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Integrating green hydrogen into building-distributed multi-energy systems with water recirculation

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ABSTRACT

This study proposes integrating a building-distributed multi-energy system (BDMES) with green hydrogen to decarbonise electricity generation for buildings. By producing and consuming green hydrogen locally at the building site, using a water electrolyser and proton exchange membrane fuel cell (PEMFC), the reliance on costly, energy and carbon-intensive hydrogen transportation is eliminated. This integration presents an opportunity for energy autonomy, achieved by locally green hydrogen production, storage, and usage. More importantly, the proposed system enables water recirculation between the electrolyser and PEMFC, an effective option worldwide to conserve water resources, and reduce environmental impact. Models are developed to investigate the interaction mechanisms among the photovoltaic (PV) module, water electrolyser, fuel cell, and cooling system. Case study results for a residential building in Aberdeen, UK are presented and discussed, maximum 75 solar panels can be installed on the 150m^2 roof area. Since less solar energy can be harvested in this area, in the peak hour of one summer day, 11 solar panels are required to meet 100 % daily maximum building energy demand and ensure 100 % water recirculation. In one winter-day, total 75 solar panels can only meet 26 % of total building energy demand.

1. Introduction

Energy systems across the globe are under extensive strain due to increasing demands for heating and cooling, two necessities to lead a comfortable life. Technologies for heating and cooling maintain people's safety, comfort, and health while also having a ripple effect on the environment. The energy consumed for heating, cooling, and power consumption accounts for about 28 % of all global CO_2 emissions, according to the World Green Building Council [1]. The electrification of heating and cooling provisions in the UK is an essential step towards decarbonising the energy system and reducing greenhouse gas emissions. Heating and cooling account for a significant portion of the UK's energy consumption and carbon emissions, and electrification can help to reduce these emissions by shifting to low-carbon electricity sources [2]. Several governmental measures also support the UK's electrification of heating and cooling. Examples include the Future Homes Standard, which mandates that new homes have low-carbon heating systems. It aims to ensure that new homes built in 2025 will produce 75–80 % fewer carbon emissions than homes built under the current Building Regulations. Several technologies and strategies are being used to electrify heating and cooling provisions in the UK. Heat pumps are one of the most often used techniques since they can take heat from the air, earth, or water and utilise it to heat buildings. In comparison to conventional heating systems, heat pumps are much more energy-efficient and can significantly cut down on both energy use and carbon emissions [3]. Another approach is to use renewable energy sources such as solar thermal, biomass, and geothermal energy to provide heating and cooling. These technologies can be combined with heat pumps to provide a reliable and sustainable energy supply [4,5]. Incentive programs like the Renewable Heat Incentive (RHI) grants provide financial support for installing renewable technologies, encouraging private households, communities, and businesses to adopt renewable energy solutions for heating purposes [6,7].

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1.1. Hydrogen-integrated building-distributed multi-energy system

The decarbonisation for building heating and cooling in the UK is a key part of the transition towards a low-carbon energy system. While challenges remain to be addressed, such as the cost of equipment and infrastructure, using renewable energy is a promising solution for reducing carbon emissions and improving energy efficiency in buildings. The building-distributed aspect of the system is designed to be deployed on a small scale, typically for individual buildings or clusters of buildings. This allows for greater flexibility in managing energy supply and demand and can reduce reliance on the grid [8,9]. The multi-energy aspect of the system can incorporate multiple energy sources, including renewable sources, to provide a reliable and resilient energy supply.

Hydrogen integration into power networks has gradually advanced, ranging from production and storage to re-electrification and safety concerns. Numerous research attempts to define the current development in hydrogen system integration employing distinct methodologies [8,10–13]. They included hydrogen storage and converter technologies, fuel cell-based hydrogen re-electrification, electrolytic hydrogen production, and hydrogen re-electrification. The systems incorporated electrolysers, hydrogen storage tanks and fuel cells. Hydrogen is a primary energy carrier in this system and is created by the electrolysis of renewable resources. Hydrogen can be stored and utilised for energy applications or as a fuel for fuel cells. This can help to improve energy efficiency and reduce the carbon footprint of the building [14].

1.1.1. Photovoltaic renewable energy source

Solar energy is considered a green and clean energy source because of its almost negligible impact on the environment and health compared to fossil energy sources [15]. The use of solar energy to generate energy has good prospects for development. The high energy conversion efficiency of photovoltaic modules (~40 %) makes PV systems one of the essential energy components worldwide. Over the last three decades, usage of renewable energy sources such as solar and wind power systems have witnessed rapid growth with reducing capital costs and electricity generation prices along with other performance-related improvements [16]. Hydrogen production by using renewable energy sources can be an option to reduce greenhouse gas emissions and dependency on imported transportation fuels.

1.1.2. Electrolysers and fuel cells

Green hydrogen pathways are based on water electrolysis, which is splitting water into its parts, hydrogen, and oxygen, using an electric current. The use of electrolysis for hydrogen production is seen as a promising solution for decarbonising the energy sector since it can be powered by renewable sources such as solar or wind power [17]. Several pilot-scale renewable energy systems using fuel cells and electrolysers have been demonstrated in recent decades with an eye toward the hydrogen economy [18–20]. Water electrolysis can be accomplished through three different types of electrolysis processes with the use of solid oxide electrolysers (SOE), alkaline water electrolysers (AWE), and polymer electrolyte membrane (PEM) electrolysers to produce hydrogen.

PEM electrolysis is a promising option for hydrogen generation in conjunction with renewable energy sources. The deionised water is split into oxygen, protons, and electrons by providing the DC current to electrodes. Protons flow through the polymer electrolyte membrane and unite with electrons on the cathode to generate hydrogen. Proton transport is accompanied by water transport via the membrane. PEM electrolysers are generally made up of metallic components. Platinum or platinum alloys are commonly used as catalysts [21]. PEM electrolysers are light in weight, energy efficient, and use less electricity than alkaline electrolysis and solid oxide electrolysis. The electrodes used in PEM are mostly iridium and platinum which expensive and rare earth metals this is one of the reasons for electrolysers being expensive. The efficiency of these electrolysers is around 65 to 82 % [22].

Electrolysers have a limited but slow-growing market, with growth rates far slower than those of other technologies like solar photovoltaic [23]. The commercially available PEM electrolysers operate more effectively with variable input currents and integrate more seamlessly with intermittent power sources such as wind and solar [24]. The PEM electrolysers are safer than the other electrolysers as they don't need corrosive or caustic electrolytes. Additionally, they can generate hydrogen through electrochemical compression at greater pressures. The higher initial cost of PEM electrolysers could be decreased through innovation and deployment, which could result in the adoption of PEM systems to a greater extent.

1.1.3. Fuel cells

A fuel cell is an electrochemical device that converts chemical energy from fuel into electrical energy without combustion. The chemical reaction in a fuel cell is similar to that in a battery, but unlike a battery, a fuel cell does not store energy but converts chemical energy directly into electrical energy as long as fuel and oxidant are supplied. Proton exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), and molten carbonate fuel cells (MCFCs) are the different types of fuel cells available for electricity generation. PEMFCs are the most prevalent kind of fuel cell and are frequently employed in stationary power and automotive applications. In comparison to MCFCs, which are employed in large-scale power generation, SOFCs are often used in stationary power applications [25].

Proton exchange membrane fuel cells also known as polymer electrolyte membrane fuel cells transfer protons between the anode and cathode using solid polymer electrolyte membranes. Typically, the membrane comprises a perfluorinated polymer called nafion, which allows protons to pass through but not electrons [26]. PEMFCs normally operate at temperatures between 60 and 80 °C and at atmospheric pressure. However, using various composite membrane materials and higher pressure of up to 3 bar allows the water-based PEMFCs to operate at temperatures up to 130 °C. PEMFCs can function at temperatures of up to 200 °C by switching the polymer electrolyte from a water-based to a mineral acid-based system, employing phosphoric acid [27]. PEMFCs are superior to other kinds of fuel cells in various ways including high power density, quick start-up times, and low operating temperatures. They are ideal for portable applications, and electric vehicles due to their small architecture and relatively lightweight. PEMFCs have several challenges, including high costs associated with using expensive constituents like platinum, susceptibility to impurities and pollutants, and the requirement for a hydrogen source [28].

Several control strategies have been employed for fuel cells in building-distributed multi-energy systems, focusing on dynamic optimization, predictive control, and hybrid approaches. For instance, Pareek et al. explored predictive algorithms to optimize energy flow, minimizing hydrogen losses in residential systems [29]. Similarly, Ham et al. demonstrated a simplified model for cogeneration applications, emphasizing operational stability [30]. Our work extends these efforts by integrating water recirculation, which uniquely reduces system water footprint, a gap previously unaddressed.

1.1.4. Hydrogen storage

Hydrogen is one of the most promising future fuels due to its tremendous mass-based energy density. However, storing the same amount of hydrogen as hydrocarbon fuels requires more space. Consequently, developing hydrogen storage technologies is a key consideration for hydrogen-powered energy systems. In contrast to conventional systems, which store hydrogen as compressed gas and cryogenic liquid, large-scale applications favour underground storage. Solid-state hydrogen storage has grown tremendously and is considered the safest. One possibility is storing hydrogen in a hydrogen-integrated power system for building applications using a steel gas cylinder. Hydrogen can be compressed into -cylinders at up to 700 bar pressure

[31]. The heat transfer process during compression could be a technological problem that must be resolved. Composite degradation can happen when the temperature within the tank rises during the compression. These issues could be prevailed by deploying high thermal conductivity materials and structural design [32].

1.2. System water footprint

The water footprint of electrolytic hydrogen results from the direct use of fresh water during the electrolysis process and the freshwater use related to producing the needed electric energy. Water is needed not only for the electrolysis process itself but also for cooling the electrolysis unit, cleaning, and maintenance procedures [33]. The amount of water required varies on the configuration of the system, the effectiveness of the unit, as well as losses due to evaporation or leaks. It is essential to consider water consumption and its effects on the process' sustainability while assessing the viability of a hydrogen production system [34].

Alkaline electrolysis often uses more water than PEM electrolysis since alkaline electrolysis demands a high concentration of hydroxide ions. In other words, PEM electrolysis occurs at a lower temperature and pressure, which reduces the quantity of water required to produce a given amount of hydrogen, resulting in less water consumption [35]. The water consumption of electricity generation is much higher for fossil energy compared to solar and wind power. Electrolytic hydrogen has a total water usage of 130 L/kgH_2 when using thermoelectric power. Although it is necessary to purify the water before it can be used directly in an electrolyser, doing so only uses 0.4 % of the energy used to produce green hydrogen [36]. By considering the complete demineralisation process to purify water before electrolysis and the requirements for cooling water to drive the electrolysers, researchers have emphasised that the water needs are greater and roughly 60 to 95 kg of water per kg of hydrogen [37].

Most of the water is, released back into the ecosystem. It is essential to explain and understand the significance of the water industry in the hydrogen economy. Water consumption in electrolysis can also be reduced by reusing the water used throughout the process. From the hydrogen and oxygen gases produced during It is essential to explain and understand the significance of the water industry in the electrolysis process, water can be extracted and reused in the electrolyte solution. This can drastically lower overall water usage and improve the process's sustainability. The water industry has a crucial role in framing transformation around water consumption and facilitating sustainable, circular, and socially responsible processes for the hydrogen industry [38].

Hydrogen-integrated building-distributed multi-energy system (HIBDMES) is a promising solution for improving energy efficiency and reducing carbon emissions in buildings while providing greater resilience and energy independence. Qureshi et al. provide worldwide actions related to the H_2 development policy [39], this article demonstrates details of hydrogen production methods, production costs, and its future. Water electrolysis is the prominent method of hydrogen production by renewable sources at a lower cost than synthetic natural gas [40,41]. Nasser et al. conducted a techno-economic analysis of an electrolyser integrated hydrogen production system operated with PV panels and a wind turbine. MATLAB/Simulink tool has been used to build a transient mathematical model of the overall system. The system performance is analysed regarding system efficiency, energy storage, and cost. The study's outcome reveals that the overall system efficiency and production cost range from 7.69 % to 9.37 % and from 4.54$/kg to 7.48$/kg, respectively [42].

The existing research investigated green hydrogen production using renewable energy [39–42] or proposed fuel cell system powered by renewable energy for building application [43–45]. However, the system is still in the early development stage and there are challenges to be addressed, such as the cost of the equipment and infrastructure and the need for standardised regulations and policies to support its deployment. Moreover, green hydrogen production through water electrolysis, system upscale, and hydrogen economy development potential cause high water consumption, which requires us to propose a new system to solve this problem.

1.3. Novelty of the study

As depicted in Fig. 1, integrating water electrolyser and fuel cell in the system and encouraging water recirculation can be an effective option worldwide to conserve water resources and reduce environmental impact. To the authors' knowledge, this paper is a first-of-a-kind analysis related to modelling and investigation of both water electrolyser and fuel cell integration in distributed multi-energy systems for building application.

This study assesses the feasibility and potential of the HIBDMES as a sustainable energy solution. By harnessing green hydrogen, buildings can achieve energy autonomy, improve energy efficiency, and contribute to carbon emission reduction, addressing energy, climate, and geopolitical challenges. This work will explore the utilisation of photovoltaic renewable energy sources in hydrogen production and the integration of electrolysis and fuel cells in the HIBDMES. Additionally, the water footprint of electrolytic hydrogen will be considered to ensure the viability and sustainability of hydrogen production. By investigating these aspects, this study aims to provide valuable insights into the potential of hydrogen integration in building applications and inform decision-making processes for a sustainable energy transition.

2. Methodology

The methodology of this study involves the design and simulation of a proposed system for integrating green hydrogen into building applications. The schematic diagram of the proposed system is shown in Fig. 2. The system aims to achieve a material cycle of water, oxygen, and hydrogen in an electrolytic cell-fuel cell system, under the following assumptions:

- The supply of water is unlimited
- The cooling system is perfectly capable of absorbing the heat generated in the system
- No additional losses of material during the transport process
- **H_2O cycle**

In the electrolytic cell system, water flows through a cooling system to reduce its temperature to around 20 °C. The water is then pumped into an ion exchange resin cartridge to remove any particles that may be present, preventing damage to the electrolytic cell. Within the stack, the water acts as both a feedstock and a coolant, undergoing electrolysis into H_2 and O_2 using solar energy as the power source. The O_2 produced during electrolysis, along with the high-temperature water not involved in the reaction, flows from the anode to the gas-liquid separator, where the high-temperature water is separated from the O_2. The separated water enters the cooling system to complete a new cycle. The cathode also produces H_2 along with high-temperature water. The gas-liquid mixture from the cathode flows to the gas-liquid separator, where the high-temperature water passes through the separator and enters the cooling system controlled by a return valve.

In the PEMFC system, water is generated as a product and reacts with the cooling solution at the cathode. The generated water and unreacted oxygen pass through a return valve into the gas-liquid separator at the cathode. The separated high-temperature water is then passed into the cooling system for transportation back to the electrolytic cell for the reaction to occur again.

- **O_2 cycle**

Oxygen is produced at the anode of the electrolytic cell system and transferred to the anode gas-liquid separator with the unreacted water.

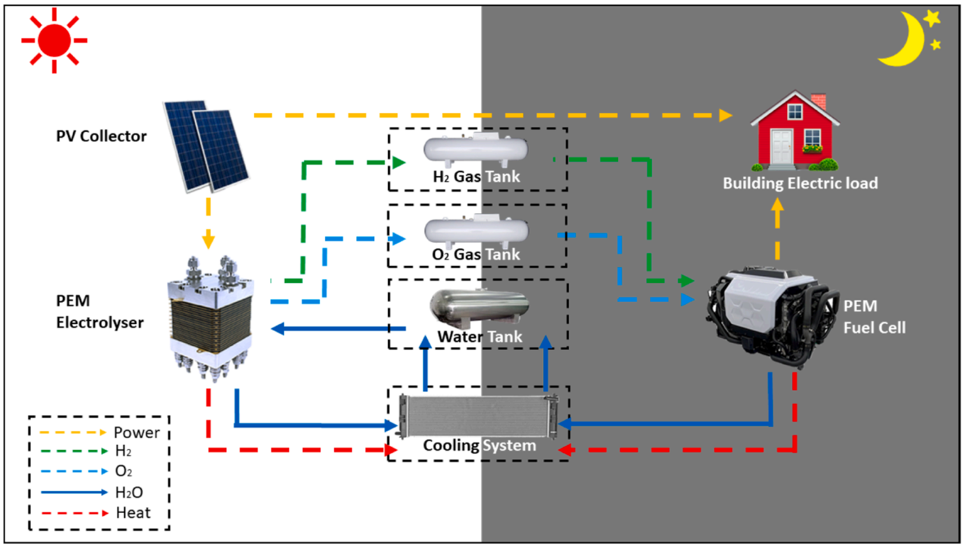

Fig. 1. Graphical representation of the proposed system.

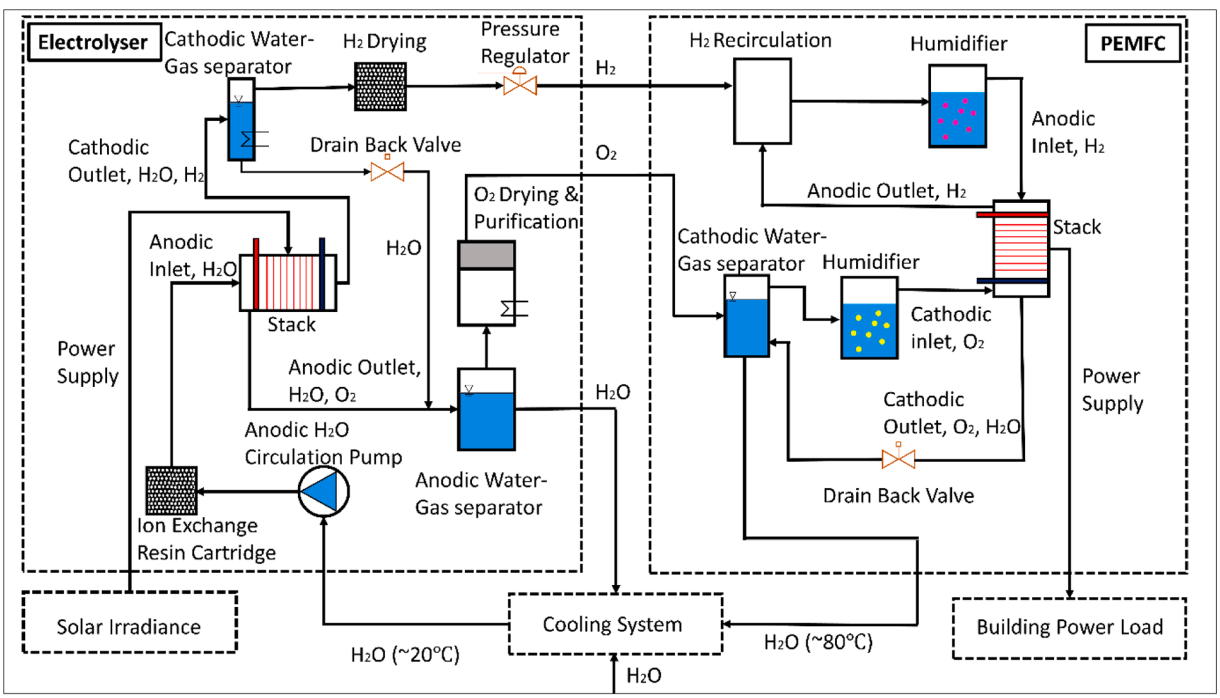

Fig. 2. Schematic diagram of the proposed system.

The separated oxygen undergoes drying and purification before being passed to the PEMFC system. In the PEMFC system, the O_2 from the electrolytic cell system enters the cathode gas-liquid separator and then goes into the humidifier. The wet O_2 is transferred to the cathode of the stack, where it reacts to produce water and generates a significant amount of heat. The unreacted O_2 and water are continuously fed into the cathode gas-liquid separator under pressure valve control to complete the cycle.

- **H_2 cycle**

The cathode of the electrolytic cell system generates H_2 through the electrolysis of water. The excess water, along with the H_2, goes into the gas-liquid separator of the cathode. The wet H_2 is then fed into the hydrogen recovery system of the PEMFC system, undergoing drying and humidification before entering the stack for reaction. Any incomplete hydrogen is passed into the hydrogen recovery system for recovery.

2.1. Solar PV

The simulation and modelling of solar irradiance are one of the most important stages in collecting electricity from the PV panels, in which the characteristics of PV systems are calculated and summarised for different weather conditions obtained [46,47]. Since introducing the Feed-in Tariff scheme in the UK in 2010, which encourages the use of small-scale PV systems for residential electricity generation, simulation studies of PV systems have become increasingly important. Data for solar irradiance in the UK was obtained from official sources, covering 20 substations and 10 residential buildings over a period of 480 days [48]. Simulations were performed for long and short sunlight days to analyse the seasonal variation. The parameters of the solar panels used in the simulations are presented in Table 1.

2.2. PEM electrolyser and fuel cell

PEMFC stands for Proton Exchange Membrane Fuel Cell, and the PEMFC's design parameters are shown in Table 2. It is a type of fuel cell that uses hydrogen fuel and oxygen from the air to produce electricity through an electrochemical process. PEMFCs are commonly used in transportation and stationary power applications due to their high-power density, low operating temperature, and low emissions [49,50].

PEMFCs use a proton exchange membrane as the electrolyte, typically made of a polymer material. The membrane allows only protons to pass through while blocking the flow of electrons. Hydrogen gas is supplied to the anode side of the cell, where it is split into protons and electrons through a catalytic reaction. The protons pass through the membrane to the cathode side, while the electrons are forced to travel through an external circuit to generate electricity.

At the cathode side, oxygen from the air is supplied and reacts with the protons passing through the membrane and the electrons traveling through the external circuit, producing water as a by-product.

Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode: $O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$

The overall reaction is: $H_2 + 1/2O_2 \rightarrow H_2O$ + electricity

PEMFCs have several advantages over other types of fuel cells, including their high efficiency, fast start-up time, and ability to operate at low temperatures.

An electrolyser is a device that uses an electrical current to split water into its constituent elements, hydrogen, and oxygen, through a process called electrolysis [51–54] (Table 2).

Two electrodes are placed in a water container in an electrolyser, and an electric current is passed through the water between them [55,56]. The electrodes are usually made of a conductive material, such as platinum, and are separated by a membrane or a diaphragm. The positive electrode, or anode, attracts the negatively charged oxygen ions, while the negative electrode, or cathode, attracts the positively charged hydrogen ions. When the water molecules come into contact with the electrodes, they are split into their constituent elements, with oxygen released at the anode and hydrogen released at the cathode.

The following equation can represent the chemical reaction that occurs during electrolysis:

Anode: $2O^{2-} \rightarrow O_2 + 4e^-$

Cathode: $H_2O + 2e^- \rightarrow H_2 + O^{2-}$

Reaction: $2H_2O \rightarrow 2H_2 + O_2$

Table 3 provides the key parameters of the PEM electrolyser and PEMFC systems used in this study. These parameters are drawn from the simulation results and supported by references to established literature.

Electrolysis is energy-intensive, as a significant amount of electrical energy is required to split the water molecules [57]. Both electrolytic cells and fuel cells (FCs) generate significant amounts of heat during operation [58,59], and water is commonly utilised as a heat transfer fluid to manage this thermal energy. Water's high specific heat capacity (~4000 *J*) makes it an optimal heat transfer medium. Water management in this context encompasses various processes, including control, distribution, and treatment. This involves the application of water resource management principles, as well as the design and maintenance of water distribution systems, and wastewater treatment methodologies.

Table 1
Parameter design of a solar panel.

Parameter	Value	Unit
Length	200	cm
Width	100	cm
Thickness	3–5	cm
Average power	350	W

Table 2
Parameters design in the stack of electrolyser and the fuel cell.

Parameter	Value	Unit
number cell	400	–
cell area	280	cm^2
Membrane thickness	125	um
Gas diffusion layer thickness	250	um
Gas channel width/height	1	cm
Number of gas channels	8	–
Exchange current density	10^{-5}	A/cm^2
Charge transfer coefficient	0.7	–
Water diffusivity in GDL	0.07	cm^2/s
Density of dry membrane	2000	kg/m^3

Table 3
Key parameters of PEM electrolyse and PEMFC.

Parameter	Value
PEM Electrolyser Efficiency%	65–82
PEMFC Efficiency%	60–70
Electrolyser Operating Temp. °C	60–80
Fuel Cell Operating Temp. °C	60–80

The system model includes detailed equations governing electrolyser and fuel cell operations, with inputs such as solar irradiance, temperature, and energy demand. Validation was conducted by comparing simulation results with established benchmarks from the previous research works [30,34], showing deviations within 5 % for hydrogen production rates and energy efficiencies.

2.3. Residential building energy demand

The integrated system with electrolyser and fuel cell is designed to meet building heating, cooling, and electricity demand for decarbonisation in buildings. The building energy demand needs to be estimated to design and simulate the integrated system's operational characteristics under the proposed strategy. Thus, a prototype residential building has been developed in the EnergyPlus environment [60], which is a free open-source program for building energy analysis and thermal load calculations. More information about the residential building and weather data used as input for building energy demand calculation will be presented.

The residential building, shown in Fig. 3 below, has a total floor area of $452m^2$ (4866 ft^2), with a window-to-wall ratio of 11.49 % on the north of the building, 12.07 % on the south, 0 % on the east and 1.35 % on the west. The residential building is kept at 18°C in heating and 23°C in cooling [61]. The U-values of the materials and the air infiltration rate are defined according to UK government regulations. Lighting density was then set, based on the CIBSE's SLL Lighting Handbook [62]. The roof U value is 0.16 W/m^2-K, wall U value is 0.26 W/m^2-K and the floor U value is 0.18 W/m^2-K. The residential building is located in Aberdeen Dyce, UK and the weather files used was sourced from EnergyPlus. Schedules were then created to match the people's activity in the residential building. This defines timelines regarding parameters such as: number of people per room; personal heat generated per room; lighting activity; electrical equipment activity; infiltration rate per room.

2.4. Economic implications and scalability

The economic viability of the HIBDMES is a critical factor in its widespread adoption. By eliminating the need for hydrogen

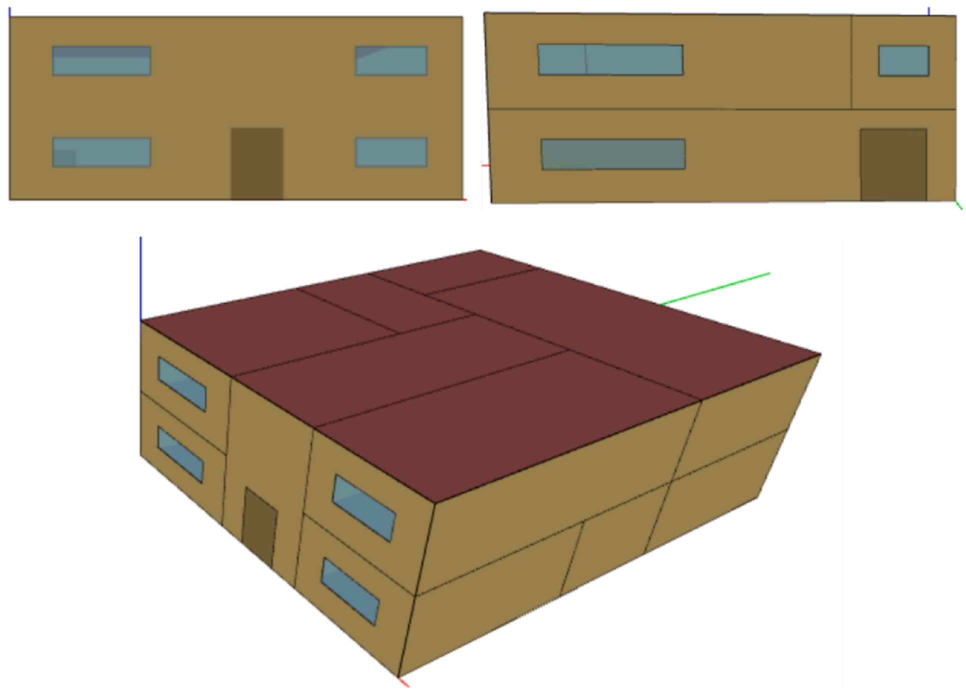

Fig. 3. Residential house model, the front and back of the house model (top row), and the isometric view of the house model.

transportation and storage infrastructure, the system offers substantial cost savings compared to centralised hydrogen production models. The initial investment costs for the HIBDMES, including the PV panels, electrolyser, fuel cell, and cooling system, can be offset by reduced energy bills and potential revenue generation from selling excess electricity back to the grid. Additionally, exploring the availability of financial incentives, such as tax credits or subsidies for renewable energy systems, can further enhance the economic attractiveness of the proposed system.

The scalability of the HIBDMES is a crucial aspect to consider for its broader application in the built environment. While the current study focuses on a residential building, the system's design can be adapted to meet the energy demands of larger buildings or even entire building clusters. For larger-scale applications, increasing the number of PV panels, electrolysers, and fuel cells would be necessary to match the higher energy consumption. Additionally, the system's configuration may need to be optimised to ensure efficient energy distribution and management across multiple buildings.

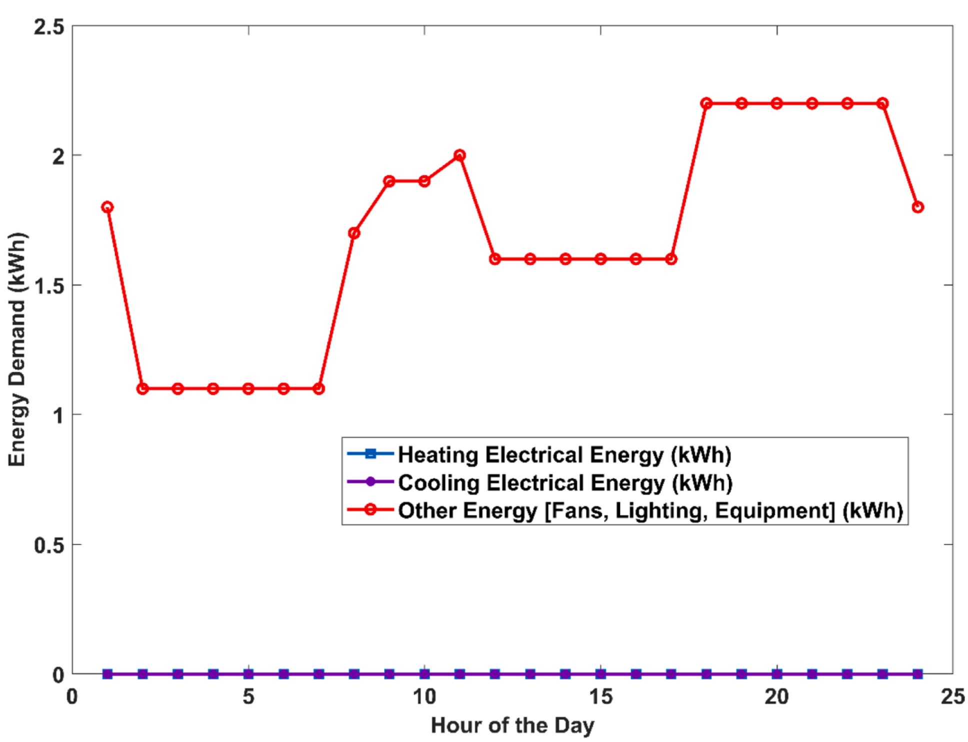

Fig. 4. Hourly electrical consumption of the residential building, a summer day in Aberdeen.

2.5. Heat management assumptions

The assumption regarding the cooling system's capacity to absorb heat is based on stable operation conditions where peak thermal loads remain within system limits. While the non-linear nature of thermal processes may introduce errors, these are minimised by system design, which includes heat-resistant materials and optimized flow dynamics. The potential error is deemed negligible in this study, as the focus is on energy integration rather than precise thermal management. Future studies may incorporate advanced heat transfer models to refine these estimates.

3. Results and discussions

The residential building's energy demand has been calculated using Energy Plus and the methodology introduced in Section 2.3 to design and simulate the integrated system's operational characteristics under the proposed strategy. Figs. 4 and 5 represent the building heating, cooling, and electricity demand for summer and winter days respectively, for a residential house in Aberdeen, UK, for summer and winter days respectively.

Fig. 4 shows the hourly electrical consumption during a summer day (1st July) of the house model located in Aberdeen. The consumption pattern aligns with the expected seasonal variations, with more pronounced peaks during typical activity periods. The highest consumption is observed at 18:00, with a value of 2.165 kWh. There is no cooling present during this day. This is expected due to the temperature in Aberdeen on July 1st not exceeding the temperature of 23°C – at which the cooling would be activated. No electrical energy required for heating due to the higher summer temperatures, keeping the house naturally within a comfortable temperature range.

Fig. 5 shows the hourly electrical consumption during a winter day (12th December) of the house model located in Aberdeen. The highest consumption is observed at 20:00, with a value of 11.36 kWh. The total consumption requirement is highest during the night. This is because the temperature at night is considerably colder than that during the daytime. Therefore, more energy is required to heat the house to keep it at a comfortable temperature during the night-time hours.

It is highly noticeable that the house model consumes a larger amount of electricity during a winter day than a summer day. The total electricity consumption during a summer day is just 28 % of the total electricity consumption during a winter day. This is because there is a prominent necessity for heating during the winter due to low temperatures in the UK, whereas summer temperatures in the UK usually are within the range of a comfortable temperature for a home.

Two case studies were conducted to assess the proposed system's feasibility. Based on the roof area and the available space for solar panels, a maximum of approximately 226 solar panels could be installed to supply energy. Consequently, the PV irradiance was processed to limit the maximum energy to 0.175 kWh/m^2.

3.1. Case study 1: summer day

For the first case study, a summer day (1st July) was selected, and the corresponding solar irradiance is shown in Fig. 6. The figure demonstrates relatively good sunlight from 6am to 8pm. with a dip in irradiance around 9am and 6pm, likely due to cloudiness or rain showers affecting light intensity.

The solar power generated is directed to the electrolyser for green hydrogen production. The maximum capacity of the solar panels is 0.175 kW/m^2, this limits the maximum input power in the electrolyser as presented in Fig. 7. This figure displays the electrolyser's water consumption, hydrogen production, and oxygen production on July 1st. The trends of substance consumption and production follow the solar irradiance pattern. However, the ratio of consumption and production for the three substances is approximately 1:0.1:0.87. This indicates that for every 1 mole of water consumed, 0.1 mol of H_2 and 0.87 mol of O_2 are produced.

Fig. 8 illustrates the production of water and consumption of oxygen and hydrogen in the fuel cell, which also correspond to fluctuations in solar irradiance. However, due to the low overall power consumption, the consumption of oxygen and hydrogen remains relatively stable

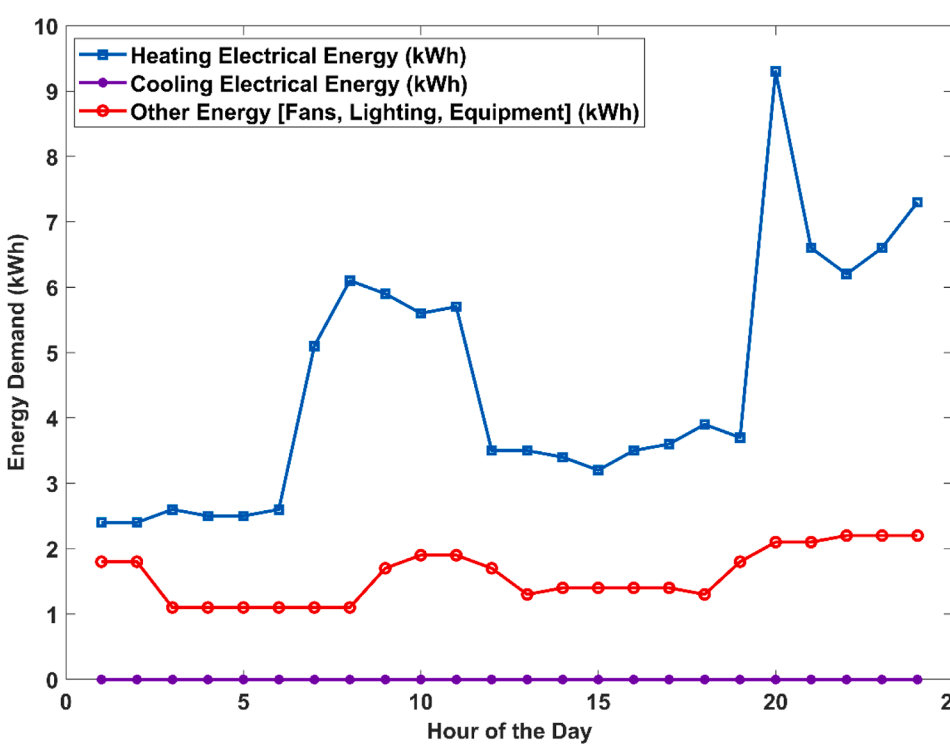

Fig. 5. Hourly electrical consumption of the house model during a winter day in Aberdeen, UK.

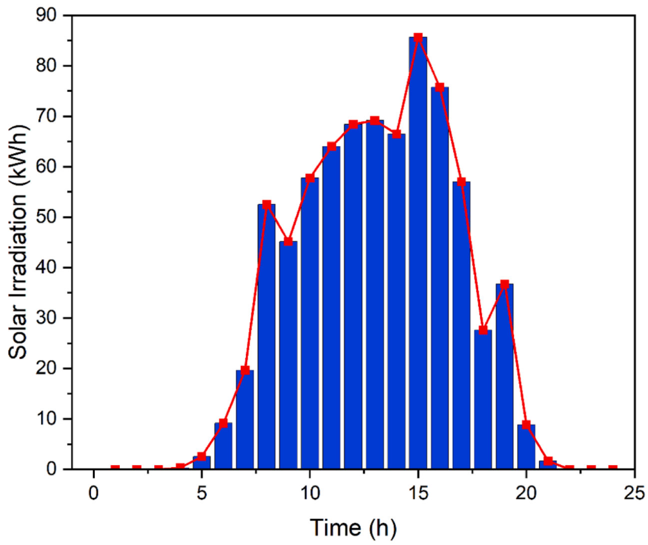

Fig. 6. Solar irradiance (kWh) on the 1st of July.

without significant fluctuations. The ratio of water to H_2 to O_2 is approximately 1:0.11:0.89. During this summer day case study, the PEMFC system consumes H_2 at a rate of about 0.02 g/s in peak (around 7pm), while the maximum H_2 production rate in the electrolyser is approximately 0.15 g/s (from 8am to 7pm). Only about 11 solar panels are needed to meet the H2 supply in the PEMFC, and the water production rate in the electrolyser is about 0.21 g/s. The roof area for the residential building is 150 m^2, thus maximumly up to 75 solar panels can be installed on the roof.

Ensure 100 % water recirculation, although the amount of water produced by the PEMFC under non-intense light conditions is sufficient to meet the electrolyser's consumption, as light intensity increases, the total water produced becomes insufficient, requiring additional water (~0.03 g/s) to be added to the cells. The consumption rate of O_2 in the PEMFC is much lower than the production rate in the electrolytic cell, and atmospheric air can directly supply this feedstock.

3.1.1. *Cooling energy demand during high-consumption periods*

To account for cooling energy demand during summer, we introduced an operational scenario where additional cooling energy is required for high-irradiance periods. Simulation results show that incorporating this demand increases peak power consumption by 15 %, with solar panels meeting 80 % of this increased load. This highlights the system's robustness but also indicates the need for additional energy sources or improved energy storage during peak summer conditions.

3.2. *Case study 2: winter day*

The second case study was conducted using a winter day (6th December). Fig. 9 depicts the corresponding solar irradiance for that day. During winter in the UK, sunlight hours and intensity are significantly reduced compared to summer, as evident in Fig. 9. Simultaneously, the house's energy consumption, as shown in Fig. 5, is substantially higher than during summer due to the colder winter temperatures. Energy consumption during winter is approximately 4–6 times greater than during summer. Notably, there is a significant increase in energy demand during non-working hours (6am - 10am) compared to midnight due to the absence of daylight.

Fig. 10 represents the water consumption and hydrogen and oxygen generation of the selected winter day by the electrolyser. The maximum water consumption in Fig. 10 (~0.9 g/s around 1pm) is lower than in the summer day case (Fig. 7) (~1.5 g/s) due to reduced light availability. Consequently, the production of H_2 and O_2 is also significantly lower, with winter's H_2 production (Fig. 10) being approximately 33.33 % less than that of summer (Fig. 7), and O_2 production (Fig. 10) being about 39.13 % lower. Therefore, the production of H_2 is more unsusceptible to

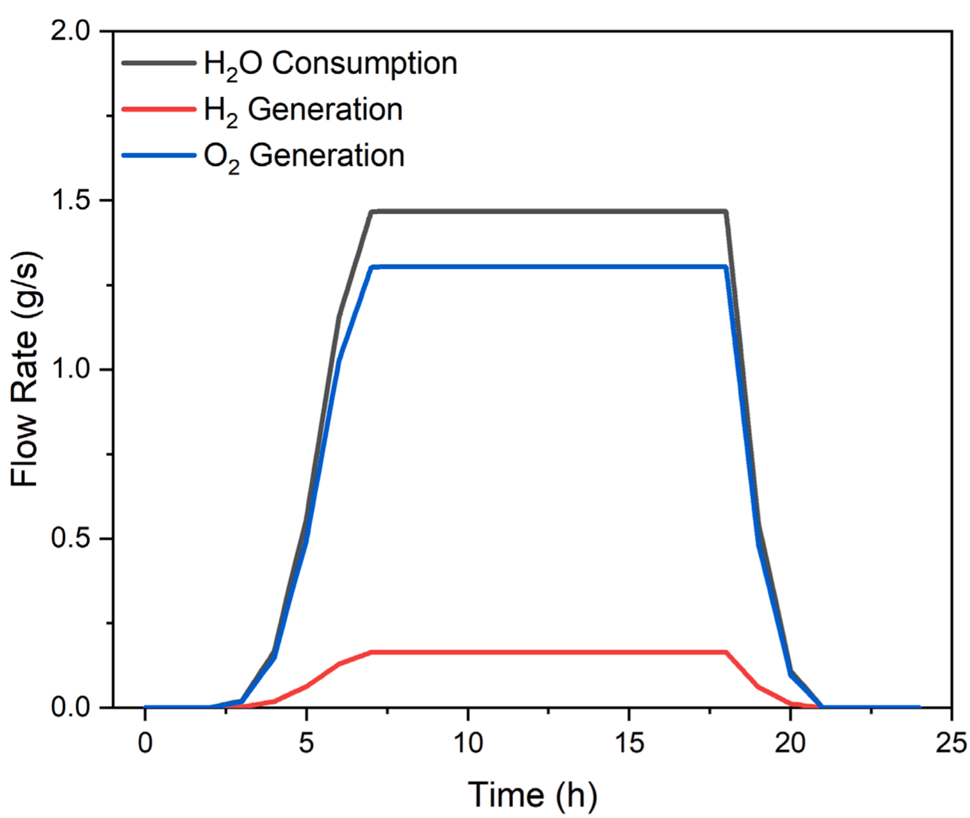

Fig. 7. Electrolyser's H_2O consumption, H_2 generation, and O_2 generation.

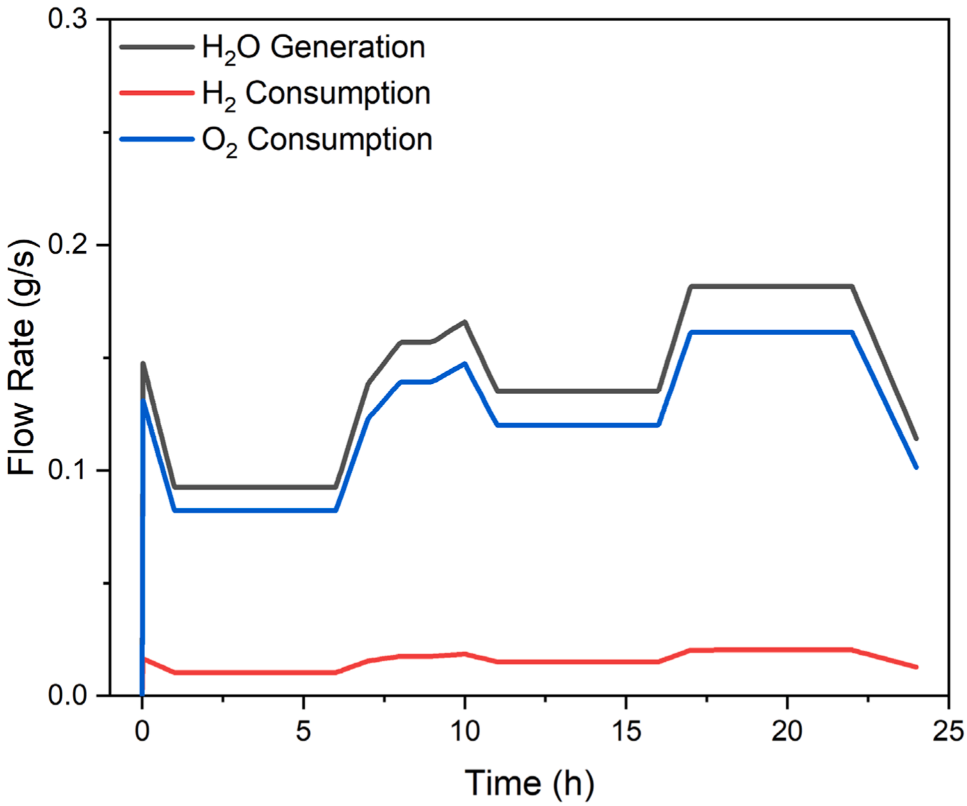

Fig. 8. PEMFC's H_2O generation, H_2 consumption and O_2 consumption.

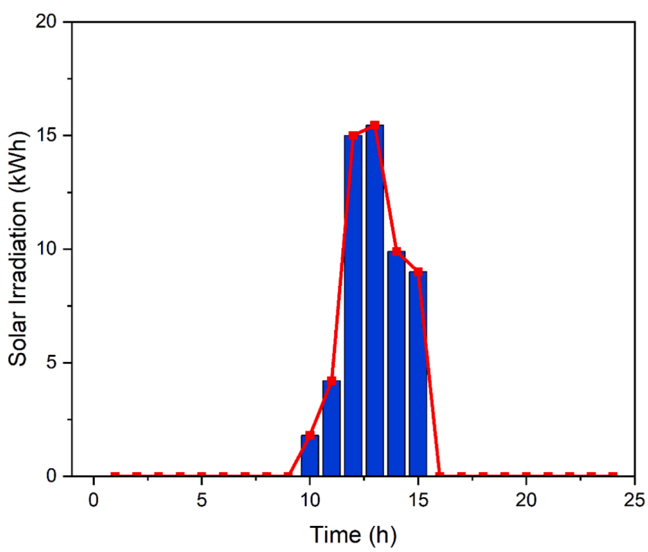

Fig. 9. Solar irradiance on the 6th of December.

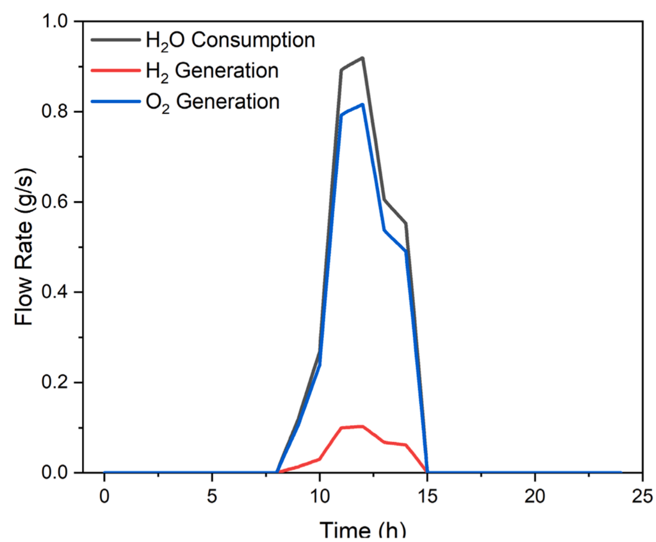

Fig. 10. Electrolyser's H_2O consumption, H_2 generation, and O_2 generation.

seasonal variations.

The trend in water production in the fuel cell (Fig. 11) mirrors the variation in electricity consumption in residential buildings. Table 4 presents the results of electrolyser hydrogen generation and fuel cell hydrogen consumption. The fuel cell produces water at an efficiency of approximately 1.0 g/s, which is sufficient to meet the electrolytic cell's water consumption requirements. Because of the increase in household electricity consumption, the production efficiency of H_2 can be seen in Fig. 11 to be about 0.11 g/s, nearly five times the summer figure (Fig. 8), a figure that shows about 5.6 times the rate of O_2 consumption. In the electrolytic cell model, all solar panels working at total capacity still have a shortfall of approximately 10 % H_2. However, as in the summer, the water produced by the PEMFC can still meet the consumption requirements of the electrolytic cell. Table 5 summarising the significant seasonal variations in energy demand and generation.

3.3. Energy demand analysis

The system's capacity to meet building energy demand was tested under diverse scenarios. In summer, 11 solar panels sufficed for peak demands, achieving 100 % energy self-sufficiency. However, in winter, even with all 75 panels operating, only 26 % of the demand could be

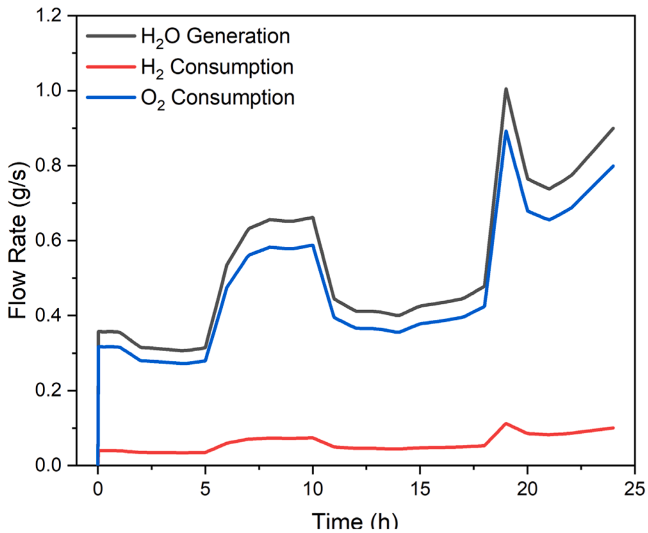

Fig. 11. PEMFC's H_2O generation, H_2 consumption, and O_2 consumption.

Table 4
Electrolyser H_2 generation and fuel cell H_2 consumption.

Case study	Electrolyser H_2 generation (mol H_2/mol H_2O)	Fuel Cell H_2 consumption (mol H_2/mol H_2O)
Summer	0.1	0.11
Winter	0.11	0.11

met. These findings underscore the necessity of supplemental systems, such as wind turbines or grid support, to address seasonal shortfalls. The overall system performance and efficiency of the system is tabulated in Table 6.

3.4. Energy flow in the proposed system

A Sankey diagram has been developed to comprehensively illustrate the flow of energy and resource distribution across the system. For example, as shown in Fig. 12, the solar input provides a total energy supply of 100 units, which is allocated across key components. The electrolyser consumes 45 units of energy for hydrogen production, while 20 units are directed toward satisfying the building's energy demand. The remaining 35 units are attributed to system losses, arising from inefficiencies and conversion limitations. This diagram effectively highlights the energy pathways, resource utilisation, and the system's performance, providing valuable insights for identifying areas to enhance efficiency and minimise losses.

4. Conclusions

This study presented a proton exchange membrane water electrolyser and fuel cell system powered by renewable energy to meet building energy demands, achieve electricity decarbonisation and energy autonomy. The water recirculation for the system has been considered. Case study results for a residential building in Aberdeen, UK are presented and discussed, maximum 75 solar panels can be installed on the 150m^2 roof area. Analysis results show that in one summer day (July 1st), at 7pm when the daily energy demand is at peak, 11 solar panels are required to meet the maximum daily building energy demand and to ensure 100 % water recirculation. In one winter day (December 6th) at 1pm, even all 75 solar panels operate simultaneously, system can only meet 26 % of the total building energy demand.

It is worth noting that the system's H_2 conversion efficiency is less significantly affected by seasonal variations, suggesting that the system's ability to supply H_2 remains relatively consistent throughout the year and is not affected by diurnal fluctuations. By eliminating hydrogen transportation needs and focusing on local water reuse, this approach

Table 6
Performance and overall efficiency of the system.

Parameter	Details
Electrolyser Performance	
Water Consumption	~0.9 g/s (winter) and ~1.5 g/s (summer).
Hydrogen Production	33 % higher in summer than in winter due to increased solar irradiance.
Oxygen Production	Maintains a stoichiometric ratio with hydrogen, with minor variations due to operational efficiency
PEMFC Performance	
Hydrogen Consumption	Matches electrolyser production in summer but exceeds availability in winter
Water Generation	Efficient recirculation ensures minimal water loss, meeting electrolyser needs.
Subsystem Efficiency	
Solar Panel Efficiency	Maximum ~40 %, limited by UK weather conditions
Overall System Efficiency	~75 % in summer and ~65 % in winter, accounting for conversion losses.

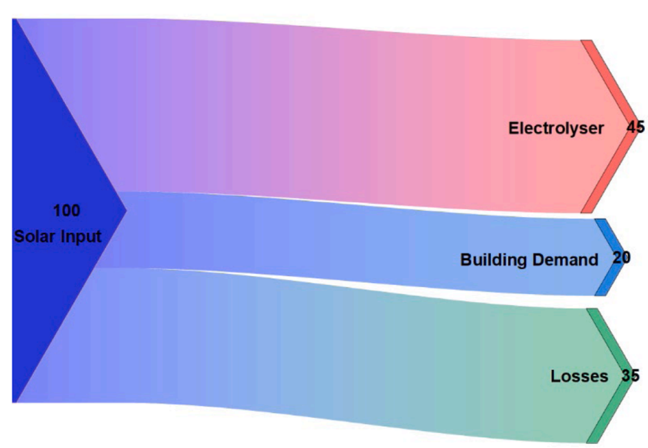

Fig. 12. System's flow of energy and resource distribution.

Table 5
Seasonal variations in energy demand and generation.

Parameter	Summer Day (July 1st)	Winter Day (December 6th)
Energy Demand	Peaks at 2.165 kWh at 18:00 (Fig. 4). Minimal demand for cooling or heating.	Peaks at 11.36 kWh at 20:00 (Fig. 5). High demand due to heating needs.
Energy Generation	Solar panels meet electrolyser's power requirements and produce adequate hydrogen for the PEMFC system (Fig. 7).	Reduced solar irradiance leads to lower hydrogen production (~0.1 g/s at peak, Fig. 10).
Hydrogen Production	~0.15 g/s (peak).	~0.1 g/s (peak).
Water Management	The maximum water consumption in Fig. 7 is ~1.5 g/s.	The maximum water consumption in Fig. 10 is ~0.9 g/s around 1pm due to reduced light availability.
Comparison	Energy generated meets all electricity demands; surplus hydrogen is stored for later use.	Only 26 % of total energy demand is met. Auxiliary energy sources (e.g., wind turbines, grid electricity) required.

offers a scalable solution for reducing carbon and water footprints. Although the simulation focused on assessing the feasibility of an electrolyser-PEMFC system in areas with significant diurnal variations, it is important to recognise the limitations of the study. The simulations were conducted for only one day in each season, and factors such as weather conditions and occasional changes were not extensively accounted for. To enhance the stability and reliability of the system, future studies should extend the simulation period to minimise the impact of weather-related variations and validate the system's performance over a longer timeframe. These findings provide valuable insights into the potential implementation of an electrolyser-PEMFC system in real-life applications. Considerations for infrastructure development and feedstock supply should be considered to ensure the successful establishment of such systems in practice.

The successful deployment of HIBDMES is contingent upon a supportive policy and regulatory framework. Governments and policymakers play a crucial role in incentivising the adoption of green hydrogen technologies in the built environment. Existing policies, such as feed-in tariffs for renewable energy generation and building codes that promote energy efficiency, can be leveraged to encourage the implementation of HIBDMES. Furthermore, the development of standardised regulations and codes specifically for HIBDMES can ensure their safe and efficient operation, fostering public confidence and accelerating their adoption. Policymakers should also consider providing financial incentives, such as grants or tax breaks, to offset the initial investment costs and stimulate market demand for HIBDMES.

CRediT authorship contribution statement

Hanhui Lei: Writing – original draft, Software, Methodology, Investigation, Formal analysis. **Joseph Thomas:** Software, Formal analysis. **Oliver Curnick:** Writing – review & editing, Investigation. **K. V. Shivaprasad:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization, Funding acquisition. **Sumit Roy:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization, Funding acquisition. **Lu Xing:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

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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Data availability

Data will be made available on request.

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