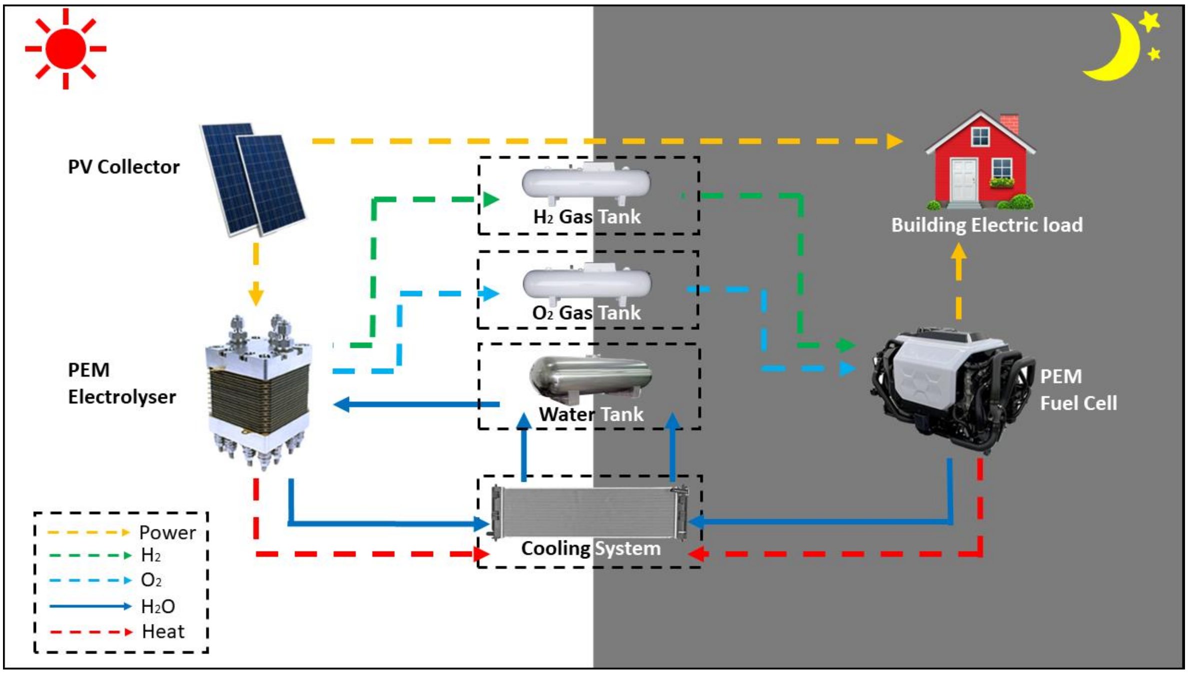
# Distributed green hydrogen for building heating and cooling decarbonisation



## Final Report

## June 2023

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## Abstract

For the UK and many European countries, the electrification of heating and cooling provisions via heat pumps, electric heaters, or electric boilers provides a pathway for carbon emissions reduction. We propose developing a building-distributed multi-energy system (BDMES) integrated with hydrogen to decarbonise the electricity generation for building heating, cooling, lighting, etc. Green hydrogen is produced and consumed locally at the building site, will eliminate the high cost and energy requirements for hydrogen transportation. This suggests the possibility of energy autonomy, which is essential due to the energy, climate, and war crisis. Distributed systems can also connect to the smart grid, enabling real-time energy, carbon trading, and optimisation.

Based on the dynamic simulation, this project aims to comprehend the interaction mechanism between the PV module, water electrolyser, fuel cell, and batteries. Comprehensive BDMES system assessment from a holistic perspective is crucial for evaluating the system's feasibility. This project also tries to develop a techno-economic-environmental integrated assessment model for comprehensive BDMES system evaluation for sustainable development to explore distributed green hydrogen opportunities and limits in a circular economy. 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. System feasibility study was extended to an office building located in London, UK and one year of system operation results have been simulated and analysed. Preliminary techno-economic-environmental analysis for the hydrogen-integrated building-distributed multi-energy system was performed.

## Novelty of the study

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 electrolyse and fuel cell integration in distributed multi-energy systems for building application. This study assesses the feasibility and potential of the hydrogen integrated BDMES as a sustainable energy solution. 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.

## 1. Introduction

The electrification of heating and cooling provisions in the UK is an essential step towards decarbonizing 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 [1]. 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. Renewable Heat Incentive (RHI) grants offer financial support for installing renewable heating technologies. Among other heat pump grants, the RHI grant is established to encourage private households, communities, and businesses to install renewable energy technologies for heating purposes through financial support [2, 3]

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. Compared to conventional heating systems, heat pumps are much more energy-efficient and can significantly cut down on energy use and carbon emissions [4]. 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 [5, 6]. The electrification of heating and cooling provisions in the UK is a vital 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 and heat pump technologies is a promising solution for reducing carbon emissions and improving building energy efficiency.

## 2. Hydrogen-integrated building-distributed multi-energy system

A system that integrates numerous energy sources and technologies to supply a building with a dependable and effective energy supply is known as a hydrogen-integrated BDMES. The system includes hydrogen tanks, batteries, solar panels/wind turbines, 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. 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 [7,8]. The multi-energy aspect of the system can incorporate multiple energy sources, including renewable sources, to provide a reliable and resilient energy supply. HIBDMES is a promising solution for improving energy efficiency and reducing carbon emissions in buildings while providing greater resilience and energy independence. However, the system is still in the early stages of development and there are challenges to be addressed, such as the cost of the equipment and infrastructure and the need for standardized regulations and policies to support its deployment.

### 2.1 Electrolysis and electrolysers

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 [9]. Electrolysers have a limited but slow-growing market, with growth rates far slower than other technologies like solar photovoltaic [10]. Each electrolyser has advantages and disadvantages, depends on factors such as efficiency, cost, and scalability. 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 [11].

### 2.2 Fuel cells

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 [12]. PEMFCs typically operate at temperatures between 60 - 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 ($H_3PO_4$) [13]. PEMFCs are superior to other fuel cells, 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.

### 2.3 Optimal control strategies

This brief progress report reviews some recent works related to optimal control of hydrogen energy systems. The review aims to understand why certain optimization methods are suitable for different applications, the optimisation targets and problem constraints in each leading control application, and which control strategies are suitable for the optimal control of distributed green hydrogen systems designed for building heating and cooling decarbonisation. Control strategies for hydrogen-based energy systems can be broadly grouped into hysteresis band control and optimisation-based control strategies.[14]

The reviewed optimisation-based control strategies for hydrogen based systems can be categorised as linear programming, dynamic programming, and reinforcement learning algorithms. Reinforcement learning (RL) is a subset of machine learning that allows an agent (an Artificial Intelligence-driven system) to learn for itself through trial and error, the optimal policy to achieve optimal control actions that maximize a reward function (usually the objective function of the problem) [15]. Like a human, agents need to construct and learn their own knowledge directly from raw data such as a historic PV generation, energy demand and electricity prices.

The optimisation problem is formulated as a Markov-decision making process consisting of a state space $S_t$, an action space $A_t$, a reward function $R_t$ and a discount factor $\gamma$ (Littman, n.d.). At every time $t$, the agent learns for itself the optimal control policy through trial and error by selecting control actions $A_t$ based on its perceived state $S_t$ of the environment. In return, the agent receives a reward $R_t$ and the next state $S_{t+1}$ from the environment without explicitly knowing the transition probability function. RL-based methods have the following advantages: (i) they are model-free, and the agents learn optimal control policies without the explicit knowledge and rigorous mathematical models of the environment [16], (ii) they have self-adaptability and can operate in an on-line way without requiring forecast information about the energy system environment [17] and (iii) they are data-driven and capable of determining optimal control actions in real-time even in complex energy system environments [18]. Given the several advantages, RL-based approaches have found application in hydrogen-based energy systems [19]–[23]. In [22], [23] RL is applied to minimise building carbon emissions in a microgr, including batteries, hydrogen energy system and constant building loads. Similarly, operating costs are minimised in [19] and [20]. However, these studies use a single control agent to manage the multiple energy storage systems. Energy management of a microgrid is usually a multi-agent problem where an action of one agent affects the actions of others, making the energy system environment to be non-stationary from an agent's perspective [16]. Single agents have been found to perform poorly in non-stationary environments [24]. A multi-agent RL-based control approach for optimal operation of a hydrogen based multi-energy systems is proposed in [21] to address the drawbacks of the single agent. The multi-agent RL method is proposed in [25] to optimize both the energy storage systems and energy demand.

## 3. Circular Economy

A circular economy (CE) is one in which waste generated during production and usage is recycled into the same or a different production process. When a product approaches the end of its life cycle, the resources still exist in the system, allowing for several uses of that product to provide value to the production process. Since it deals with waste management, prevention, and resource efficiency, the circular economy might be seen as the core of the green economy [26]. The "three Rs" of reduce, reuse, and recycle, are the basis of the well-established circular economy concept. The first step is to reduce waste by designing long-lasting products that can be easily repaired or upgraded. The second step is to reuse products or materials that would otherwise be thrown away, by finding new uses for them or repairing them. Finally, any waste that cannot be reduced or reused is recycled, with the materials being recovered and used to create new products [27, 28]. Notwithstanding the transition to a circular economy, it is beneficial to choose the actions that help evaluate the value chain over the whole life cycle of the materials used in the process. Information to assess the technical elements and environmental effects of various waste use is necessary to establish sustainable resource exchanges within the production plant [29].

## 3.1 Techno-economic analysis

A techno-economic analysis (TEA) of a hydrogen electrolyser integrated system includes evaluating the benefits and costs of an electrolysis unit with additional components such as a power source, hydrogen storage, and distribution system to produce hydrogen. TEA's objective is to determine the most economically viable option system configuration that would achieve performance and sustainability goals. In addition to the cost analysis, TEA also includes assessing the system's environmental and societal effects. This incorporates evaluating the water use, carbon footprint, and environmental consequences of the production and distribution of hydrogen [30]. The electrolysis unit's cost makes up much of the hydrogen production system's overall cost. The size and type of the electrolysis unit, the working circumstances, and the price of raw materials are some of the factors that could influence the cost of the electrolysis unit. The TEA assesses several electrolysis unit configurations to determine the most economical choice that satisfies the required performance standards [31]. Qureshi et al. provide worldwide actions related to the $H_2$ development policy. This article details hydrogen production methods, production costs, and future [32]. The article confirms that water electrolysis is the prominent method of hydrogen production by renewable sources at a lower cost than synthetic natural gas [33, 34]. 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 [35].

## 3.2 **Environmental analysis**

### 3.2.1 Life cycle assessment

Life Cycle Assessment (LCA)can play an essential role in comparing different waste resource utilisation approaches and figuring out which technological solution is best to optimise the value of the waste material. The LCA technique has evolved into a useful tool for understanding the trade-offs between benefits and drawbacks in addition to being a way to evaluate environmental performance [36]. The literature shows different LCA studies based on water electrolysis for hydrogen production [37-40]. Lajunen and Lipman performed the LCA for hybrid buses' fuel cell and battery system by considering the lifecycle costs including purchase, operating, maintenance, and possible carbon emission costs.

The study concludes that lithium-based batteries offer good performance and energy density, but their costs are still quite high and their operational lives can be short in energy-intensive operations [41]. The article of Zucaro et al. guides the LCA application to fuel-cell technologies, processes, and systems according to the international reference life cycle data system. The commercial SimaPro 7.3 software was used to assess the aspects of data quality, background/foreground data, improvement potential fuel cell stack and balance of system. Uncertainty and its consequences on results were addressed through a Monte Carlo analysis, a built-in capability of the SimaPro 7.3 software [42]. Ge et al. proposed a techno-economic-environmental integrated assessment model for comprehensive system evaluation. Entropy-TOPSIS method was used to evaluate the distributed energy system techno-economic-environmental performance under various operation strategies. [43].

### 3.2.2 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 the production of 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 [44]. 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 [45].

In addition, the water footprint of green hydrogen generation that is powered by solar or wind is about 30 L water/kg$H_2$ [46]. Green hydrogen would use 2.1 billion of fresh water annually to meet the world's current 70 Mt/yr demand for hydrogen. To manufacture hydrogen, technologies are being developed to directly electrolyze seawater rather than freshwater [47, 48]. The average solar to hydrogen water footprint is 43 L of water per kg of hydrogen when considering a comprehensive life cycle study [49]. 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. Water can be extracted and reused in the electrolyte solution from the hydrogen and oxygen gases produced during the electrolysis process. 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 hydrogen industry [50].

## 4. 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 Figure 1. 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

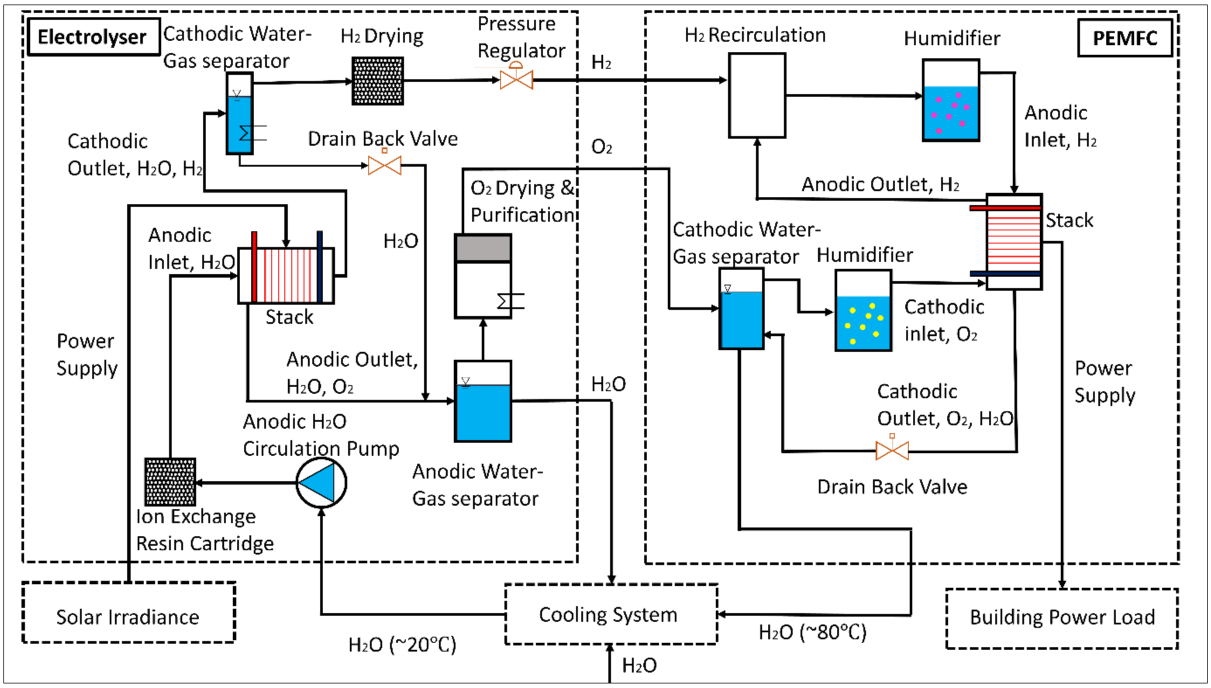

Figure 1: Schematic diagram of the proposed system

- H2O 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 H2 and O2 using solar energy as the power source. The O2 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 O2. The separated water enters the cooling system to complete a new cycle. The cathode also produces H2 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.

- O2 cycle

Oxygen is produced at the anode of the electrolytic cell system and transferred to the anode gas-liquid separator with the unreacted water. The separated oxygen undergoes drying and purification before being passed to the PEMFC system. In the PEMFC system, the O2 from the electrolytic cell system enters the cathode gas-liquid separator and then goes into the humidifier. The wet O2 is transferred to the cathode of the stack, where it reacts to produce water and generates a significant amount of heat. The unreacted O2 and water are continuously fed into the cathode gas-liquid separator under pressure valve control to complete the cycle.

- H2 cycle

The cathode of the electrolytic cell system generates H2 through the electrolysis of water. The excess water, along with the H2, goes into the gas-liquid separator of the cathode. The wet H2 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.

### 4.1 PEM electrolyser and fuel cell

PEM stands for Proton Exchange Membrane, and the electrolyser and fuel cell 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. 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. Electrolysis is energy-intensive, as a significant amount of electrical energy is required to split the water molecules. Both electrolytic cells and fuel cells (FCs) generate significant amounts of heat during operation, and water is commonly utilised as a heat transfer fluid to manage this thermal energy.

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 | $kg/m^3$ |

### 4.2 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. Thus, a prototype residential building has been developed in the EnergyPlus environment for building energy analysis and thermal load calculations. The residential building, shown in Figure 2 below, has a roof area of 150 m$^2$, with a window-to-wall ratio of 11.49% on the north of the building, 12.07% on the south. The residential building is kept at 18$^o$C in heating and 23$^o$C in cooling. 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. 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.

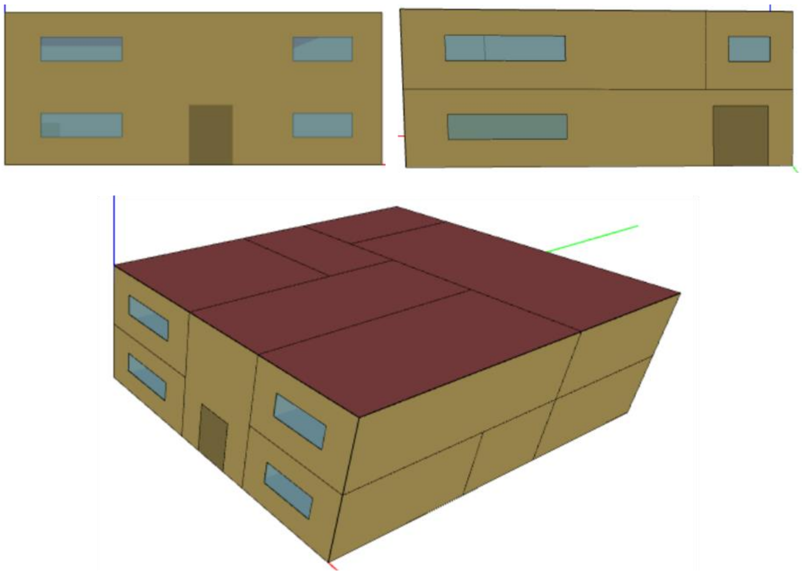

Figure 2: Residential house model

## 5. Results and discussions

Figure 3 (a) shows the hourly electrical consumption during a summer day (1$^{st}$ 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 2.2 kWh. Figure 3 (b) shows the hourly electrical consumption during a winter day (12$^{th}$ December) of the house model located in Aberdeen. The highest consumption is observed at 20:00, with a value of 11.4 kWh. The total electricity consumption during a summer day is just 28% of the total electricity consumption during a winter day.

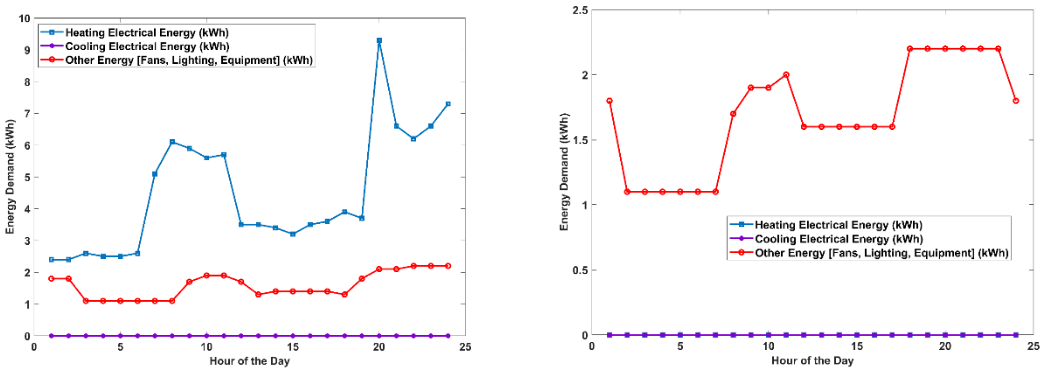

Figure 3: Building hourly electrical consumption in Aberdeen, a) summer day, b) winter day

The corresponding solar irradiance used as input to the solar PV model in the summer day and winter day is shown in Figure 4 (a) and (b). The Figure 4(a) demonstrates relatively good sunlight from 6 am to 8 pm. with a dip in irradiance around 9am and 6 pm, likely due to cloudiness or rain showers affecting light intensity. During winter in the UK, sunlight hours and intensity are significantly reduced compared to summer, as evident in the figure.

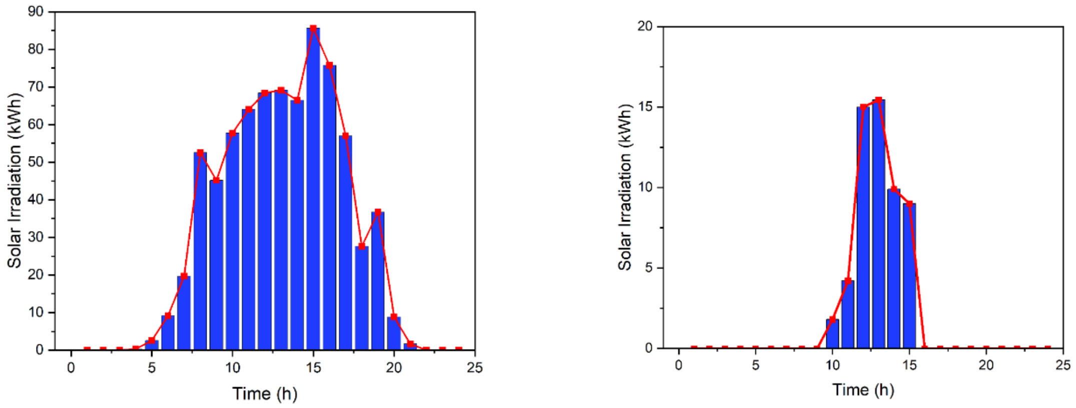

Fig. 4: Solar irradiance (kWh) (a) summer day (b) winter day

### 5.1 Case study 1: Summer Day

The solar power generated from solar PV with irradiance presented in Figure 4 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 Figure 5(a). This figure displays the electrolyzer'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 moles of $H_2$ and 0.87 moles of $O_2$ are produced.

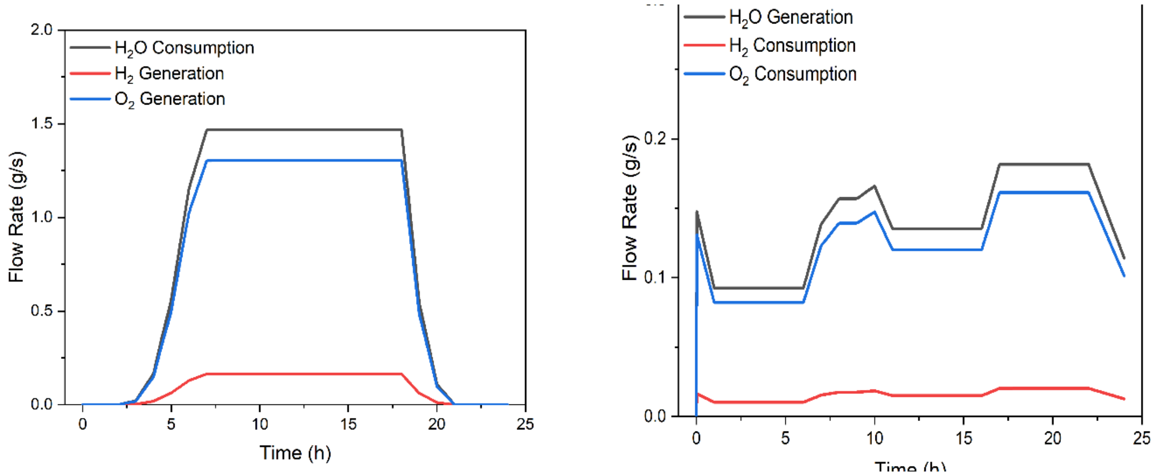

Fig. 5: (a) Electrolyser's $H_2O$ consum., $H_2/O_2$ generation (b) fuel cell $H_2O$ generation, $H_2/O_2$ consum.

Figure 5(b) illustrates the production of water and consumption of oxygen and hydrogen in the fuel cell, which also correspond to fluctuations in solar irradiance. Due to the low overall power consumption, the consumption of oxygen and hydrogen remains relatively stable 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 7 pm), while the maximum $H_2$ production rate in the electrolyser is approximately 0.15 g/s (from 8 am to 7 pm). 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.

### 3.2 Case study 2: Winter Day

Figure 6(a) represents the water consumption and hydrogen and oxygen generation of the selected winter day by the electrolyzer. The maximum water consumption in Figure 10 (~0.9 g/s around 1 pm) is lower than in the summer day case (~1.5 g/s) due to reduced sunlight availability. Consequently, the production of $H_2$ and $O_2$ is also significantly lower, with winter's $H_2$ production being approximately 33.33% less than that of summer, and $O_2$ production being about 39.13% lower. The production of $H_2$ is more unsusceptible to seasonal variations. The trend in water production in the fuel cell in Figure 6 (b) mirrors the variation in electricity consumption in residential buildings. 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.

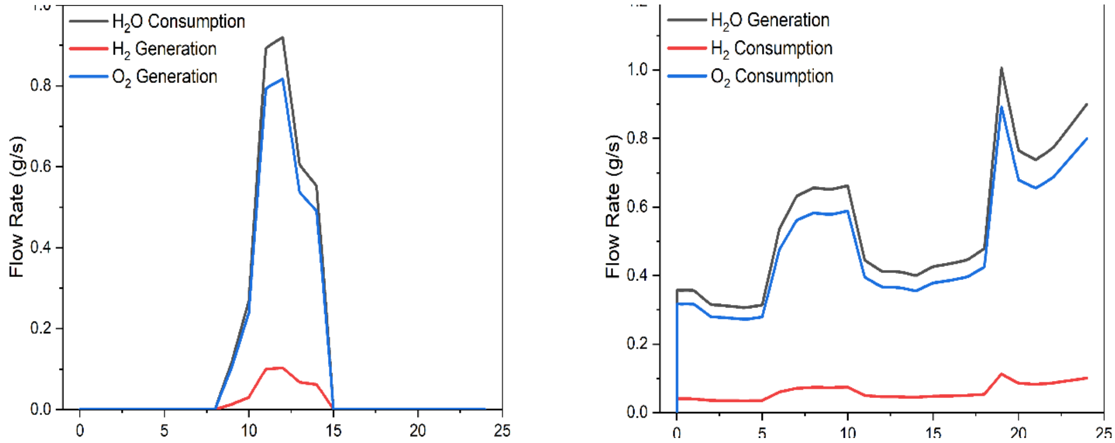

Fig. 6: (a) Electrolyser’s $H_2O$ consum., $H_2/O_2$ generation (b) fuel cell $H_2O$ generation, $H_2/O_2$ consum.

## 6. 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. 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. Feasibility of the system for office building located in London, UK for one year of time and techno-economic-environmental assessment analysis have both been performed, details of the extended research work is not presented in this report due to page limit constrain and is planned to be submitted to a peer review journal. The simulation focused on assessing the feasibility of an proton exchange membrane water electrolyser/fuel cell integrated system for different building applications, these findings provide valuable insights into the potential implementation of the distributed green hydrogen system in real-life applications. Infrastructure development and feedstock supply should be considered to ensure the successful establishment of such systems in practice.

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