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Article

Design and Optimal Sizing of a Hydrogen Uninterruptable Power Supply (UPS) System for Addressing Residential Power Cutoffs

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Abstract: Hydrogen (H2) offers a green medium for storing the excess from renewables production instead of dumping it, thus being crucial to decarbonisation efforts. Hydrogen also offers a storage medium for the grid's cheap electricity to be used during grid peak demand or grid power cutoffs. Funded by the Scottish Government's Emerging Energy Technologies, this paper presents the design and performance analysis of a hydrogen uninterruptible power supply (H2GEN) for Cygnas Solutions Ltd., which is intended to enable continuity of supply in the residential sector while eradicating the need for environmentally and health risky lead–acid batteries and diesel generator backup. This paper presents the design, optimal sizing and analysis of two H2Gen architectures, one powered by the grid alone and the other powered by both the grid and a renewable (PV) source. By developing a model of each architecture in the HOMER space and using residential location weather data, the home yearly load–demand profile, and the grid yearly power outages profile in the developed models, the optimal sizing of each H2Gen design was realised by minimising the costs while ensuring the H2Gen meets the home power demand during grid outages To enable HOMER to optimise its selection, the sizes, technical specifications and costs of all the market-available H2GEN components were added in the HOMER search space. Moreover, the developed models were also used in assessing the sensitivity of the simulation outputs to several changes in the modelled system design and settings. Using a residential home with frequent power outages in New Delhi, India as a case study, it was found that the optimal sizing of H2Gen Architecture 1 is comprised of a 2 kW electrolyser, a 0.2 kg type-I tank, and a 2 kW water-cooled fuel cell directly connected to the AC bus, offering an operational lifetime of 14.3 years. It was also found that the optimal sizing of Architecture 2 is comprised of a 1 kV PV utilised with the same 2 kW electrolyser, 0.2 kg type-I tank and 2 kW water-cooled fuel cell connected to the AC bus. While the second design was found to have a higher capital cost due to the added PV, it offered a more cost-effective and environmentally friendly architecture, which contributes to the ongoing energy transition. This paper further investigated the capacity expansion of each H2GEN architecture to meet higher load demands or increased grid power outages. From the analysis of the simulation results, it has been concluded that the most feasible and cost-effective H2GEN system expansion for meeting increased power demands or increased grid outages can be realised by using the developed models for optimally sizing the expanded H2Gen on a case-by-case basis because the increase in these profiles is highly time-dependent (for example, an increased load demand or increased grid outage in the morning can be met by the PV, while in the evening, it must be met by the H2GEN). Finally, this paper investigated the impact of other environmental variables, such as the temperature and relative humidity, on the H2GEN's performance

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and provided further insights into increasing the overall system efficiency and cost benefit through utilising the H2GEN's exhaust heat in the home space for heating/cooling and selling the electrolyser exhaust's O_2 as a commodity.

Keywords: hydrogen; uninterruptible power supply (UPS); solar PV; grid integration

1. Introduction

Uninterruptable power supplies (UPSs) are indispensable for data centres [1], hospitals [2], nuclear power plants [3] and many other services that rely on a stable energy supply in the event that a grid outage, natural disaster or any other incident occurs. This is especially true in countries that do not have access to a stable grid supply, such as India and some countries in Africa, which can see periods of extended blackouts. Other than being a general nuisance to the local populace, as this will prevent the use of many electrical appliances, it is critical for those undergoing life-saving treatment, as the full disconnection of the power supply could result in loss of life. Typically, UPSs in these instances are powered using diesel generators; however, given that civilisation is undergoing a climate crisis, many individuals and states are looking to cut the dependency on these systems. The current alternative is lithium-ion batteries, which can be driven by renewable energy sources as well as by the grid, where the energy produced by solar, wind or other sources is used to charge the battery, thus avoiding emissions at the point of use and making it green; however, this method is dubious as the technology requires energy-intensive extraction as well as materials that are limited in quantity [4], and it can be a significant challenge to tackle as a fire hazard [5].

Hydrogen (H2) technology is seen as an alternative for energy storage and as a fuel in specific applications. Significant financial and labour investments in the development of this technology [6] have led to fuel cells (FCs), electrolysers and storage tanks being refined and developed towards the consumer scale [7] and entering the market. Green Hydrogen, with the electricity used in electrolysis being generated from renewable clean sources such as solar or wind, offers green power generation at the point of use. Hydrogen, therefore, could be utilised in UPSs. A UPS is a battery in essence; however, the components of such an H2 UPS (H2GEN) have significant financial and technical challenges that need investigation before the H2GEN can be implemented meaningfully. These challenges include the significant costs of electrolysers and fuel cells and their relatively low efficiencies, which add the need for a means of cost and system optimisation for the H2GEN design. HOMER is a popular software used to financially optimise energy systems and evaluate their performance. HOMER has been utilised across many academic works; thus, it is an ideal platform for evaluating novel H2 systems.

While some work was carried out on renewable hydrogen systems for residential applications, some based on single houses and some based on several households, several of these studies have been carried out based on the continental European household demand and the grid profiles and climate examples include microgrids for Spain [8,9], techno-politico-economic analysis for Milan [10], and hybrid hydrogen systems for standalone households on Slovenia's coast [11]. Similar scenarios have also been investigated for other continents and regions, such as North America [12,13]. There have also been some investigations of other developing areas with less robust grids, such as Diyala, Iraq [14] and rural India [15]; however, these studies did not tend to address urban or suburban environments, where decarbonisation is urgently required if climate change goals are to be achieved and, thus, the work proposed in this paper is necessary.

The novelty of this work is the comprehensive design, optimal sizing and performance analysis of urban hydrogen UPS systems to replace diesel generators, a key challenge to near-term decarbonisation. The challenge for this study is to develop a bespoke hydrogen UPS microgrid system that can meet the demands of a New Delhi household, considering the challenges of grid outages in this location, whilst making use of the available solar resources.

This paper presents the development of two H2GEN designs, one with grid supply only and the other with both grid and solar PV supplies, and the equivalent model for each design was developed in the HOMER space to be used in the evaluation and cost optimisation. The sizing of each H2GEN design was optimised for private residences in New Delhi, India, based on their location weather data, as well as their average load and grid outage profiles, in such a manner that makes the H2GEN cover almost 100% of the expected outages. The simulation results for each of the H2GEN designs were then analysed to evaluate the potential of each design in terms of typical evaluation parameters such the net present cost (NPC) and technical parameters such as the load demand met. An hourly load demand profile for a New Delhi home was developed based on the average demand data, and similarly, a grid outage profile was developed to model the effect of the unstable energy supply. These profiles were used as data in the HOMER space within a developed model as well as in that from a market review to determine the cost curves and technical behaviour [16]. Finally, a variety of setups and variables were considered when running the simulations to conclude on the best system.

This paper is structured as follows. Section 2 presents brief market and literature reviews on, respectively, the market-available hydrogen-based UPS systems and the utilisation of HOMER in the literature research work; then, it further presents a literature review on the technologies implemented in H2GEN systems. Section 3 presents the methodology section, which provides two designs for the proposed H2GEN, with the development of their models in the HOMER space and applies these to a residential case study. Section 4 presents the simulation results and their evaluation. Section 5 presents additional considerations like the environmental impacts on the proposed H2GEN and further insights for increasing the H2GEN's overall efficiency and cost benefit. And finally, Section 6 provides the concluding remarks on the work. Figure 1 shows a flowchart of the research methodology.

Figure 1. Flowchart of the research methodology.

2. Review on Hydrogen UPS Systems

Literature and market reviews were firstly undertaken to evaluate the available technologies, determine the novelty of the proposed H2GEN and determine the viability of HOMER for its design, optimal sizing and evaluation.

In terms of UPSs, technologies have been present to support countries with unstable grids, with lead batteries [17] and diesel generators [18] being the most common. The technology that can compete with hydrogen UPSs are lithium-ion-based technologies such as the Tesla Powerwall [19]; however, it is undesirable to have this technology as the sole technology, as lithium is a finite material [4] that is also needed in a range of industrial applications. In terms of energy storage, new battery technologies keep developing [20] to provide an ever-diversifying range of potential technologies. Other energy storage mechanisms include flywheel energy storage [21]; however, this system is generally only utilisable for short-term energy storage and has significant costs. Other alternatives include mineshaft [22], compressed air [23] and elevator energy storage [24]. Regarding hydrogen energy storage, this technology has developed significantly with the recent investment in clean, renewable energy storage mechanisms. Hydrogen UPS systems have emerged recently, with products such as the Lavo hydrogen system [7] and HPS Picea [25] among them; however, the entry price points for these systems tend to be significant, and the design and sizing of these systems have not been optimised based on their installation location nor on their application load demand and grid outage profiles. Based on this review, it becomes crucial to design and optimally size H2-based UPSs while considering these parameters.

The literature review has shown that HOMER was utilised by researchers as a tool for evaluating H2-based systems, where the HOMER library allows modelling of hydrogen generators (electrolysers) and storage tanks [26]. While the literature review has shown some studies on the application of H2 systems in hospitals in areas with intermittent grid service, the application of hydrogen systems as UPSs for residential applications with unstable grid service in the literature was scant.

The literature review has revealed some studies on the implantation of renewable-based energy storage. A grid-tied photovoltaic system utilising battery storage was proposed in [27] to supply reliable power for a household in Pakistan while considering various parameters. The study considered the daily load of the household in question to be 13.2 kWh, the deferrable load to be 0.52 kWh and the peak load to be 0.6 kW. It was found in this study that the proposed system was more economically and environmentally friendly than only utilising a battery with the unstable grid. This study is relevant to what is being proposed because it demonstrated a similar scenario; however, it used a battery for storage instead of an H2 storage system.

A similar study was performed for a village in India [28]. In this study, a hybrid renewable energy system was designed to sustainably and reliably meet the demand of the village using a combination of technologies, namely PV, wind turbine, biomass, biogas, batteries and a fuel cell, and an optimal configuration was suggested to enable a 0% capacity shortage. This study illustrated that the utilisation of diverse energy supplies is advantageous; however, this could potentially lead to using some downrated equipment to save on the overall system cost, leading to lower performance and consumer dissatisfaction.

Another study of intertest was reported in [29], where ABB developed a business case study to evaluate different UPS scenarios that could be used for a glass maker in India that is crippled by frequent outages, inflicting significant damage to the process and plant. In this study, four scenarios were simulated and optimised, considering battery upgrades and the integration of photovoltaic generation. The study concluded that the diesel generator system that was initially used by the company was inferior to the combination of solar and battery integration potentially reaching the 15 MW factory demand. Although not the same application or storage technology to what is being proposed, this study illustrated how HOMER is used for comparative analysis of different scenarios.

Studies were also carried out in the healthcare industry, and although the power demand of hospitals is understandably stricter and greater than the average household demand, the concept of achieving a resistant supply remains of interest [30]. This study was based on an establishment in Tehran, Iran, showing that a resilient supply was obtained using a wind turbine system, energy storage system, diesel generator and a bi-directional converter, maintaining the supply 100% of the time, whereas a more economical system was the same but without the energy storage system. What was relatively appealing in this study was the idea of using wind rather than solar PV in such a location.

An example of using HOMER for the design optimisation of hybrid renewable systems with battery storage was presented in [31]. The designed system combined several renewables (solar, wind turbine, hydro) with battery storage to address the persistent load shedding at Amrita University in India.

In conclusion, the literature review has shown that it is indeed possible to achieve, for a variety of applications, an in-depth analysis of various states of grid outages using HOMER, from scenarios that have relatively infrequent outages to those with significant recurrent outages. While the literature has demonstrated the use of HOMER in the design and analysis of hybrid renewable–battery systems for addressing such grid outages, HOMER is indeed suitable for the design and analysis of the potential renewable–hydrogen UPS system.

2.1. Review the Technologies Implemented in the H2GEN System Components

The core components of the H2GEN are the electrolyser, or some other H2 production system, an H2 storage system (storage tank), a fuel cell to convert H2 back into electricity (with heat as a potential by-product) and a controller that coordinates the operation of the system components. Like any engineering problem, the relevant literature review is completed to understand the potential of the different technologies available for each component and, accordingly, identify the most appropriate technologies to apply in the proposed H2GEN.

2.1.1. The Fuel Cell (FC) Technology

According to the literature, there are several FC technologies; however, for the purpose of use in the proposed H2GEN, the FC technologies that were proposed for use are those mainly with lower operating temperature, a light weight, cost efficiency, a fast response, ability to be used with simple feedstock, and ability to be locally sourced. Three fuel cell technologies are commonly identified to fulfil these requirements, these are polymer electrolyte membrane fuel cells (PEMFCs), alkaline fuel cells (AFCs) and direct methanol fuel cells (DMFCs). Table 1 presents a summary of the reviewed FC technologies for the proposed H2GEN. As can be seen, PEMFCs, with a potential 70–90% efficiency, offer the most potential as an alternative for small-scale UPS and other consumer-oriented applications after factoring in their combined heat and power characteristics, low operating temperatures, quick start-up and less wear of system components, resulting in a longer lifespan [32].

Table 1. Summary of the reviewed fuel cell technologies.

Type	Temperature (°C)	Output Power (kW)	Electrical Efficiency (%)	Combined Heat/Power Efficiency (%)	Advantages	Disadvantages
AFC	90–100	10–100	60	>80	Platinum catalyst can be changed, cost-effective, fast reaction rate, quick start-up	Reduced performance with CO_2 presence, high hydrogen purity
DMFC	60–200	0.001–100	40	80	No toxic emissions, high energy density, methanol storage is easy, methanol less expensive	Possible reactant mixing, fuel concentration effects performance, expensive catalyst, electrode is easily poisoned
PEMFC	50–100	<1–250	53–58	70–90	Wide operational range, simple scaling, quick start-up, high power density	Reduction can be slow, heat management needed, excess cell water, possibility of CO poisoning, high fuel purity

2.1.2. The Hydrogen Generator (Electrolyser) Technologies

Similarly, there are different mechanisms available for hydrogen generation. Table 2 summarises the electrolyser technologies [33]. Ultimately, the device selected for the H2GEN is the PEME, which, although more expensive, tends to be more compact and less dense, allowing for the potassium hydride recycling demand to be avoided. The PEME's compactness allows deployment when space is finite, and thus it is more suited for the residential H2GEN application. Additionally, PEME systems have a high level of market penetration and are commercially available in many designs of various capacities.

Table 2. Summary of the reviewed electrolysis technologies.

Type	Temperature (°C)	Demonstrated Rated Power (kW)	Typical Current Efficiency (%)	Advantages	Disadvantages
AE	65–100	2.8–3534	50–70.8	Technologically mature, low cost, long-term stable, cheap, robust, cheaper catalyst	Corrosive electrolyte, low current densities, low operating pressure
AEM	50–70	1.3–4.8	39.7	Low cost, compact, non-corrosive electrolyte, no leaking, high operating pressure, cheaper catalyst	Early stage, low durability, membrane degradation, low current densities
PEME	70–90	1.8–174	48.5–65.5	High performance, higher efficiency, fast system response, compact	High cost, corrosive acid, lower durability, expensive catalyst

2.1.3. The Hydrogen Storage Technologies

Having produced through electrolysis the H2 to be utilised as a feedstock by the FC for electricity production, there is a need for a storage medium for this hydrogen. To identify the storage technology to be employed in the proposed H2GEN, this section provides a brief review of the available H2 storage mechanisms.

2.1.4. Compressed Hydrogen Storage Tanks

The first potential mechanism is simply taking the produced hydrogen, compressing it and storing it in some form of cylinder or tank. However, selection of the tank to be utilised is based on the tank material, which is represented by the "type" classified by a number from I–IV. Type-I tanks are the most conventional, being all metal, generally steel or aluminium, whereas type-IV tanks are polymer-lined tanks fully wrapped with carbon fibre. Table 3 presents a summary of the available compressed air storage technologies [34]. Additionally, there is a fifth mechanism being developed, which is referred to as type-V, where the liner is dismissed in favour of a structure that is entirely composite; however, this is at the cutting-edge of the technology. The specific benefit of compressed hydrogen storage is the fact that it is a mature and relatively simple technology, albeit not the least expensive.

Table 3. Summary of the reviewed compressed hydrogen storage tank types.

Storage Tank	Structure	Operating Pressure (Bar)	Advantages	Disadvantages
Type-I	All metal	500	• Good safety • Good strength • Low cost	• High weight
Type-II	Thick metal wrap with hoop reinforcement	Not limited	• Better resistance to metal liner fatigue and hydrogen embrittlement • Not limited in terms of operating pressure	• More expensive

Table 3. *Cont.*

Storage Tank	Structure	Operating Pressure (Bar)	Advantages	Disadvantages
Type-III	Metal liner but thin and fully wrapped with resin	450	• Half the weight of type-I containers.	• More expensive, double the cost of type-I
Type-IV	Polymer or, occasionally, ultra-thin metal liner wrapped with fibre resin composite	700	• Lightest of these vessels	• Most expensive

2.2. Chemical Hydrogen Storage Mechanisms

The mechanism stores the hydrogen within a medium rather than storing it by itself, like in the case of the compressed hydrogen tank. This could be achieved through converting it into ammonia (NH_3), formic acid (CH_2O_2) or even carbohydrate ($C_6H_{10}O_5$), which is abundant biologically.

2.3. Selecting the H2 Storage Technology for the H2GEN

Table 4 shows a summary of the two technologies reviewed in this study. Based on the reviews in Tables 3 and 4, the type-IV storage tank was initially identified to be the best for application in the proposed H2GEN, as, despite being more expensive, its compact nature is favourable for household applications and the incorporation of thermoplastic and composite material into its manufacturing implies resistance against the hydrogen embrittlement seen in alternatives. These tanks also avoid the need for the compression stage, and typical volumes should fulfil the demands of typical households. However, based on market research concerning the needed tank size, it was found that the cost of a type-IV tank is significantly higher than its type-I alternative, thus implying the benefit of the selection of a type-I tank for the H2GEN. On the other hand, although metal hydride tanks were found to be the most appropriate for consumer purposes as they are energy-efficient, compact and safer than compressed storage, they were found to be heavier as absorbing metal adds weight, requiring temperature control to manage hydrogen release, and can be more expensive, depending on the metals used [35].

Table 4. Summary of the suitable hydrogen storage technologies.

Hydrogen Storage Technology	Volumetric Capacity (kg m^{-3})	Temperature (°C)	Pressure (bar)	System Cost (USD/kWh)	Advantages	Disadvantages
Compressed H2 Storage	<40	0	700	12–16	• Light weight • Occupies small space • Energy effective	• Requires high pressure cylinder • Volumetric and gravimetrically inefficient
Chemical H2 Storage	150	100–300	1	8–16	• High storage density • Low reactivity • Short storage time	• Reacts with moist air • Cumbersome to handle • Absorbs impurities • Lack of reversibility • Desorption at elevated temperatures

2.4. The Controller

To manage the operation of the H2GEN system with the grid-integrated residential load and possibly an integrated renewable supply, and to allow energy management across the integrated components, a control mechanism is essential. HOMER embeds typical strategies such as load-following and cycle-charging [36] mechanisms, which were both employed and compared in this study to see if such a mechanism selection will affect the results.

3. The H2GEN Design Methodology

This section proposes two H2GEN designs for addressing the grid outages in residential applications and presents the development of a model for each design in the HOMER space. The developed models were then applied in a case study residential application in New Delhi, India to enable optimal sizing while assessing their performance under different sensitivity factors.

3.1. Simulation of the Proposed H2GEN Architectures in HOMER

The first H2GEN design (Architecture 1) employs an AC-busbar-coupled electrolyser connected to a hydrogen storage tank, which feeds the hydrogen fuel cell. The fuel cell, with a built-in inverter, is then coupled to the AC busbar to supply, together with the grid, the load demand of the case study New Delhi homestead. The second H2GEN design (Architecture 2) has a similar setup to the first but with an integrated solar PV to act as an additional source of power. A model has been developed for each H2GEN design in the HOMER space to enable assessment of its feasibility and performance, and to optimally select and size each component of the H2GEN to ensure that each design can meet the home power demands during outages efficiently and at the least possible cost. To aid the selection of components, several simulation scenarios were run to explore the impact of selecting different technologies for the H2GEN components. Moreover, to refine the selection of the electrolyser and the fuel cell minimum load ratio (MLR), as well as their efficiencies in the developed H2GEN models, a sensitivity analysis was carried out.

3.1.1. The HOMER Optimisation Space

HOMER's algorithm optimises the sizing of the selected H2GEN system components based on the global minima on the NPC curve of the system based on the multidimensional parameter space, which can be continuous or discrete, depending on the type of system implemented and the simulation demands. HOMER selects and optimises the sizing of the H2GEN components using the available database, the simulation constraints and the sensitivities. Some of the metrics considered in HOMER includes the NPC [37,38], LCOE [39], capital and operational costs [40], and the breakdown of the costs associated with each component. Other measures include the unmet load [41], predicted lifespan [42], FC capacity factor [43] and the FC fixed generation cost [44].

Table A1 presents the values of the economic parameters used in this study and Table A2 presents the simulation constraints used.

3.1.2. Sensitivity Analysis of Minimum Load Ratio and Efficiency

In addition to the previously discussed considerations in this study, the sensitivity of the H2GEN design sizing, performance and/or projected NPC to some variables were simulated to accordingly refine their selection in the developed H2GEN models. Firstly, a sensitivity analysis was carried out to explore the effect of changing the controller setup. The effect of changing the values of the MLR for the electrolyser (EMLR) and for the FC (FCMLR) was also assessed. Traditionally, setting an MLR is intended to prevent a system from operating when it is not optimal, i.e., when it is less fuel efficient, or as a method to prevent additional wear of the components through preventing excess use. From the HOMER MLR default values and manufacturers' datasheets, the EMLR values selected for this sensitivity analysis were 0% and 20%, and for FCMLR, 10% and 25%, and the results were analysed to evaluate the effect of the MLR on the cost and lifespan. Similarly, a sensitivity analysis of the efficiency changes was also completed to evaluate the effect of lowered efficiency on the system performance, where lowered efficiency could occur over time due to physical phenomena, such as the catalyst, membrane degradation or other mechanics, that could degrade the system. Again, from the HOMER default values and manufacturers' datasheets, the efficiencies considered in this sensitivity analysis were 10% and 50% for the fuel cell (FCE) and 50% and 80% for the electrolyser (EE).

3.1.3. Simulation Scenarios for Optimisation of Hydrogen UPS

For completing all the previously mentioned design analyses, a number of simulation scenarios were developed using the models developed in the HOMER space for both the H2GEN designs (i.e., Architectures 1 and 2). Table 5 summarises these simulation scenarios.

Table 5. Summary of the simulation scenarios.

Scenario Number	Scenario Description
1. Architecture 1 Scenario 1.1	H2GEN Architecture 1 (Controller Setting Sensitivity Analysis: Cycle Charging (CC) vs. Load Following (LF))
Scenario 1.2	H2GEN Architecture 1 with CC Setting (Fuel Cell-Type Analysis: Water-Cooled Fuel Cell vs. Air-Cooled Fuel Cell)
Scenario 1.3	H2GEN Architecture 1 with Water-Cooled Fuel Cell and CC Setting (Storage Tank-Type Analysis: Type I versus Metal Hydride)
Scenario 1.4	H2GEN Architecture 1 with Water-Cooled Fuel Cell, Type-I Tank and CC Setting (Increased Load Demand Analysis: Double Load)
2. Architecture 2 Scenario 2.1	H2GEN Architecture 2 with Water-Cooled Fuel Cell, Type-I Tank and CC Setting (PV Addition Analysis)
Scenario 2.2	H2GEN Architecture 2 with Water-Cooled Fuel Cell, Type-I Tank and CC Setting (PV Connection Analysis: PV connected via AC Bus vs. DC Bus)
Scenario 2.3	H2GEN Architecture 2 with Water-Cooled Fuel Cell, Type-I Tank and CC Setting and PV connected via AC Bus (Increased Load Demand Analysis: Double Load Demand)
Scenario 2.4	H2GEN Architecture 2 with Water-Cooled Fuel Cell, Type-I Tank and CC Setting and PV connected via AC Bus (Increased Grid Outage Analysis—Double Outage Profile)
3. Sensitivity Analysis Scenario 3.1	H2GEN Architecture 2 with Water-Cooled Fuel Cell, Type-I Tank and CC Setting and PV connected via AC Bus (Electrolyser and Fuel Cell Minimum Load Ratio (MLR) Sensitivity Analysis)
Scenario 3.2	H2GEN Architecture 2 with Water-Cooled Fuel Cell, Type-I Tank and CC Setting (PV connected via AC Bus—Electrolyser and Fuel Cell Efficiency Sensitivity Analysis)

3.2. The Proposed H2GEN Architectures and Their Developed Models in HOMER

In this study, two architectures were considered for the design of the proposed H2GEN, one to be charged by the grid alone and the other to be charged by both the grid and a renewable source (solar PV for India). For each architecture, a model has then been developed in the HOMER space and used in several simulations and sensitivity analyses to refine the selection of the H2GEN components, connections and some parameters. Figure 2 shows the models developed for each design in the HOMER space.

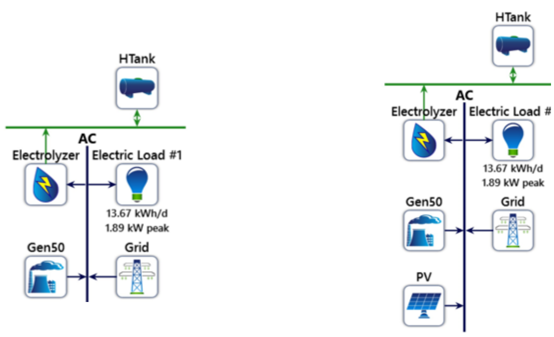

Figure 2. (**Left**) Architecture 1: H2GEN driven only by the grid. (**Right**) Architecture 2: H2GEN driven by both the grid and solar PV.

3.3. Applying the Developed Models for Both Architectures to a New Delhi Residential Case Study

This paper utilises the developed H2GEN models to design two possible H2GEN designs for a case study residential application in New Delhi, India and, ultimately, to select, based on the analysis of both designs' simulation results, the best-suited H2GEN.

As the case study residential application is in India, the initial investigation started with a review to explore the country's grid and other problems in Indian residential applications, the renewable energy potential in India and the products available on the Indian market for manufacturing the H2GEN.

3.3.1. Review on Indian Grid, Potential Renewables and Market-Available Technologies

According to the literature [45], the electrical grid in India is not different structure-wise from any other grid; however, it faces many key issues that affect its performance. Ageing and inefficient system components have rendered it prone to failure as well as leaving it unable to meet the growing demand of citizens. These problems are further compounded by the continuous growth of the Indian population. It was quantified that India has a peak electricity deficit of 1 GW (0.6%) and an energy shortage of 600 MU (0.5%). Despite the significant potential of renewable sources in India, their grid-integration problems prevent this abundant source of energy from being capitalised upon. Cumulatively, these problems result in a grid that is prone to failure, with regular blackouts being a feature of Indian life.

Looking into India's/New Delhi's renewable potential, the climate has significant potential for harvesting energy from renewable sources [46]. The potential of solar power is significant, as it sees 300 sunny days a year, with a theoretical power reception on its land of 600 TW, and the average solar incidence energy varies between 4 and 7 kWh/m^2, with 1500 to 2000 h of sunshine available per annum. Manufacturing facilities are now present in India, with 9 solar cell, 22 solar module and 50 solar system manufacturers present. Thus, it can be said that solar energy harvesting is readily available in India. However, it is not a simple solution, given the fact of New Delhi having significant swathes of inner-city populace, and there should be careful placement to avoid shade from nearby buildings [47]. As such, PV is proposed as the renewable source to be integrated into our proposed H2GEN Design 2. Figure 3 shows the profile used to simulate the solar resource available for the PV integrated into the proposed H2GEN Design 2. It is anticipated that this system will be biased in optimisation as it is disproportionately cheaper than the hydrogen systems discussed; however, it is key to analyse the technical effect of the PV integration in terms of the hydrogen system sizing. A specific limitation that is considered in the system design regarding the PV system is the access to an area big enough to contain a significant solar presence; thus, it was key to consider only a small PV system profile of 1 kW.

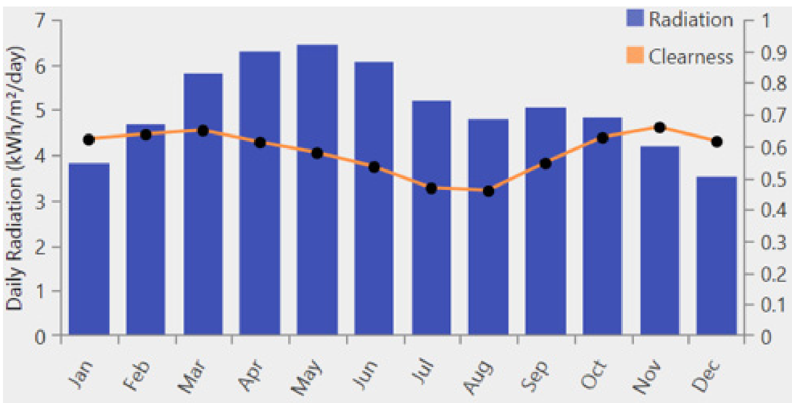

Figure 3. The solar radiation profile utilised in H2GEN Design 2.

A similar investigation carried out on India's hydrogen potential [48] showed that India has been hesitant in adopting hydrogen technologies locally due to misconceptions regarding the complexity and hazards (leakage and explosion) of such systems. As such, unlike European countries, hydrogen vehicles have not yet been adopted in India and no infrastructure exists for hydrogen fuel transport. A key fundamental barrier to hydrogen deployment in India is the high initial cost compared to a standard lead–acid battery or diesel generator, and thus no local H2 technologies industry exists. Thus, for the purpose of this study, the H2 system components considered in the proposed H2GEN are implied to be imported from China, where such systems are commercially available on the market [49].

3.3.2. Case Study: Data Collection for the Developed H2GEN Models in HOMER

A residential case study in New Delhi, India was selected to apply the two proposed H2GEN designs on, analyse their operation and optimise their sizing. For this purpose, data were accordingly collected for use in the developed models.

Firstly, the location of the residential case study was entered in the HOMER models to enable the development of the solar radiation profile (Figure 3), which was needed as input to the solar PV model existing in H2GEN Design 2. Additionally, the local temperature profile shown in Figure 4 was also generated as it directly impacts the performance of the PV system. HOMER imports these from the NASA database.

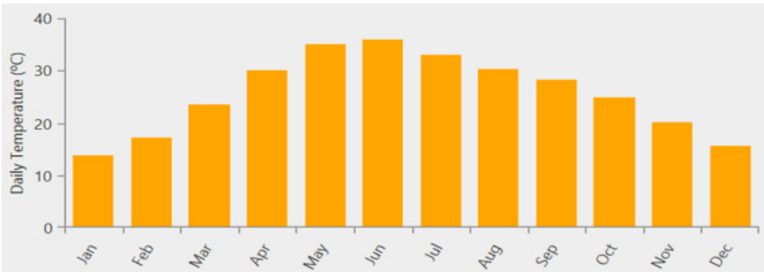

Figure 4. The temperature profile for New Delhi based on NASA data.

Using the India National Energy End-use Monitoring Dashboard website [50], a load demand profile for the average household in New Delhi was generated (Figure 5). Unlike the northern hemisphere, where power consumption peaks during the winter months when heating is switched on, the Indian peaks are pronounced during the summer months, when the excessive heat drives air conditioner (AC) usage. Figures 6 and 7 show, respectively, the generated daily and seasonal load profiles for the case study residence based on the derived data. The yearly load profile is shown in Figure 8.

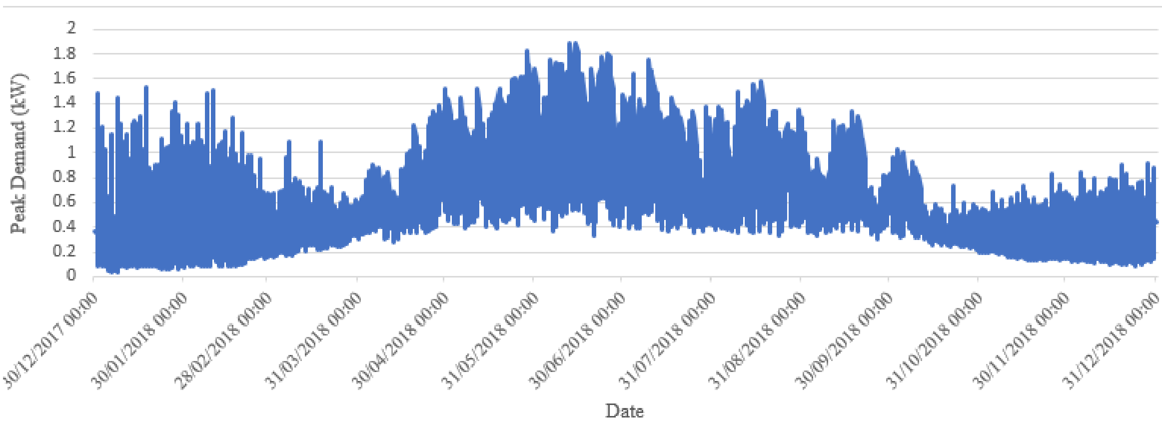

Figure 5. The load demand profile for an average Indian homestead in New Delhi.

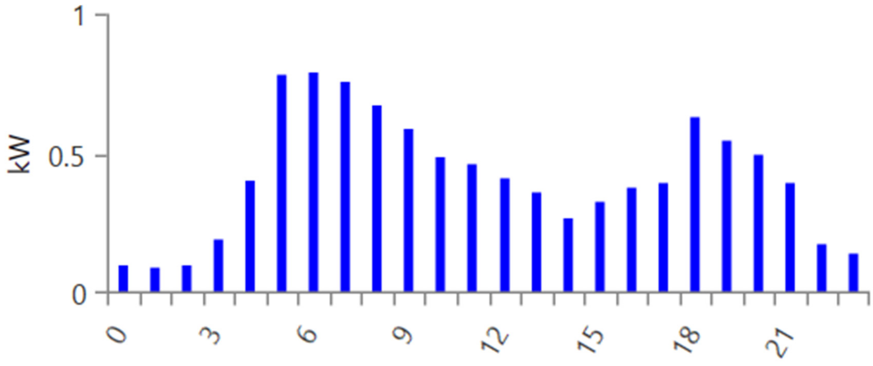

Figure 6. The residence's daily load profile.

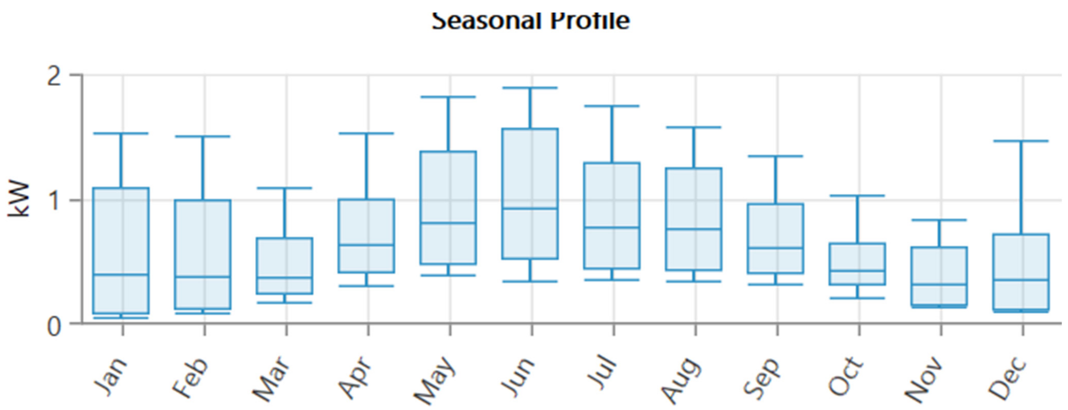

Figure 7. The seasonal load profile.

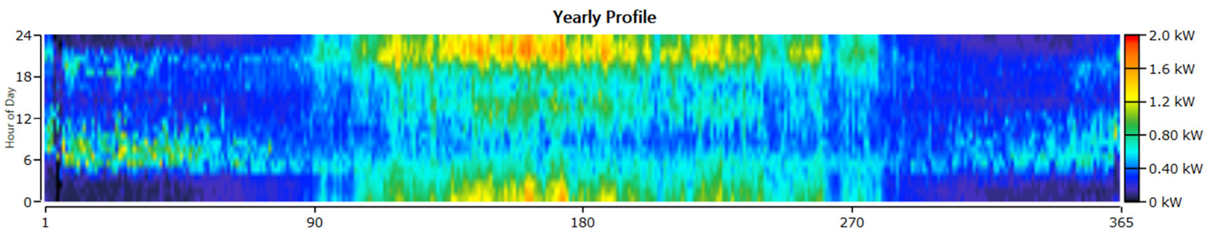

Figure 8. The yearly load profile for the residence.

As India's grid struggles to ensure the continuity of supply, a grid outage profile was developed based on consumer feedback in the region. This grid outage profile, as shown in Figure 9, was used in the developed H2GEN models. Additionally, for this simulation, India's grid rate of 6.4 p was used.

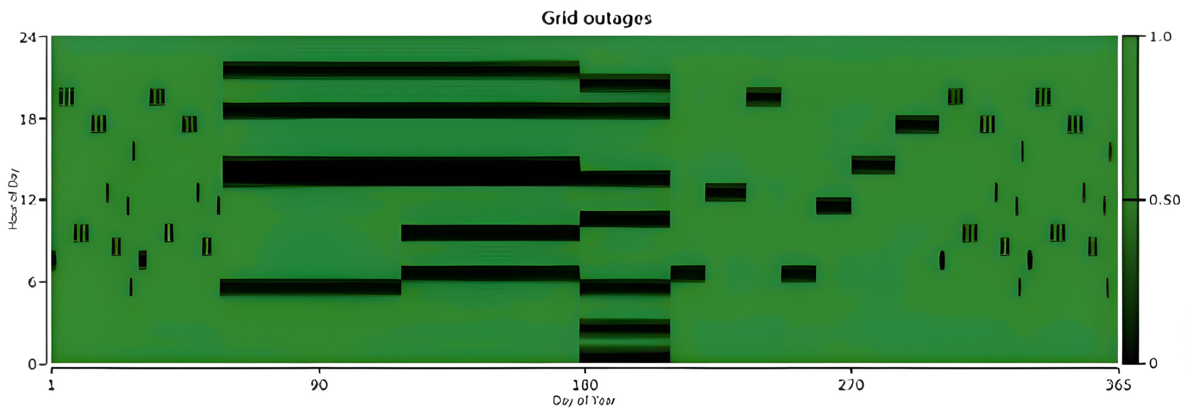

Figure 9. The grid power outage profile.

To enable the analysis and sizing optimisation of the two proposed H2GEN designs for the case study home, firstly, the optimisation search space in HOMER was updated to accommodate the data collected for the photovoltaics, fuel cells, electrolysers and hydrogen storage tanks available on the New Delhi market. The information used as inputs was all derived from the market and literature research to ensure that the simulation results are valid and practically possible to apply. The market review derived a series of costs for each of the hydrogen system components to create a relevant cost curve for each component in HOMER. In the simulations, because hydrogen is generated on-site through water electrolysis powered by the grid and/or solar PV, there are no charges added for hydrogen to be delivered. With the market review showing that the cost-efficient technology that enables meeting consumer needs is dominated by PEM technology for both electrolysis and FCs, the behaviours of this technology were accordingly used in the models to inform the system efficiency and other relevant parameters for the H2GEN simulation. Similarly, two types of hydrogen tanks were considered and analysed in the simulation. These were metal hydride [51] and type-I [52] tanks, where the simulation implied that the compressor prices are included in the storage tank price. With air-cooled fuel cells found to be cheaper but to have a shorter lifespan, while water-cooled fuel cells were found to be more expensive but with a longer lifetime, both air-cooled and water-cooled PEMFCs were considered in the simulation to analyse their performance within the case study residential application. The simulation implied that the inverters are built into the fuel cells. Based on the data collected from manufacturers during the market review, Tables A3 and A4, respectively, summarise the parameters used for modelling the water-cooled and air-cooled fuel cells in HOMER. Similarly, Table A5 summarises the parameters used for modelling the electrolyser system in HOMER. Tables A6 and A7, respectively, present the parameters utilised in modelling the type-I and metal hydride tanks. The PV system was modelled based on the data collected for locally sourced equipment in India, where similarly, these data were used to develop a cost curve and inform the appropriate technical parameters and behaviour [34]. For the solar PV design purposes, the metrics of interest lie predominantly in its capacity sizing, cost and pragmatism. Capacity-sizing-wise, the system must be big enough to meet the home load demand and mitigate grid outages as much as possible, yet it must be optimised cost-wise to justify its presence on the market among other UPS options. Pragmatically, it is important to consider the household premises, especially the access and space required for the solar PV. As such, there were bounds considered in selecting the PVs. Table A8 summarises the parameters used for simulating the solar PV in HOMER.

For simulating the converters used in converting the DC power to AC, the data given in Table A9 were utilised.

The final component to be considered in the simulation was the controller, which enables efficient, reliable and stable operation by managing and co-ordinating the energy flow across the various energy resources, storage systems and loads. In HOMER, load-following and cycle-charging dispatch strategies are available and thus were used and compared in the analysis.

Thus, all the fundamental parameters needed for modelling the H2GEN system components and other aspects was integrated into the simulation. Additionally, it is also key to discuss that HOMER has in-depth modelling features, boundaries and simulation parameters that control the behaviour of the simulation, most of which were not relevant to this study; thus, these were generally left as their default values unless mentioned in this section. At the time of compiling this study, HOMER had not integrated a continuous search space for H2 systems and was using a discrete search; thus, it was computationally bounded to specific simple options. This study first aimed at optimising the sizing of the two proposed H2GEN architectures to ensure that they can meet, at the minimal possible cost, any given grid outage. This study also aimed at assessing the performance of both designs and exploring the impact of adding the PV in Design 2. The assessment also included the impact of changing the fuel cell PEM technology from air-cooled to water-cooled as well as the impact of changing the H2 storage tank type. In this study, a sensitivity analysis was also included for parameters such as the minimum load ratio (MLR) and efficiency to explore their impact on the H2GEN's cost and sizing. Beyond this, there were further investigations into the expansion of the proposed H2GEN for meeting a higher load demand and for meeting increased outage profiles. Therefore, to achieve all this, several simulation scenarios were executed in this study and the results were analysed.

4. Results and Analysis

In this section, the two designed H2GEN architectures' optimisation results are presented and analysed while considering the technical and economical parameters as well as the inherent sensitivities and constraints. For the sake of the collaborative company H2GEN product disclosure, the costs results are presented in relative terms to each other rather than as specific quantitative costs.

4.1. H2GEN Architecture 1 Simulation Scenarios—Results and Analysis

Firstly, the Scenario 1.1 simulation was used to investigate whether the selection of load-following or cycle-charging setting would change the performance of the H2GEN system, and the results showed that it does not. Therefore, for consistency, it has been decided to use the same setting (cycle charging (CC)) in all our simulation scenarios.

The Scenario 1.2 simulation was then used to enable the optimal sizing, costing and performance analysis of the proposed H2GEN Architecture 1 with a water-cooled fuel cell (WC-H2GEN) versus that with an air-cooled fuel cell (AC-H2GEN). The obtained results showed that the optimal sizing for the cost-effective Architecture 1 H2GEN that can meet the case study home demand during grid power outages is similarly comprised of a 2 kW fuel cell (AC or WC), 2 kW electrolyser, and 0.2 kg H2 Tank. The Scenario 1.2 cost simulation results were then used to enable the relative comparison of the WC-H2GEN costs versus those of the AC-H2GEN over the twenty-five-year period, as demonstrated in Table 6. It can be seen from the table that while the capital cost of the WC-H2GEN is about 20% higher, the other costs are significantly less. Further comparative analysis of the costs results showed that the WC-H2GEN total NPC is about 131% less than that of the AC-H2GEN, its LCOE is similarly about 131% less and its operating cost is about 306% less. The longer lifespan of the water-cooled system plays a significant role in lowering the NPC, albeit at the expense of a higher initial investment. From the analysis of the electrical simulation results, it was found that the percentage of unmet load for both the WC-H2GEN and AC-H2GEN systems is the same value (0.0005%), confirming that the selected H2GEN sizing successfully enabled meeting 99.9995% of the demand. From the analysis of the fuel cell simulation results, discrepancies can seen between their performance in terms of the lifespan and the fixed generation cost on an hourly basis, where the water-cooled fuel cell's operational life, capacity factor and fixed generation costs are found, respectively, to be 14.3 years, 5.71% and GBP 1.06/hr versus 1.91 years, 5.71% and GBP 5.37/hr for the air-cooled fuel cell—meaning that using a water-cooled fuel cell in the proposed H2GEN offers a longer operational life and less fixed generation costs.

Table 6. Costs of WC-H2GEN relative to the costs of AC-H2GEN.

Component	Capital	Replacement	Salvage	Total NPC (Over 25 Years)
WC-H2GEN versus AC-H2GEN	20.61%	−553.34%	−88.38%	−131.36%

Based on this comparative analysis shown in Figure 10, air-cooled fuel cells are ruled out for the proposed H2GEN application and water-cooled fuel cells have therefore been selected for both the proposed H2GEN designs and, accordingly, used in all the upcoming simulation scenarios.

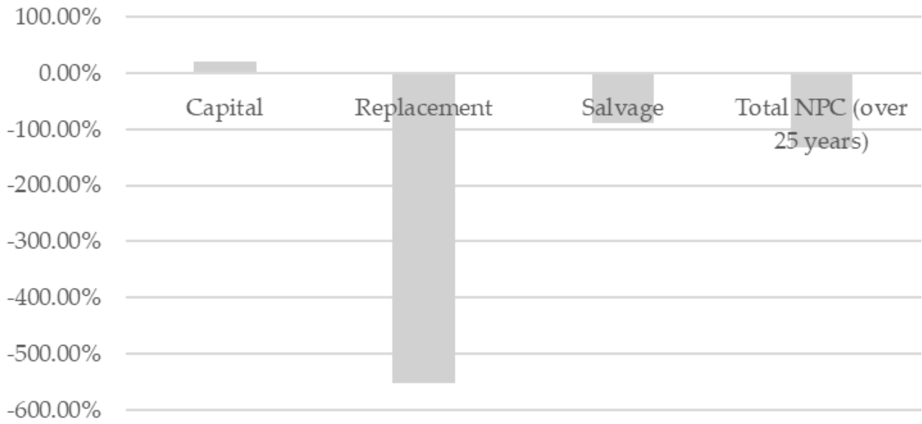

Figure 10. Water-cooled H2GEN compared to air-cooled H2GEN.

The Scenario 1.3 simulation was then used to further investigate the impact of changing the tank type on this H2GEN architecture. The investigation enabled a comparative analysis of H2GEN Architecture 1 with a type-I tank versus that with metal hydride. The results showed that changing the tank type does not change the optimal sizing of the H2GEN, the electrical results or the fuel cell lifetime, capacity factor and generation cost. Cost-wise, Table 7 shows that using metal hydride tanks will add around GBP 1650 to the cost of the H2GEN. A comparative analysis of the overall H2GEN architecture costs over its 25-year lifetime showed that using metal hydride tanks increases the overall H2GEN capital cost by GBP 1646 versus only a GBP 49 drop in O&M costs, while the replacement cost remained the same. Based on this comparative analysis and given that the size of the tank needed for the H2GEN residential application is small, type-I is found to be more cost-effective and thus is used in the proposed H2GEN and, accordingly, in all the simulation scenarios; however, it should be noted that because HOMER is primarily an economic optimisation tool that does not consider any technical ramifications of integrating a specific technology, it is suggested to revise the tank selection on a case-by-case basis to consider the size and specs of the tank needed for each specific application.

Table 7. Difference in costs of the H2GEN with metal hydride versus H2GEN with type-I tanks.

Tank Technology	Capital (£)	Replacement (£)	O&M (£)	Total NPC (£)
H2GEN with Metal Hydride versus H2GEN with Type-I	+£1646	0	−£49	+£1632

The Scenario 1.4 simulation was finally used to further investigate the expansion of this H2GEN architecture for meeting higher load demands. To analyse how a higher demand impacts the design of the base demand H2GEN, the load demand profile was doubled. From the simulation results, it was found that the optimal sizing of the electrolyser and fuel cell required for the H2GEN to meet the doubled load demand profile was scaled up proportionately to a 4 kW FC and 4 kW electrolyser; however, to avoid underutilisation, the tank size was less than doubled (0.3 kg). From the electrical summary results, it was found that the sized system enabled 0% of the unmet load. From the fuel cell summary, it was found that the fuel cell's operational life remained 14.3 years, the capacity factor slightly dropped from 5.71% to 5.64%, and the fixed generation cost increased slightly from 1.06 to 1.27 GBP/h. Cost-wise, the NPC of the expanded demand H2GEN increased but was less than doubled, and comparing the capital cost increases showed that the expanded demand H2GEN is GBP 8280 cheaper than the cost of using two units of the base-demand H2GEN. From the comparative analysis of the expanded demand H2GEN results versus those if the previous results obtained were doubled for the H2GEN base demand unit, it has been concluded that because the cost of the expanded demand H2GEN and its tank size (i.e., needed space) are less, a more viable and cost-effective expanded demand H2GEN can be realised by using the developed HOMER model for optimally sizing it based on the given increased load–demand profile, rather than using multiple base demand H2GEN units.

4.2. H2GEN Architecture 2 Simulation Scenarios—Results and Analysis

Similarly, a thorough investigation was carried out for our proposed H2GEN Architecture 2, which integrates a solar PV. The added PV, which produces cheaper power than fuel cells, is intended to support the H2GEN in meeting some of the home power demand during grid outages as well as to power the electrolysis process. With the PV power being clean, this architecture has an added benefit of reducing the carbon footprint.

Firstly, the Scenario 2.1 simulation used the Architecture 2 model developed in the HOMER space to optimally size this H2GEN Architecture 2 and analyse its costs and performance versus those of Architecture 1. Compared to Architecture 1, the optimal sizing of the H2GEN components remained the same: 2 kW water-cooled fuel cell, 2 kW electrolyser, and 0.2 kg H2 tank, but with an added 1 kW PV.

Compared to Architecture 1, cost-wise, when looking into the cost summary results, we found that the capital cost of H2GEN Architecture 2 was GBP 1010 more due to the added PV cost, the replacement cost remained the same as there is no replacement cost for the PV, the O&M cost was GBP 2765 less due to the drop in the grid's O&M costs with the contribution of PV generation and the total NPC was GBP 1719 less due to the PV extra feed of electricity; therefore, it can be concluded that Architecture 2 is more cost-effective.

Performance-wise, the % of unmet load remained 0% in this H2GEN architecture, confirming that it is capable of meeting the residential demands during grid outages. The fuel cell's operational lifetime remained 14.3 years, the fuel cell fixed generation cost remained 1.06 GBP/h, and the fuel cell capacity factor was reduced by 1.69% due to the reduced operation of the fuel cell with the presence of PV generation. It should be noted that this suggests that if the solar PV can take on more of the FC's operation during outages, this will accordingly prolong the life of the FC, the more expensive component, decreasing its maintenance and frequency of component replacement costs. However, using a larger solar PV capacity is highly dependent on the available space for installation and will increase the H2GEN's capital cost.

Environment-wise, adding a renewable source (PV) to this H2GEN architecture results in a reduced carbon footprint due to the reduction in the grid fossil fuel power and also because some of the H2GEN-produced H2 comes from the use of PV, making the power produced by the H2GEN clean.

Based on the above comparative analysis, Architecture 2 of the H2GEN offers a more cost-effective and environmentally efficient architecture for our proposed residential H2GEN. Figure 11 presents a schematic diagram of the Architecture 2 assembly.

Scenario 2.2 then investigated the impact of connecting the H2GEN to the residential load via a DC bus and external inverter instead of directly connecting it to the load AC bus (implying that the fuel cell has a built-in inverter). This change in configuration was found to have a significant impact on the H2GEN component sizing and costs. Optimal-sizing-wise, all the system components, except the fuel cell, increased in size, with the electrolyser increasing to 3 kW, the PV to 7 kW and the hydrogen tank to more than double at 0.5 kg. This increased sizing, together with the added inverter cost, resulted in increased H2GEN costs, as summarised in Table 8. The capital cost of this H2GEN architecture was found to be increased by around GBP 12,000, the replacement cost increased by around GBP 3000, and the NPC increased by around GBP 7000; however, the O&M costs dropped by around GBP 6000 due to the increased sizing of the PV, leading to reduced fuel cell operation costs. The LCOE was also found to be reduced due to the fact that the significant sizing of the PV system leads to less power being taken from the grid, thus reducing the grid O&M cost, plus more revenue from selling this increased PV power back to the grid. Performance-wise, the % of unmet load remained almost 0%, while the fuel cell operational life increased to 18.8 years and its capacity factor dropped by 1.33%, correlating with the fuel cell's reduced operation associated with the increased PV sizing. From the analysis of the above observations, it has been concluded that despite the benefits added by the increased the PV sizing in this configuration, such an H2GEN sizing is unfeasible for residential applications and is not cost-effective. Therefore, a more feasible and cost-effective H2GEN is to be realised by the utilisation of specially manufactured fuel cells with built-in inverters to allow the direct connection of the H2GEN to the load AC bus. Therefore, the AC-coupled H2GEN configuration is used in the developed models and in all our simulations. Figure 12 visualises the results of this simulation.

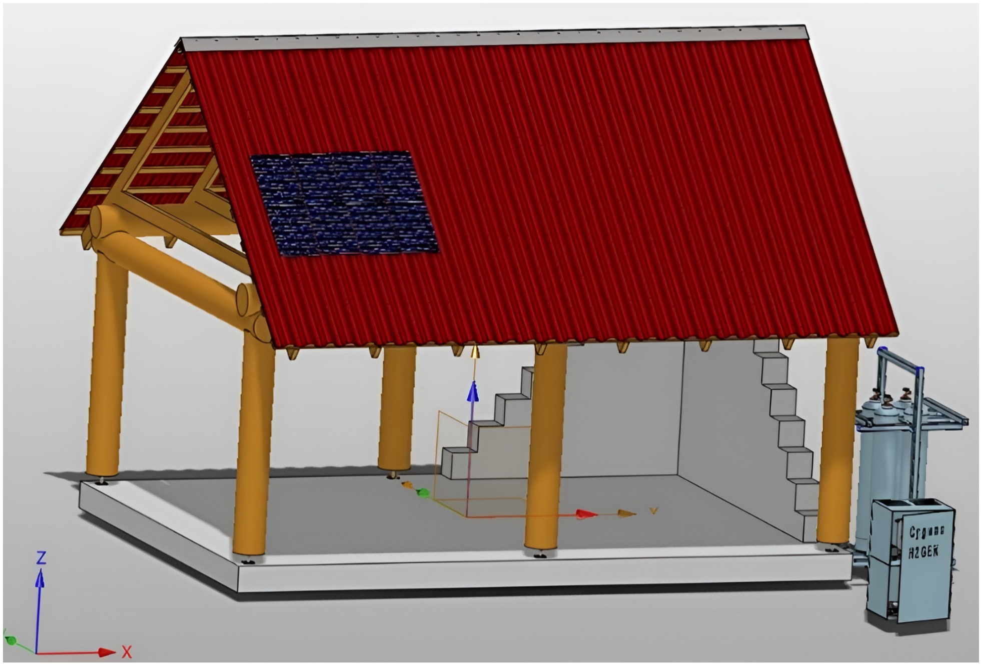

Figure 11. The proposed H2Gen assembly.

Table 8. Costs of the H2GEN when connected to the AC bus versus that when connected to the DC bus.

Component	Capital (%)	Replacement (%)	Salvage (%)	Total (%)
H2GEN with AC Bus versus with DC Bus	−58.67	−32.24	−144.25	−14.11

Scenario 2.3 investigated the expansion of this H2GEN Architecture 2 to meet higher power demands. To select the best expansion option, the load profile used in our HOMER model was doubled and the corresponding system sizing, performance and costs of the expanded demand H2GEN that can meet this double demand were compared to those if using two of the base demand H2GEN units. Optimal-sizing-wise, while the PV in the double demand H2GEN remained 1 kW, similar to the previous Architecture 1 expansion simulation, the electrolyser and fuel cell sizes doubled to 4 kW and the storage tank increased to less than double (0.3 kg).

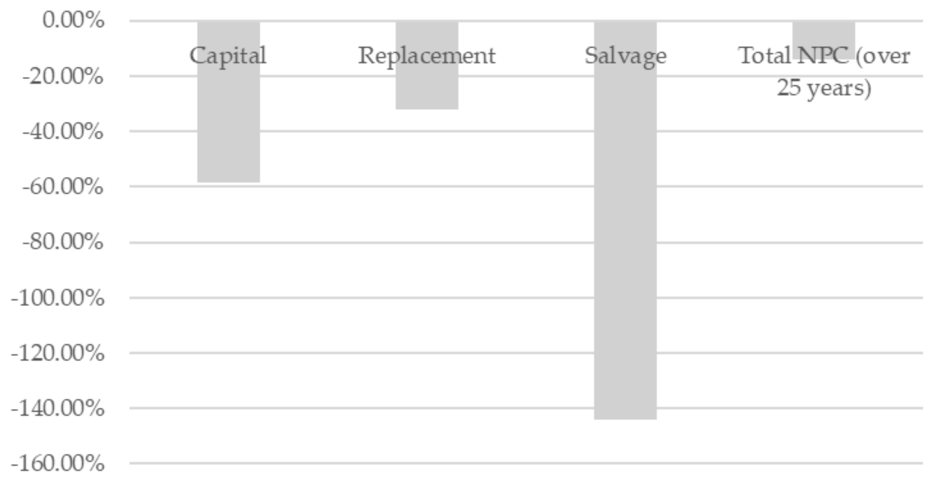

Figure 12. H2GEN Architecture 2's cost change when on the AC bus compared to the DC bus.

Performance-wise, the double demand H2GEN was found to be able to meet the doubled load profile during grid outages with 0% unmet load. The fuel cell's operating lifespan remained 14.3 years, with an increased fixed generation cost of less than double and a slight increase in the FC capacity factor from 4.02% to 4.67%.

Cost-wise, the capital cost of the double demand H2GEN increased due to the additional costs of the bigger electrolyser, fuel cell and tank; however, this increase was less than double. Similarly, the replacement cost, O&M cost and the total NPC increased but were still less than double, showing that optimally sizing the double demand H2GEN for realising double the power capacity is more cost-efficient than using double the base demand H2GEN units. Therefore, it has been concluded that whenever an H2GEN system expansion is required to meet increased power demand, it is recommended to optimally size this expanded demand H2GEN on a case-by-case demand increase basis rather than using multiple of the base demand H2GEN units.

To investigate the expansion of the H2GEN for meeting increased grid power outages, Scenario 2.4 was used to optimally size this H2GEN architecture so that it can meet double the grid power outage profile whilst assessing the system performance and costs. The original grid power outage hours were firstly doubled, resulting in the increase of outage hours from 1047 to 2094 h, and a random distribution was used for the power outage profile, as seen in Figure 13. This profile was then used in the developed H2GEN model in the HOMER space and the results were compared to those obtained when using the original grid power outages profile.

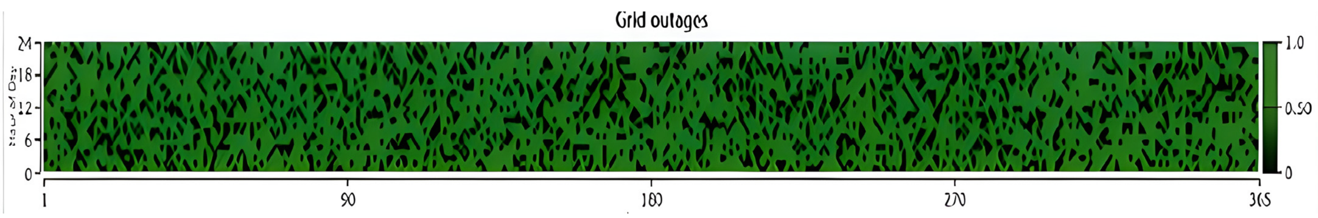

Figure 13. Random distribution of the grid doubled power outage hours.

The optimal sizing of the expanded outage H2GEN was found to be comprised of the same 1 kW PV but with a 6 kW electrolyser, 0.3 kg tank and 4 kW fuel cell, meaning that expanding the system for meeting double the power outages resulted in doubling the fuel cell size, less than double for the tank, and more than double for the electrolyser, while the PV remained the same.

Cost-wise, this increase in the sizing of the H2GEN system components resulted in an increase in the system capital cost, but this was found to be less than double, as well as increases in both the O&M and replacement costs to more than double, respectively, due to the increased grid power O&M costs and replacement cost of the more than doubled electrolyser. The total NPC also increased to more than double and the LCOE almost tripled. Thus, the costs have an increased more than double for each of these key costs through the doubling of the outage profile. This increase in the system sizing and the associated system costs are highly dependent on the profile of the doubled power outage used in the simulation scenario, where a profile with increased evening outages will need to be met by the H2GEN (not PV), meaning that the electrolyser needs to be bigger than double to produce more hydrogen.

In terms of the electrical profile, the used grid outage profile has been found to slightly increase the unmet load to 0.045%; however, this is still relatively insignificant. The FC operational lifespan has been found to be halved to 7.2 years due to fuel cell's increased operation with the increased outages that cannot be met by either the grid or the PV. This reduction in the fuel cell lifetime caused the increase in the replacement cost due to the more frequent replacements, and the fuel cell fixed generation cost was also found to be increased. It should be noted, however, that these results are dependent on the grid outage profile used in the model, and these results may vary if a different grid-outage profile is used.

From the analysis of the above scenario findings, it can be concluded that doubling the grid power outage profile results in the need for increased H2GEN sizing and, accordingly, increased costs; however, this increase is mainly dependent on the grid outage profile (so, for example, if most of the grid outages are happening out of the PV production hours, then a bigger electrolyser will be needed for producing more H2 for the fuel cell operation and, accordingly, more power will be drawn from the grid to power the electrolyser, increasing the grid O&M costs and associated emissions; additionally, the fuel cell lifetime will be reduced due to its increased operation). Therefore, it is recommended that the optimal sizing of the expanded system capacity for meeting increased grid outages needs to be completed on a case-by-case basis to allow for identifying the most feasible and cost-effective configuration suited for the given power outage profile.

4.3. Sensitivity Analysis on the Electrolyser and Fuel Cell Minimum Load Ratio (MLR) and Efficiency

Finally, a couple of simulation scenarios were used to investigate how sensitive the simulation outputs are to the changes in the efficiency and minimum load ratio of both the electrolyser and the fuel cell to, accordingly, identify the values to be used in the developed H2GEN models.

Scenario 3.1 firstly assessed the sensitivity of the results to the changes in the electrolyser and fuel cell minimum load ratio (MLR). For this analysis, we ran a number of simulations using different values of the EMLR and FCMLR in the developed H2GEN system model to reveal how sensitive the simulation results are to the changes in these values. The values used in these simulations were obtained from HOMER's default and from the collected data sheets. From the analysis of the results, it has been found that shifting the EMLR between the HOMER default of 0% and the manufacturer's 20%, while keeping the FCMLR constant at 10%, had no impact on the system sizing or on the % of unmet load, and only a slight increase was noticed in the grid O&M costs due to a slight increase in the grid power usage. Similarly, changing the FCMLR from the HOMER default of 25% to the manufacturer's 10%, while keeping the EMLR constant at the default 0%, had no impact on the system sizing or on the % of unmet load, but a slight drop was noticed in the grid O&M costs. Therefore, because changing the MLR has a marginal effect but the 10% FCMLR value is slightly more economic, it has been decided to use the HOMER default EMLR of 0% and the manufacturer's FCMLR of 10% in the setting of our developed H2GEN models.

Scenario 3.2 then assessed the sensitivity of the results to the changes in the electrolyser and fuel cell efficiencies to, accordingly, identify the values of the electrolyser efficiency (EE) and the fuel cell efficiency (FCE) to be used in our developed H2GEN system models. For this analysis, we ran several simulations in which we entered into our developed system model different EE and FCE values (obtained from the HOMER default or from data collected) to reveal how sensitive the simulation outputs are to the changes in these values. The values used in our simulations are (50%, 80%) for the EE and (10%, 50%) for the FCE. The analysis of the results showed that the impact of efficiency is more notable.

The impact of changing the fuel cell efficiency (FCE) from the HOMER default of 10% to the highest manufacturer efficiency of 50%, while keeping the electrolyser efficiency constant at 50%, was found to have a far more profound effect on the system sizing and costs. The increase in the FCE resulted in a vast drop in the system's capital, replacement and O&M costs due to the drop in the system sizing and in the grid O&M costs. In conclusion, it can be said that the FCE is a key component for realising a cost-efficient and feasibly sized H2GEN and, therefore, an efficient fuel cell should be employed in the H2GEN. Figure 14 visualises the results of this simulation. Table 9 shows the cost change for this simulation when compared to the H2GEN with a PV system that is connected to the AC bus.

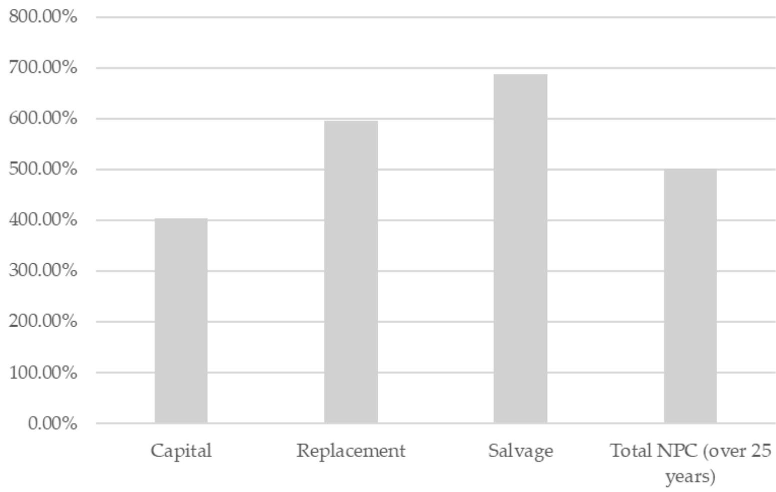

Figure 14. H2GEN Architecture 2's cost change when the FCE is dropped to 10%.

Table 9. Cost changes for the H2GEN with PV when connected to the AC bus and with 10% fuel cell efficiency.

Component	Capital	Replacement	Salvage	Total NPC (Over 25 Years)
H2GEN with PV and AC Bus (10% FCE)	402.86%	596.16%	687.49%	500.68%

The impact of changing the electrolyser efficiency (EE) from 50% to the highest possible manufacturer's efficiency of 80% was found to have similar ramifications for the system sizing and cost. The increased electrolyser efficiency reduced its size and the associated capital and replacement costs. It also reduced the grid O&M costs. In conclusion, it can be similarly said that the EE is another key component for realising a cost-efficient and feasibly sized H2GEN and, therefore, an efficient electrolyser should be employed in the H2GEN. Figure 15 visualises the results of this simulation. Table 10 shows the cost change for this simulation when compared to the H2GEN with a PV system that is connected to the AC bus.

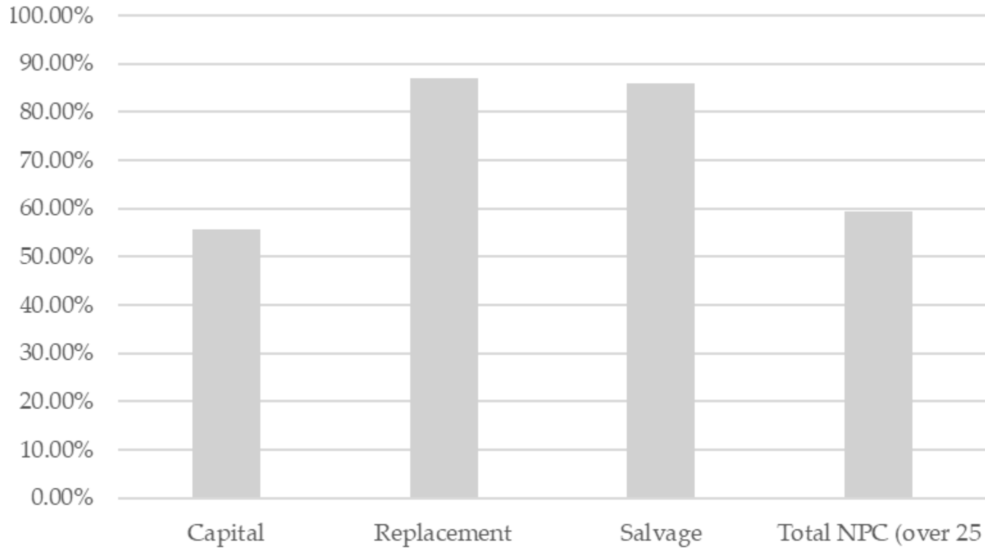

Figure 15. H2GEN Architecture 2's cost change when the EE is dropped to 50%.

Table 10. Cost changes for the H2GEN with PV when connected to the AC bus and with 50% electrolyser efficiency.

Component	Capital	Replacement	Salvage	Total NPC (Over 25 Years)
H2GEN with AC Bus with PV (50% EE)	55.57%	87.02%	85.96%	59.24%

5. Further Insights into Other H2GEN Design Considerations

Finally, other factors that may affect the performance of the H2GEN based on the location were considered in the proposed system design. Additional sensitivities that were identified as potentially affecting the H2GEN performance included locale parameters such as the temperature and relative humidity. The first consideration was the ambient temperature, which the fuel cell in the H2GEN is sensitive to. This, however, is manageable with appropriate, modern cooling systems. Because Delhi is a location that is consistently hot relative to locations such as Great Britain, with temperature peaks swinging between 25 and 40 °C, overheating of the system may occur, resulting in a dehydration effect on the membrane, which results in various levels of failure from a drop in efficiency to complete failure of the membrane. Thus, the H2GEN cooling system must be designed while acknowledging that although the PEMFC operates at higher temperatures than ambient, it will still be necessary to keep it hydrated by preventing evaporation through appropriate cooling that keeps the temperature stable.

The relative humidity (RH) becomes another problem as the performance is high when the intake air has high RH; however, there are times when the humidity drops and that is mainly when the H2GEN system is to be used in Delhi during summer, when load-shedding occurs mostly due to high levels of air-conditioning use. Thus, there is a paradox that needs to be solved as to how to enable the H2GEN to operate when it is most needed but with the environmental conditions being least favourable to its good operating performance. Ultimately, this will require a method of humidifying the inlet air to enable the system to operate without degrading the chemical performance. Thus, in addition to the cooling system, there is a need to design a humidifier to enable optimal performance of the H2GEN. Moreover, water scarcity should also be considered when using such an H2GEN system in New Delhi, particularly during summer, when the rain-fed rivers dry out. Consequently, there could be a need to store water when it is present in excess to utilise it later when scarce. Alternatively, the H2GEN could be implemented in a manner where the same feedstock is utilised repeatedly.

Further insights into increasing the H2GEN efficiency suggested utilising the H2GEN's exhaust heat in the home space for heating/cooling, thus increasing its overall efficiency while lowering the home heating/cooling footprint. Moreover, the electrolyser's exhaust O_2 can be sold as a commodity to further increase the system's cost-efficiency.

6. Conclusions and Discussion

This paper presents the design and optimal sizing of two H2GEN architectures for use as a back-up power supply for residential homes in New Delhi, India, with an in-depth techno-economic assessment of each design option. Both H2GEN architectures employ an electrolyser, hydrogen storage tank and a fuel cell, with Architecture 1 powered by the grid alone, while Architecture 2 combines the grid and PV power to drive the electrolyser for producing hydrogen locally and storing it to be used later in the fuel cell to produce electricity during grid outages.

A model was developed for each H2GEN architecture in the HOMER space and the optimal system sizing for each architecture was derived based on the average residential load profile of several dwellings in New Delhi and using India's grid power outages profile. Using the developed models, numerous simulations were then carried out to investigate the impact of the following on the H2GEN design: type of fuel cell, tank types, the electrolyser and fuel cell MLR, the electrolyser and fuel cell efficiencies, connecting the H2GEN to the DC bus versus connecting it directly to the load AC bus, and finally, expanding the H2GEN to meet an increased load demand or increased grid outages. Firstly, based on the results obtained from the MLR and efficiency sensitivity analyses, the identified values were entered in the H2GEN models. Using these models, the above simulations were completed.

From the results of the undertaken simulations for both configurations, it was found that the optimum configuration for the H2GEN Architecture 1 that can meet the home load demand during grid outages in the most cost-efficient manner is comprised of a 2 kW electrolyser, a 0.2 kg type-I tank and a 2 kW water-cooled fuel cell. For the H2GEN Architecture 2, this was found to be comprised of a 1 kW PV, a 2 kW electrolyser, 0.2 kg type-I tank and a 2 kW water-cooled fuel cell directly connected to the load AC bus. It was found that the presence of the PV in Architecture 2 reduced the burden of the fuel cell during grid outages. While adding the PV did not impact the optimal sizing of the electrolyser, tank or fuel cell, it was found that adding the solar PV increased the H2GEN capital cost but reduced both the O&M cost (due to the drop in the grid O&M costs) and the NPC (due to the revenue from the PV power sold to the grid). Moreover, Architecture 2's PV adds the environmental benefit of reducing the carbon footprint because it reduces the grid power use and because it makes the H2 produced from powering the electrolyser green, thus making the power produced by the H2GEN fuel cell clean too. In conclusion, Architecture 2 offers a more cost-effective and environmentally friendly architecture that contributes to the ongoing energy transition.

Finally, from the analysis of the results obtained from the H2GEN expansion simulation for realising higher power capacities to meet higher load demands or more grid power outages, it has been concluded that the optimal sizing of the expanded capacity H2GEN needs to be obtained on a case-by-case basis to allow for identifying the optimal sizing of the most feasible and cost-effective configuration suited for the given increased load–demand profile or increased power outage profile since this profile impacts the design based on the timing of the increase.

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Nomenclature

UPS	Uninterruptible Power Supply
FC	Fuel Cell J
ST	Storage Tank
H2	Hydrogen
H2GEN	Hydrogen UPS
NPC	Net Present Cost
PEMFC	Proton Exchange Membrane Fuel Cell
DMFC	Direct Methanol Fuel Cell
AFC	Alkaline Fuel Cell
PEME	Proton Exchange Membrane Electrolyser
DME	Direct Methanol Electrolyser
MLR	Minimum Load Ratio
EMLR	Electrolyser Minimum Load Ratio
FCMLR	Fuel Cell Minimum Load Ratio
EE	Electrolyser Efficiency
FCE	Fuel Cell Efficiency
LF	Load-following
CC	Cycle Charging
PV	Photovoltaics
AC	Air Conditioning
WC-H2GEN	Water-Cooled H2GEN
AC-H2GEN	Air-Cooled H2GEN
RH	Relative Humidity
LCOE	Levelised Cost of Energy
O&M	Operation and Maintenance

Appendix A

Table A1. The economic parameters.

Parameters	Values
Nominal Discount Rate (%)	8
Expected Inflation Rate (%)	2
Project Lifetime (Years)	25
Capacity Shortage Penalty (GBP/kWh)	0

Table A2. Simulation constraints.

Parameters	Values
Maximum Annual Capacity Shortage (%)	0
Minimum Renewable Fraction (%)	0
Operating Reserve as percentage of load:	
Load in current time step (%)	10
Annual peak load (%)	0
Operating Reserve as percentage of renewable output:	
Solar power output (%)	80
Wind power output (%)	50

Table A3. Water-cooled FC parameters.

Parameter	Value
Capacity (kW)	1–3
Cost (GBP)	14,000–17,000
Efficiency (%)	50
Lifetime (h)	15,000–20,000
Minimum Load Ratio (%)	25
Operational Cost (GBP/h)	0.02–0.03

Table A4. Air-cooled FC parameters.

Parameter	Value
Capacity (kW)	1–3
Cost (GBP)	5700–14,600
Efficiency (%)	50
Lifetime (h)	2000–3000
Minimum Load Ratio (%)	25
Operational Cost (GBP/h)	0.01–0.03

Table A5. Electrolyser parameters.

Parameter	Value
Capacity (kW)	1–3
Cost (GBP)	3150–10,900
Efficiency	80
Lifetime (Years)	13
Minimum Load Ratio (%)	5
Operational Cost (GBP/yr)	126.2–436

Table A6. Type-I hydrogen tank parameters.

Parameter	Value
Capacity (kg)	0.4–1.2
Cost (GBP)	3970–5970
Lifetime (Years)	25
Operational Cost (GBP/yr)	0

Table A7. Metal hydride tank parameters.

Parameter	Value
Capacity (kg)	0.4–1.2
Cost (GBP)	3300–10,730
Lifetime (Years)	25
Operational Cost (GBP/yr)	0

Table A8. Solar PV parameters.

Parameter	Value
Rating (kW)	3–10
Cost (GBP)	2520–7080
Lifetime (Years)	25
Area	16.78–51.07

Table A9. Converter parameters.

Parameter	Value
Rating (kW)	1–3
Efficiency (%)	90
Cost (GBP)	130–279

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