previously investigated systems. In terms of economic performance, the LCOE of the system configurations are also comparable with previously investigated SOFC based systems.

5. Conclusion

This study presents a comprehensive feasibility assessment of SOFC based energy hub to fulfil local-scale electricity and heating demands in the United Kingdom. The proposed energy hub comprises two cogeneration systems configurations a) SOFC-CHP system and b) SOFC-HP-CHP system, designed to supply electricity and heating requirements to a residential community, a commercial building, and a small brewing and beverage industry in the UK. The techno-economic performance indicators of proposed system configurations fuelled by natural gas and hydrogen were thoroughly assessed and compared. Furthermore, environmental assessment of the SOFC-CHP and SOFC-HP-CHP system configurations fuelled by natural gas was carried out. The major conclusions of this study are summarised below:

- The SOFC-based cogeneration system, running on natural gas yields energy efficiency of 60.64 %, exergy efficiency of 45.09 %, electrical efficiency of 44.81 %, and heating efficiency of 15.82 %. However, the system's performance significantly improved when powered by hydrogen, reaching efficiencies of 82.54 % (energy), 61.51 % (exergy), 57.58 % (electrical), and 24.96 % (heating).
- The SOFC-Heat Pump-based cogeneration system, fuelled by natural gas, exhibited high energy efficiency (93.04 %), electrical efficiency (44.48 %), exergy efficiency (39.13 %), and heating efficiency (48.65 %). However, the system's performance with hydrogen as the fuel achieved the highest energy efficiency (96 %), electrical efficiency (52.43 %), exergy efficiency (58.38 %), and heating efficiency (43.89 %).
- In terms of economic considerations, the LCOE for PEM hydrogen, ALK hydrogen and natural gas fuelled SOFC cogeneration system is estimated to be 0.2505 £/kWh, 0.24$/kWh and 0.1791 £/kWh, respectively. On the other hand, the LCOE for the NG-fuelled SOFC-HP system is 0.1603 £/kWh, while it is 0.2218 £/kWh for the PEM hydrogen-fuelled system and 0.213 £/kWh for the ALK hydrogen-fuelled system.

Table 3
Performance comparison of proposed SOFC based systems with other systems.

System configuration	Fuel used	Methods	Major results	Ref.
SOFC-CHP system	Natural gas	Energy analysis	Electrical efficiency: 47.38 %. Thermal efficiency: 28.98 %, Total energy efficiency: 76.37 %	[54]
SOFC-CHP system	Biogas	Energy analysis	Net electrical efficiency:55.6 % CHP efficiency:85 %	[55]
SOFC-Gas Turbine and WT integrated system	Biomass	Economic and environmental	Cost of power: 25.58–27.22 $/GJ, Emission: 0.167–0.192 kg/kWh	[56]
SOFC-solar power tower and supercritical CO_2 Brayton cycle	Hydrogen	Thermodynamic, and economic analyses	Exergy efficiency = 56.86 % Cost rate:481.59$/hr	[57]
SOFC-s-CO_2 integrated system	Methane and Hydrogen	Thermodynamic and economic analyses	**Hydrogen**: Energy efficiency = 73.37 %; LOCE = 0.2123£/kg **Methane:** Energy efficiency = 64 %, LCOE = 0.18 £/kWh	[58]
SOFC-Internal combustion engine-s-CO_2 integrated CHP system	Natural gas	Thermodynamic, exergoeconomic and environmental analyses	Energy efficiency = 65.82 %; Exergy efficiency = 42.28 %. Total unit cost of the product = 42.98 $/GJ	[59]
SOFC-Alkali metal thermal electric converter and thermoelectric generator integrated energy system	95 %H_2 + 5 % H_2O	Thermodynamic and ecology analyses	Power density = 42 %; Ecology function density = 53.5 %	[60]
SOFC based CHP system. SOFC-Heat Pump (HP) integrated CHP	Natural gas. Hydrogen	Energy analysis, Exergy analysis, Economic analysis, Environmental analysis, Year-round energy supply and demand-based investigation	**SOFC based CHP system** (Natural gas): energy efficiency = 60.64 %, exergy efficiency = 45.09 %, LCOE: 0.1791 £/kWh (**Hydrogen**): energy efficiency = 82.54 %, exergy efficiency = 61.51 %, LCOE: 0.24 £/kWh **SOFC-HP based CHP system (Natural gas**): energy efficiency = 93.04 %, exergy efficiency = 44.48 %, LCOE: 0.1603 £/kWh (**Hydrogen**): energy efficiency = 96 %, exergy efficiency = 52.43 % LCOE: 0.213 £/kWh	Present study

- The environmental analysis demonstrated lower levelised CO_2 emissions for the natural gas-fuelled SOFC system (0.3352 kg/kWh) and even lower emissions for the SOFC system with a heat pump, achieving levelised CO_2 emissions of 0.275 kg/kWh.

This study provides valuable insights on techno-economic feasibility assessment of the SOFC-CHP and the SOFC-HP-CHP system configurations fuelled by green hydrogen and natural gas. However, it is worth mentioning that the economic performance of the study depends upon the economic assumptions, fuel costs, and equipment cost functions. In future, this study could be extended to investigate exergo-economic analysis, multi-objective optimisation and life cycle assessment of the investigated system configurations.

Nomenclature

A	Area (m^2)
$\overline{ex}_{CH}^{0}$	Standard chemical exergy of species (kJ/mol)
Ex	Exergy (kW)
F	Faraday constant (C/mol)
h	Molar enthalpy (J/mol)
H	Hours of operation (Hour)
i_n	Annual interest rate (%)
I	Current (A)
j	Current density (A/m^2)
$\dot{m}$	Mass flow (kg/s)
$\dot{n}$	Molar flow (mol/s)
N	Number of cells
$\dot{Q}$	Heat rate (kW)
R	Universal gas constant (J/mol·K)
s	Molar entropy (J/mol·K)
T	Temperature (K)
UC_{CAP}	Capital utilisation
V	Voltage (V)

(*continued on next column*)

(*continued*)

$\dot{W}$	Power (kW)
y	Molar fraction
Greek letter	
η	Efficiency (%)
Subscripts	
0	Atmospheric condition
a	anode
AC	Air compressor
c	cathode
CH	Chemical
FC	Fuel compressor/Fuel cell
in	Inlet
NG	Natural gas
out	Outlet
PH	Physical
Acronyms	
AB	Afterburner
CAP	Capital cost
CCUS	Carbon dioxide capture, utilisation, and storage
CHP	Combined heat and power
COP	Coefficient of performance
CRF	Capital recovery factor
ECO	Economiser
EVA	Evaporator
GT	Gas turbine
HEX	Heat exchanger
HP	Heat pump
HRSG	Heat recovery steam generator
LHV	Lower heating value
MCFC	Molten carbonate fuel cell
NCAP	Net capital cost
ORC	Organic Rankine cycle
PEMFC	Proton exchange membrane fuel cell
SH	Superheater
SOFC	Solid oxide fuel cell
UF	Fuel utilisation factor

CRediT authorship contribution statement

Dibyendu Roy: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Samiran Samanta:** Conceptualization, Data curation, Formal analysis, Investigation, Software, Validation, Writing – original draft. **Sumit Roy:** Formal analysis, Investigation, Validation, Writing – review & editing. **Andrew Smallbone:** Conceptualization, Formal analysis, Funding acquisition, Supervision, Visualization, Writing – review & editing. **Anthony Paul Roskilly:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing.

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

This research work was funded by the Engineering and Physical Science Research Council of UK (Grant number: EP/T022949/1).

References

[1] BEIS. UK Hydrogen Strategy. 2021.
[2] BEIS. Net zero Strategy. Build Back Greener; 2021.
[3] DESNZ. Hydrogen heating: overview. 2024. https://www.gov.uk/government/publications/hydrogen-heating-overview/hydrogen-heating-overview–2#the-h100-fife-neighbourhood-trial.
[4] Worchester. Hydrogen ready boilers. 2023. https://www.worcester-bosch.co.uk/hydrogen-blend-boilers.
[5] S&P Global. Platts hydrogen price wall. 2023. https://www.spglobal.com/commodityinsights/PlattsContent/_assets/_files/en/specialreports/energy-transition/platts-hydrogen-price-wall/index.html [Accessed on 29.06.2024].
[6] Bagherian MA, Mehranzamir K. A comprehensive review on renewable energy integration for combined heat and power production. Energy Convers Manag 2020;224:113454. https://doi.org/10.1016/j.enconman.2020.113454.
[7] EPA. CHP Benefits. 2023. https://www.epa.gov/chp/chp-benefits.
[8] Yu S, Fan Y, Shi Z, Li J, Zhao X, Zhang T, et al. Hydrogen-based combined heat and power systems: a review of technologies and challenges. Int J Hydrogen Energy 2023;48:34906–29. https://doi.org/10.1016/j.ijhydene.2023.05.187.
[9] US DOE. COMBINED HEAT AND POWER FOR RESILIENCY. 2024. n.d, https://betterbuildingssolutioncenter.energy.gov/accelerators/combined-heat-and-power-resiliency.
[10] Huang S, Yang C, Chen H, Zhou N, Tucker D. Coupling impacts of SOFC operating temperature and fuel utilization on system net efficiency in natural gas hybrid SOFC/GT system. Case Stud Therm Eng 2022;31:101868. https://doi.org/10.1016/j.csite.2022.101868.
[11] Zhang S, Liu H, Liu M, Sakaue E, Li N, Zhao Y. An efficient integration strategy for a SOFC-GT-SORC combined system with performance simulation and parametric optimization. Appl Therm Eng 2017;121:314–24. https://doi.org/10.1016/j.applthermaleng.2017.04.066.
[12] Zheng N, Duan L, Wang X, Lu Z, Zhang H. Thermodynamic performance analysis of a novel PEMEC-SOFC-based poly-generation system integrated mechanical compression and thermal energy storage. Energy Convers Manag 2022;265:115770. https://doi.org/10.1016/j.enconman.2022.115770.
[13] Wang Z, Chen H, Xia R, Han F, Ji Y, Cai W. Energy, exergy and economy (3E) investigation of a SOFC-GT-ORC waste heat recovery system for green power ships. Therm Sci Eng Prog 2022;32:101342. https://doi.org/10.1016/j.tsep.2022.101342.
[14] Ran P, Zhou X, Wang Y, Fan Q, Xin D, Li Z. Thermodynamic and exergetic analysis of a novel multi-generation system based on SOFC, micro-gas turbine, s-CO2 and lithium bromide absorption refrigerator. Appl Therm Eng 2023;219:119585. https://doi.org/10.1016/j.applthermaleng.2022.119585.
[15] Obara S. Economic performance of an SOFC combined system with green hydrogen methanation of stored CO2. Energy 2023;262:125403. https://doi.org/10.1016/j.energy.2022.125403.
[16] Veldhuizen BN Van, Biert L Van, Amladi A, Woudstra T, Visser K, Aravind PV. The effects of fuel type and cathode off-gas recirculation on combined heat and power generation of marine SOFC systems. Energy Convers Manag 2023;276:116498. https://doi.org/10.1016/j.enconman.2022.116498.
[17] Al-Rashed AAAA, Alsarraf J, Alnaqi AA. A comparative investigation of syngas and biofuel power and hydrogen plant combining nanomaterial-supported solid oxide fuel cell with vanadium-chlorine thermochemical cycle. Fuel 2023;331:125910. https://doi.org/10.1016/j.fuel.2022.125910.
[18] Zhao H, Du H, Peng Z, Zhang T. Thermodynamic performance analysis of a novel energy storage system consist of asymmetric PEMEC and SOFC combined cycle. Energy Convers Manag 2023;286:117077. https://doi.org/10.1016/j.enconman.2023.117077.
[19] Roy D. Multi-objective optimization of biomass gasification based combined heat and power system employing molten carbonate fuel cell and externally fired gas turbine. Appl Energy 2023;348:121486. https://doi.org/10.1016/j.apenergy.2023.121486.
[20] Ding A, Sun H, Zhang S, Dai X, Pan Y, Zhang X, et al. Thermodynamic analysis and parameter optimization of a hybrid system based on SOFC and graphene-collector thermionic energy converter. Energy Convers Manag 2023;291:117327. https://doi.org/10.1016/j.enconman.2023.117327.
[21] 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;48:101643. https://doi.org/10.1016/j.seta.2021.101643.
[22] Pérez-Trujillo JP, Elizalde-Blancas F, Della Pietra M, Silva-Mosqueda DM, García Guendulain JM, McPhail SJ. Thermoeconomic comparison of a molten carbonate fuel cell and a solid oxide fuel cell system coupled with a micro gas turbine as hybrid plants. Energy Convers Manag 2023;276. https://doi.org/10.1016/j.enconman.2022.116533.
[23] Zhao Y, Xue H, Jiang L, Jin X, Fu H, Xie X. Proposal and assessment of a solid oxide fuel cell cogeneration system in order to produce high-temperature steam aiming at industrial applications. Appl Therm Eng 2023;221:119882. https://doi.org/10.1016/j.applthermaleng.2022.119882.
[24] Ahmadi S, Ghaebi H, Shokri A. A comprehensive thermodynamic analysis of a novel CHP system based on SOFC and APC cycles. Energy 2019;186:115899. https://doi.org/10.1016/j.energy.2019.115899.
[25] Li H, Liang F, Guo P, He C, Li S, Zhou S, et al. Study on the biomass-based SOFC and ground source heat pump coupling cogeneration system. Appl Therm Eng 2020;165:114527. https://doi.org/10.1016/j.applthermaleng.2019.114527.
[26] Mei S, Lu X, Zhu Y, Wang S. Thermodynamic assessment of a system configuration strategy for a cogeneration system combining SOFC, thermoelectric generator, and absorption heat pump. Appl Energy 2021;302:117573. https://doi.org/10.1016/j.apenergy.2021.117573.
[27] Capuano M, Sorrentino M, Agelin-Chaab M. Design and analysis of a hybrid space heating system based on HT-PEM fuel cell and an air source heat pump with a novel heat recovery strategy. Appl Therm Eng 2023;231:120947. https://doi.org/10.1016/j.applthermaleng.2023.120947.
[28] Jin Y, Sun L, Shen J. Thermal economic analysis of hybrid open-cathode hydrogen fuel cell and heat pump cogeneration. Int J Hydrogen Energy 2019;44:29692–9. https://doi.org/10.1016/j.ijhydene.2019.03.098.
[29] Roy D, Samanta S, Roy S, Smallbone A, Roskilly AP. Techno-economic analysis of solid oxide fuel cell-based energy systems for decarbonising residential power and heat in the United Kingdom. Green Chem 2024;26:3979–94. https://doi.org/10.1039/d3gc02645k.
[30] Department for Energy Security and Net Zero, BEIS. Energy Follow Up Survey (EFUS) 2017 reports. 2017.
[31] Mauthner F, Hubmann M, Brunner C, Fink C. Manufacture of malt and beer with low temperature solar process heat. Energy Proc 2014;48:1188–93. https://doi.org/10.1016/j.egypro.2014.02.134.
[32] Wu Z, Ni M, Zhu P, Zhang Z. Dynamic modeling of a NG-fueled SOFC-PEMFC hybrid system coupled with TSA process for fuel cell vehicle. Energy Proc 2019;158:2215–24. https://doi.org/10.1016/j.egypro.2019.01.167.
[33] Thallam Thattai A, Oldenbroek V, Schoenmakers L, Woudstra T, Aravind PV. Towards retrofitting integrated gasification combined cycle (IGCC) power plants with solid oxide fuel cells (SOFC) and CO2 capture – a thermodynamic case study. Appl Therm Eng 2017;114:170–85. https://doi.org/10.1016/j.applthermaleng.2016.11.167.
[34] Wu Z, Tan P, Zhu P, Cai W, Chen B, Yang F, et al. Performance analysis of a novel SOFC-HCCI engine hybrid system coupled with metal hydride reactor for H 2 addition by waste heat recovery. Energy Convers Manag 2019;191:119–31. https://doi.org/10.1016/j.enconman.2019.04.016.
[35] Singhal S. Advances in solid oxide fuel cell technology. Solid State Ionics 2000;135:305–13. https://doi.org/10.1016/S0167-2738(00)00452-5.
[36] Bejan Adrian, Tsatsaronis George, Moran M. Thermal design and optimization. John Wiley & Sons,Inc.; 1996.
[37] Kotas JT. The exergy method of thermal plant analysis. Butterworths; 1985.
[38] Mondal P, Ghosh S. Exergo-economic analysis of a 1-MW biomass-based combined cycle plant with externally fired gas turbine cycle and supercritical organic Rankine cycle. Clean Technol Environ Policy 2017;19:1475–86. https://doi.org/10.1007/s10098-017-1344-y.
[39] Khanmohammadi S, Atashkari K, Kouhikamali R. Exergoeconomic multi-objective optimization of an externally fired gas turbine integrated with a biomass gasifier. Appl Therm Eng 2015;91:848–59. https://doi.org/10.1016/j.applthermaleng.2015.08.080.
[40] Samanta S, Ghosh S. Techno-economic assessment of a repowering scheme for a coal fired power plant through upstream integration of SOFC and downstream integration of MCFC. Int J Greenh Gas Control 2017;64:234–45. https://doi.org/10.1016/j.ijggc.2017.07.020.

[41] Samanta S, Roy D, Roy S, Smallbone A, Paul Roskilly A. Modelling of hydrogen blending into the UK natural gas network driven by a solid oxide fuel cell for electricity and district heating system. Fuel 2024;355:129411. https://doi.org/10.1016/j.fuel.2023.129411.
[42] Burrin D, Roy S, Roskilly AP, Smallbone A. A combined heat and green hydrogen (CHH) generator integrated with a heat network. Energy Convers Manag 2021;246:114686. https://doi.org/10.1016/j.enconman.2021.114686.
[43] 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.
[44] Bahari M, Entezari A, Esmaeilion F, Ahmadi A. Systematic analysis and multi-objective optimization of an integrated power and freshwater production cycle. Int J Hydrogen Energy 2022;47:18831–56. https://doi.org/10.1016/j.ijhydene.2022.04.066.
[45] Hasanzadeh A, Chitsaz A, Mojaver P, Ghasemi A. Stand-alone gas turbine and hybrid MCFC and SOFC-gas turbine systems: comparative life cycle cost, environmental, and energy assessments. Energy Rep 2021;7:4659–80. https://doi.org/10.1016/j.egyr.2021.07.050.
[46] Hosseinpour J, Chitsaz A, Liu L, Gao Y. Simulation of eco-friendly and affordable energy production via solid oxide fuel cell integrated with biomass gasification plant using various gasification agents. Renew Energy 2020;145:757–71. https://doi.org/10.1016/j.renene.2019.06.033.
[47] Chitsaz A, Mehr AS, Mahmoudi SMS. Exergoeconomic analysis of a trigeneration system driven by a solid oxide fuel cell. Energy Convers Manag 2015;106:921–31. https://doi.org/10.1016/j.enconman.2015.10.009.
[48] Zhang J, Cui P, Yang S, Zhou Y, Du W, Wang Y, et al. Thermodynamic analysis of SOFC–CCHP system based on municipal sludge plasma gasification with carbon capture. Appl Energy 2023;336:120822. https://doi.org/10.1016/j.apenergy.2023.120822.
[49] Dincer Ibrahim, Rosen AM. Exergy: energy, environment and sustainable development. Elsevier; 2007.
[50] Behnam P, Arefi A, Shafii MB. Exergetic and thermoeconomic analysis of a trigeneration system producing electricity, hot water, and fresh water driven by low-temperature geothermal sources. Energy Convers Manag 2018;157:266–76. https://doi.org/10.1016/j.enconman.2017.12.014.
[51] EIA. How much carbon dioxide is produced per kilowatthour of U.S. electricity generation?. 2023. https://www.eia.gov/tools/faqs/faq.php?id=74&t=11#:~:text=Thisequaledabout0.855pounds,efficiencyofelectricpowerplants. [Accessed on 29.09.2023].
[52] Vojdani M, Fakhari I, Ahmadi P. A novel triple pressure HRSG integrated with MED/SOFC/GT for cogeneration of electricity and freshwater: techno-economic-environmental assessment, and multi-objective optimization. Energy Convers Manag 2021;233:113876. https://doi.org/10.1016/j.enconman.2021.113876.
[53] Eisavi B, Chitsaz A, Hosseinpour J, Ranjbar F. Thermo-environmental and economic comparison of three different arrangements of solid oxide fuel cell-gas turbine (SOFC-GT) hybrid systems. Energy Convers Manag 2018;168:343–56. https://doi.org/10.1016/j.enconman.2018.04.088.
[54] Wencong L, Siyuan L, Zhe Z, Shuzhan B, Guoxiang L, Kongrong M, et al. Performance analysis of a natural gas-fueled 1 kW solid oxide fuel cell-combined heat and power system with off-gas recirculation of anode and cathode. Fuel Cell 2023;23:106–18. https://doi.org/10.1002/fuce.202200099.
[55] Wang Y, Wehrle L, Banerjee A, Shi Y, Deutschmann O. Analysis of a biogas-fed SOFC CHP system based on multi-scale hierarchical modeling. Renew Energy 2021;163:78–87. https://doi.org/10.1016/j.renene.2020.08.091.
[56] Hai T, Mansir IB, yakoop A khudhair, Mulki H, Anqi AE, Deifalla A, et al. Integration of wind turbine with biomass-fueled SOFC to provide hydrogen-rich fuel: economic and CO2 emission reduction assessment. Process Saf Environ Protect 2023;170:946–59. https://doi.org/10.1016/j.psep.2022.12.049.
[57] Zhou Y, Han X, Wang D, Sun Y, Li X. Optimization and performance analysis of a near-zero emission SOFC hybrid system based on a supercritical CO2 cycle using solar energy. Energy Convers Manag 2023;280:116818. https://doi.org/10.1016/j.enconman.2023.116818.
[58] Roy D, Samanta S, Roy S, Smallbone A, Roskilly AP. Multi-objective optimisation of a power generation system integrating solid oxide fuel cell and recuperated supercritical carbon dioxide cycle. Energy 2023;281:128158. https://doi.org/10.1016/j.energy.2023.128158.
[59] Wang Z, Ma Y, Cao M, Jiang Y, Ji Y, Han F. Energy, exergy, exergoeconomic, environmental (4E) evaluation and multi-objective optimization of a novel SOFC-ICE-SCO2-HRSG hybrid system for power and heat generation. Energy Convers Manag 2023;291:117332. https://doi.org/10.1016/j.enconman.2023.117332.
[60] Guo X, Guo Y, Wang J, Zhang H, He Z, Wu W, et al. Energy, exergy and ecology performance prediction of a novel SOFC-AMTEC-TEG power system. Appl Therm Eng 2022;217:119235. https://doi.org/10.1016/j.applthermaleng.2022.119235.