Brunel University London
Department of Mechanical and Aerospace Engineering College of Engineering, Design and Physical Sciences

Solar PV And Hybrid Energy Storage System for Smart Energy Communities

Submitted By

Akash Chidambaran Anil

Student ID: 2252035

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Academic Supervisor: Zahir Dehouche

Declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University’s Regulations and Code of Practice for Taught Programmes and that it has not been submitted for any other academic award.

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Signed: Akash Chidambaran Anil　　　　　　　　　　Date: 20/09/2023

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Solar PV And Hybrid Energy Storage System for Smart Energy Communities

[1]A.C.Anil and Z. Dehouche[1]

[1]Department of Mechanical and Aerospace Engineering, College of Engineering, Design and Physical Sciences, Brunel University London, UB8 3PH, United Kingdom

Abstract

This dissertation focuses on developing a solar PV and hybrid energy storage system to decrease a community building's carbon footprint. Through comprehensive methodology, including literature review, software simulations, design optimizations, economic analysis, and environmental assessment, the project achieves its research objectives. Using Helioscope software, a 63.4-kW solar PV system comprising 194 panels was designed for the Wilfred Brown Building at Brunel University, UK. This system can generate 7% of the building's annual electricity demand. Subsequently, HOMER Pro software was employed to model and optimize hybrid system configurations. The chosen configuration, integrating solar PV, batteries, a fuel cell, and bidirectional converters, was shown to be more viable due to project constraints and environmental considerations. Environmental analysis indicates a 53.99% annual reduction in carbon footprint compared to the grid-only system, reinforcing the benefits of renewable energy adoption. Economically, the designed system demonstrates an 8.01-year payback period and a lower levelized cost of electricity £0.221/ KWh compared to the base case £0.275/ KWh representing a 19.6% reduction in energy costs. This study contributes to sustainable energy solutions by demonstrating the technical feasibility, environmental advantages, and economic viability of solar PV and hybrid energy storage systems.

Keywords: Solar PV; Battery; Fuel cell; Electrolyser; Hybrid energy storage.

Abbreviations

PV: Photovoltaic

HESS: Hybrid energy storage system.

PEMFC: Polymer electrolyse fuel cell.

CAPEX: Capital expenditure.

OPEX: Operating expenditure.

HOMER: Hybrid optimization of multiple electric renewables.

NPV: Net present cost.

LCOE: Levelized cost of electricity (£/KWh)

NPC: Net present cost.

1. INTRODUCTION

The demand for electricity is increasing more and more each year due to the growing population and vast technological advancement. Day-to-day activities of human life greatly depend upon electricity. But with the increase in electricity demand, there is also the release of large quantities of greenhouse gas into the atmosphere thereby contributing to global warming. It's worth noting that buildings account for a substantial portion of global energy consumption, comprising one-third of the total energy usage and contributing to a quarter of global greenhouse gas emissions which is shown in Figure 1 [1].

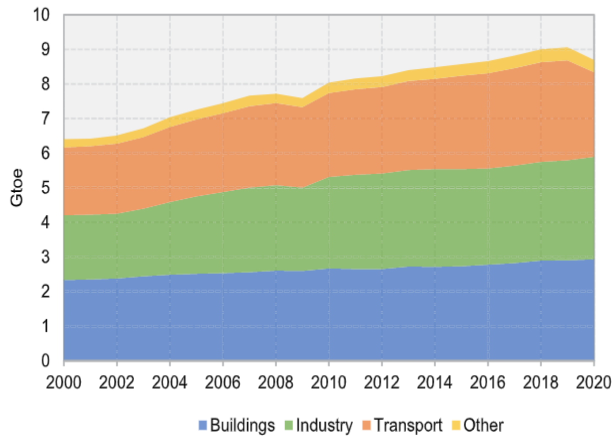

Figure 1: Global energy consumption by sector [1]

This has led to one of the urgent needs to reduce the emissions associated with electricity. Considering this, the European Union's "Fit for 55" package aims to reduce greenhouse gas emissions by 55% by 2030, with 1990 serving as the baseline [2]

To achieve a transition towards cleaner energy the potential of renewable energy sources must be explored. There are a variety of renewable sources available like solar PV, solar thermal, wind, hydro, biomass, and geothermal, as well as marine energy derived from waves and tides. The choice of selection out of these renewable technologies depends primarily on their availability and other important factors. The journey of transition toward cleaner energy began a long time ago, Figure 2 explains the installed capacity of electricity generation in the UK from 1996 to 2021. From figure 2 it is clear that the shift toward renewable energy sources. From a level of below 5 GW in 1996, the installed capacity of renewables increased to nearly 40 GW in 2021.

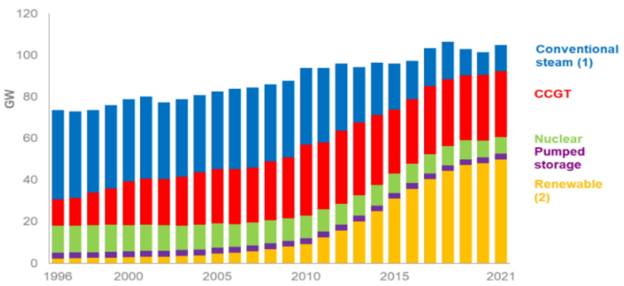

Figure 2: UK installed electricity capacity from1996 to 2021.[3]

Even though renewable energy from wind is suitable for the UK due to its climate and geography, when considering the case for individual buildings, Solar PV stands out from other renewable technologies due to its modularity, ease of installation, technological maturity, and cost-effectiveness. This is evident from Figure 3. When it comes to small-scale installed capacity, in the figure 3, it can be seen that during the period from 2010 to 2021, there is a clear increase in the installed capacity of solar photovoltaics on comparison with other renewable sources.

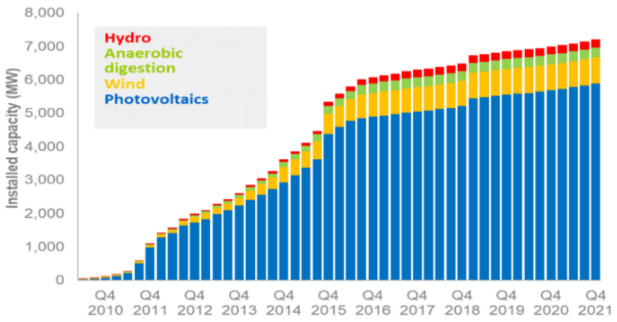

Figure 3: Installed capacity of renewable technologies.[3]

To compensate for the drawbacks of solar photovoltaics energy storage systems can be used, these energy storage systems are of various types, and these can be combined to bring the best out of each and provide a smooth functioning system. Integrating hybrid energy systems with solar photovoltaic into individual buildings thereby achieving self-sustainability, enhancing electricity reliability, and fostering the development of smart energy communities. While there are different energy storage technologies available based on the form of energy, and various combinations of hybrid energy storage systems available based on their application, this dissertation will specifically focus on the utilization of battery and fuel cell hybrid energy storage systems.

The combination of battery and fuel cells presents a suitable solution for addressing the challenges associated with solar PV integration into the building. Fuel cells offer a combination of high energy density, long lifespan, and minimal environmental impact. On the other hand, batteries excel in terms of high-power density and fast response times, making them well-suited for storing surplus solar energy and providing backup power during grid outages.

2. AIM AND OBJECTIVE

The aim of this project is to develop a solar PV and hybrid energy storage system that focuses on reducing the carbon footprint associated with the energy consumption of the building.

1. Conduct a literature review on solar PV and energy storage systems to identify the most appropriate technologies and designs for the specific community building and geographical island.

2. Develop a model using HOMER and Helioscope software to simulate the performance of the solar PV and hybrid energy storage system under various conditions and configurations.
3. Conduct an economic analysis of the project.
4. Evaluate the potential for flexible services, such as peak shaving, to enhance the effectiveness and efficiency of the energy system.
5. Provide recommendations for the implementation and operation of the solar PV and hybrid energy storage system in the specific community building based on the results of the modeling and analysis.

3. LITERATURE REVIEW

The escalating demand for electricity, driven by factors such as increasing electrification of transportation, and the growing use of electronic devices and air conditioning, is putting a strain on the global energy grid. Traditional energy production, which is heavily reliant on fossil fuels, contributes to climate change and leaves a substantial carbon footprint associated with buildings' energy consumption.

Solar photovoltaic systems and hybrid energy storage systems emerge as fascinating options within this framework, as discussed by T Sutikno et al [4]. Solar PV systems possess the ability to convert sunlight directly into electricity, presenting a trustworthy and eco-friendly means of generating power. Nevertheless, the irregular characteristics of solar energy generation give rise to obstacles in maintaining a continuous supply. On the other hand, hybrid energy storage systems integrate diverse technologies, facilitating effective storage and deployment of renewable energy, thereby tackling the concerns associated with intermittency.

These advanced systems hold the potential to reduce carbon emissions, enhance energy efficiency, and strengthen the resilience of power grids, as explained by M. M. Rana et al. and M. Alktranee in their respective studies [5], [6]. Nonetheless, there are still hurdles that need to be tackled for the widespread implementation of these systems, including the financial implications of these technologies and the necessity for supportive governmental regulations. Collaboration among stakeholders, effective policies, and technological advancements are pivotal for a sustainable global energy transition towards cleaner, more resilient energy systems.

Solar photovoltaic technology has undergone significant development across multiple generations. The first generation introduced crystalline silicon cells, which are still the most widely used PV cells today [7]. The second generation brought forth thin-film technologies like amorphous silicon, cadmium telluride, and copper indium gallium selenide. These cells have lower efficiency than crystalline silicon cells, but they are also less expensive to produce.

The third generation of PV technology encompasses multi-junction cells and intermediate-band solar cells [8]. These cells are designed to improve efficiency by capturing more of the solar spectrum. Graphene-based photovoltaic cells are also a promising technology in the fourth generation of PV technology.

Recent progress has been made in perovskite tandem cells, which combine perovskite materials with other semiconductors to achieve high-performance tandem structures. These cells have achieved impressive results, such as tandem PV panels with 29.5% efficiency as presented by Y Cheng and L Ding in 2021[9] and are expected to achieve efficiency up to 32% with further optimization.

Despite these advancements, silicon cells continue to dominate the market due to their maturity and widespread adoption. However, ongoing research efforts are still being made to enhance the efficiency of silicon cells and investigate alternative materials and manufacturing technologies to further improve solar PV systems overall. However, one limitation of solar PV systems is that their energy output is intermittent and greatly dependent on weather conditions. When commencing the installation of a solar photovoltaic system, it is of utmost significance to duly acknowledge and incorporate the following aspects. The presence and accessibility of sunlight, dimensions of the rooftop, and adherence to local guidelines constitute crucial physical influencers impacting the sizing of PV panels. Additionally, the load requisites are contingent upon the requisite electricity consumption for the concerned residential or commercial establishment, whereas economic factors engross determining the overall system expenditure, prevailing rates of grid electricity, and potential savings derived from solar energy [10]. For the further optimization of PV panels, the derate factor should be taken into account. This factor is used to adjust the rated power output of PV panels in real-world operating conditions by accounting for losses. The derate factor consists of several components, as illustrated in Figure 4. From the figure, it can be observed that a derate factor of 0.77 indicates that only 77% of the energy is available, while the remaining 23% is lost due to various components within the derate factor.

Item	Default	Range
PV module nameplate DC rating	0.95	0.80-1.05
Inverter and transformer	0.92	0.88-0.95
Mismatch	0.98	0.97-0.995
Diodes and connections	0.995	0.99-0.997
DC wiring	0.98	0.97-0.99
AC wiring	0.99	0.98-0.993
Soiling	0.95	0.30-0.995
System availability	0.98	0.00 0.995
Shading	1.00	0.0-1.00
Sun-tracking	1.00	0.95-1.00
Age	1.00	0.70-1.00
Overall	0.77	

Figure 4: Component involved in PV derate factor.[11]

By carefully considering and taking into account all of these different factors, the end result will be an effective and financially viable solar PV system.

Standalone photovoltaic power systems typically include energy storage devices. These storage systems are classified into different types according to their form of energy [12] like mechanical, electrical, chemical, etc., and are shown in Figure 5, these technologies can be used to address the imbalance between supply and demand caused by the intermittent nature of solar energy [13].

The implementation of renewable energy and storage systems within energy-sharing communities reduces the burden on the grid and lowers electricity expenses; this concept is highlighted by Xi Cheng [14].

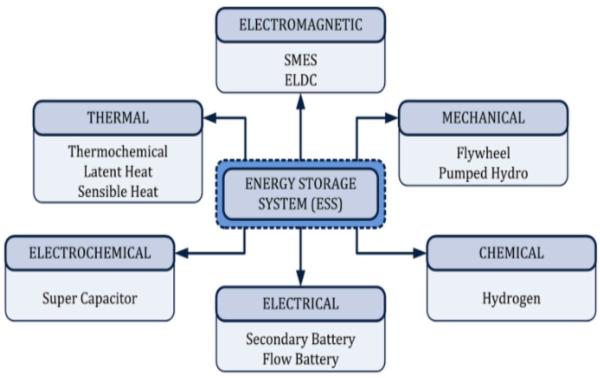

Figure 5: ESS technology classification.[12]

Other energy storage technologies that can be integrated into standalone photovoltaic systems include lithium-ion batteries, proton-exchange membrane reversible fuel cells, reversible solid oxide cells, Supercapacitors, and flywheels. These are briefly discussed by W Jing et al [15] These technologies play a significant role in balancing energy supply and demand, reducing energy costs and carbon emissions, and enhancing building resiliency. The selection of energy storage technology depends upon the field of application. The capacity range of several energy technologies is illustrated in Figure 6. This graph illustrates the relationship between energy density and power density for various energy storage technologies. It is evident that lithium-ion batteries and fuel cells exhibit favourable characteristics in terms of both power density and energy density.

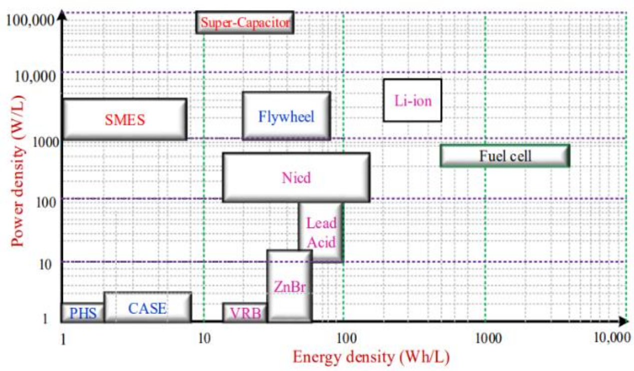

Figure 6: Power density vs. Energy density graph of various energy storage technologies.[16]

Nevertheless, it is important to note that depending solely on a single energy storage system to address the intermittent nature of solar PV energy carries various drawbacks. None of the available energy storage technologies can simultaneously meet the requirements for both power and energy densities [17]. As a solution, researchers have explored the concept of hybridizing multiple energy sources and different hybrid energy storage solutions discussed by T. Bocklisch in his journal [18]. The specific choice and combination of these energy storage technologies are contingent upon factors such as the intended application, load demands, and economic considerations.

A hybrid energy storage system is an effective approach that combines two or more energy storage technologies with supplementary operating characteristics to overcome the limitations of individual technologies. HESS is typically composed of two storage units, with one storage dedicated to meeting high power demands and the other storage for high energy demands. Batteries, particularly lithium-ion batteries, play a key role in many HESS applications [18] In most of the hybrid energy combinations batteries will be the primary storage system because a battery storage system is an advanced technological solution that enables electricity to be stored until it is needed. Among the various battery technologies, lithium-ion batteries are widely recognized for their contribution to grid enhancement, as highlighted by T. Cheng et al, they possess exceptional attributes such as high energy density, energy efficiency, and extended cycle life [19]. Additionally, lithium-ion battery storage systems offer several advantages, including increased renewable energy output, economic savings, and enhanced sustainability due to reduced consumption, as discussed by E. T. Sayed et al. [20]. How to size a battery to reduce energy costs is discussed by V. Sharma et al in this paper [21].

Despite the availability of different energy storage options that can be combined with batteries, fuel cells stand out as an incredibly suitable choice in the field of renewable energy. Fuel cells offer notable benefits by producing electricity without any CO2 emissions as a byproduct. By deriving hydrogen fuel for these cells through electrolysis using solar photovoltaic panels, we can consider the entire energy generation and utilization process completely renewable [22]. Integrating fuel cells not only addresses the intermittency issues of solar PV but also plays a role in reducing carbon emissions and promoting sustainable energy practices. Moreover, the flexibility of fuel cell systems allows for scalability, making them ideal for applications spanning from residential to industrial settings. The integration of fuel cells into energy storage systems enhances the overall efficiency, reliability, and environmental performance of renewable energy systems. Various fuel cell technologies offer unique attributes for diverse applications. Alkaline fuel cells stand out with efficient reactions, but they're prone to corrosion. Molten carbonate fuel cells excel at high temperatures but face early failures. Phosphoric acid fuel cells show durability but struggle with carbon monoxide and power density. Solid oxide fuel cells are efficient yet challenged by mechanical stresses and high temperatures. Proton exchange membrane fuel cells are versatile and suitable for applications like automotive, these different fuel cell technologies are discussed in depth by S. Ong et al [23]. Notably, PEMFCs find a niche in residential hybrid systems due to their high power density and adaptability. Similar to the derate factor for PV panels, fuel cells also exhibit losses. These losses can be categorized into several types, including ohmic losses, activation losses, and mass transport losses. Figure 7 illustrates these losses through a voltage vs. current density graph. These factors play a significant role in the efficiency of fuel cells.

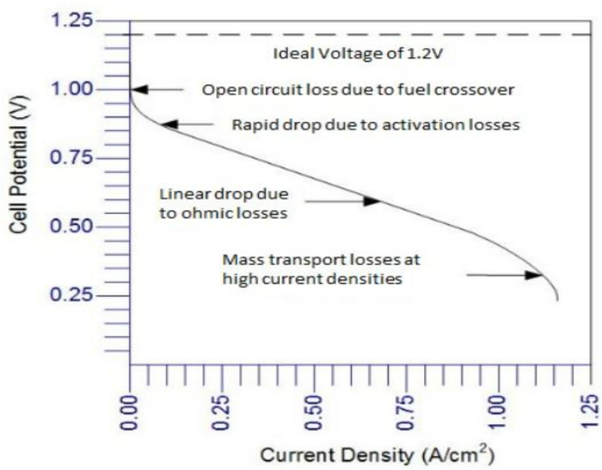

Figure 7: Fuel cell losses.[24]

The hydrogen needed for the fuel cell can be produced onsite using an electrolyser or can be purchased from outside. The different type of electrolysis technologies to produce hydrogen onsite is discussed in the studies conducted by J Chi and H Yu [25] and article published by IRENA.

Smart energy communities, also known as energy communities, are a means of organizing energy production and consumption in a manner that is more sustainable and efficient. Extensive research has been conducted on this concept since the 1970s, but its popularity has surged in recent years [26]. They can encompass a broader range of participants, including households, businesses, institutions, and communities, who collaborate in organizing energy production and consumption. This infrastructure incorporates various sources such as solar panels, wind turbines, and energy storage devices [27]. The advantages offered by smart energy communities are manifold. They contribute to reducing energy expenses, enhancing energy efficiency, and maximizing the utilization of renewable energy sources. Additionally, they play a crucial role in fostering community resilience and promoting sustainability. The expansion of smart energy communities is driven by several factors, including advancements in technology, growing energy demands, and the urgent need for sustainability. As these factors continue to gain significance, we can anticipate a widespread proliferation of smart energy communities soon.

4. METHODOLOGY

4.1. Building selection

To commence the project, a community building in the UK was chosen. After a careful evaluation between the Eastern Gateway Building and the Wilfred Brown Building at Brunel University, the latter was ultimately preferred. The primary factor considered in the selection process was the prevailing weather conditions; the performance of solar panels is greatly influenced by solar radiation and temperature. The variation in solar radiation and temperature for each month is shown in figure 8. These crucial data were acquired through the utilization of the RETScreen software. The performance of the solar panel primarily depends on solar radiation.

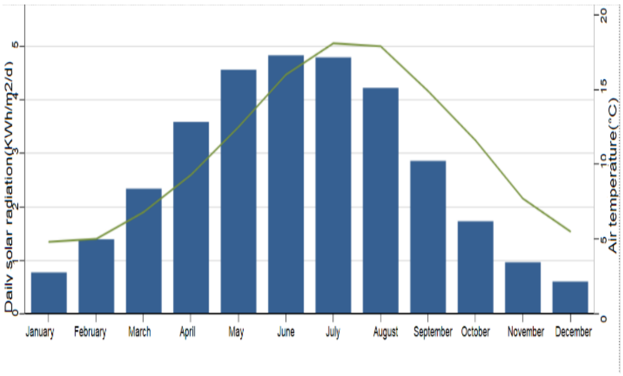

Figure 8:Daily solar radiation and temperature data of the location. RETScreen.

From Figure 8, it can be seen that there is a seasonal variation in solar radiation. During the summer months, there is a high availability of solar radiation shown by the blue bars in the graph, while during the winter months, solar radiation is considerably lower. Similarly, the temperature increases during the summer months and decreases during the winter months. Temperature has an effect on the solar panel performance; for every degree rise in temperature from the standard testing condition temperature of 25 °C, voltage reduces by 176.6 mV, and power reduces by 0.35%. These factors are also related to the derate factor of the PV panels. Given the proximity of both buildings, the variation in available solar radiation and temperature was negligible. Consequently, an additional criterion was introduced into the selection process.

The second consideration is connected to the rooftop area available for the installation of solar PV panels. Utilizing Google Maps software, a comprehensive analysis of the plans for both structures was conducted. The analysis revealed that the terrace of the Eastern Gateway Building presented numerous obstructions, limiting the potential for accommodating a significant number of panels. In contrast, the Wilfred Brown Building exhibited only three obstructions, making it a more suitable choice for the installation of solar PV panels as shown in Figure 9.

Figure 9: Aerial View of Eastern Gateway Building (Left) And Wilfred Brown Building (Right). [28], [29]

4.2. Electricity consumption of the building

The electricity consumption data was obtained from the energy management department, containing six years' worth of data, including the hourly consumption for each day of the year. For the purpose of design, the recent electricity consumption data for the year 2022 was extracted from the extensive dataset. The monthly electricity consumption data for the year is illustrated in Figure 10, and for the year 2022, the Wilfred Brown Building has an annual consumption of 843,123 kWh, in which the highest electricity consumption occurs in January and the least electricity consumption occurs in June.

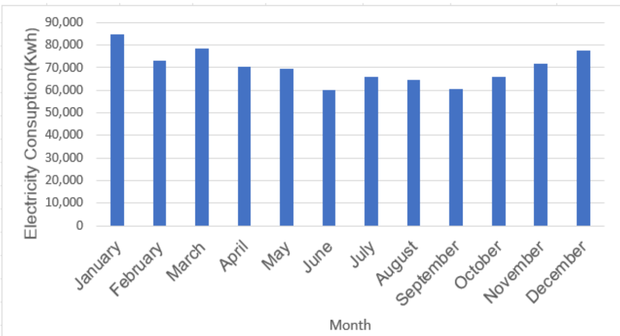

Figure 10: Monthly Electricity consumption of Wilfred Brown Building.

4.3. PV system design

The Helioscope software is employed for the design of the solar PV system. Helioscope is a cloud-based software platform that helps solar professionals design, optimize, and deploy solar PV systems. It includes a 3D solar design tool, a solar radiation database, a financial analysis tool, a permitting and compliance tool, and a documentation tool. Initially, a designated segment is delineated on the building's terrace to identify a suitable location for solar panel installation. Any obstructions impeding panel installation are subsequently removed. From the Helioscope data library, a PV manufacturer is chosen, and in this specific application, the SunPower E20 327W AC panel with an efficiency 20.4 % is selected [30]. The AC panel is preferred as it predominantly generates electricity for load supply.

To optimize electricity generation from the available solar radiation, several parameters such as racking, azimuth, tilt, setback orientation, frames, row spacing, and ground clearance ratio are adjusted to their optimal values. These optimal values include an azimuth of 177.1°, a tilt of 20°, a frame size of 2x1, a landscape horizontal orientation, a row spacing of 0.7 meters, a module spacing of 0.0127 meters, a frame spacing of 0.03 meters, a setback of 0.5 meters, and a ground clearance ratio of 0.75. The PV derate factor, which accounts for losses such as shading, soiling, and inverter efficiency, is also taken into consideration during this optimization process by the helioscope software. Upon reviewing the PV panel's specifications from the datasheet, it is determined that a single panel consists of 96 cells. Based on this information, a microinverter compatible with the panel is chosen. The Enphase IQ 7x microinverter is deemed compatible with the selected panel [31].

The rationale for opting for a microinverter lies in its advantages. In the event of a problem with a single inverter, only the panel connected to that specific microinverter would be affected, leaving the other panels to continue producing electricity independently. In contrast, with a standard inverter, an issue could disrupt the entire panel string. This potential drawback is circumvented by the choice of a microinverter to ensure the system's robustness and reliability.

Helioscope offers an additional feature for shading analysis, providing insights into the potential over-shading of panels and their subsequent limited electricity production. Following the shading analysis of the PV array, it is determined that no panel removal is necessary due to excessive shading.

Having conducted these analyses and optimizations, a PV array system with a rated capacity of 63.4 kW, consisting of 194 panels, is successfully designed.

4.4. Hybrid system design

After completing the design of the solar PV system, the subsequent phase involved the creation of a solar PV hybrid energy storage system, facilitated by the HOMER Pro software. HOMER was originally developed by the National Renewable Energy Laboratory and has undergone further enhancements by Homer Energy. This software tool is widely employed for modeling hybrid microgrid systems, accommodating both grid-connected and island mode configurations.

Within this study, two distinct design configurations were explored through the utilization of the HOMER Pro software. The initial configuration comprised several essential components: a PV system designed using Helioscope, a battery unit, an electrolyser, a hydrogen storage tank, a fuel cell, a bidirectional converter, a control system, electrical loads, and a grid connection. The operation of this configuration commences with the electricity generated by the PV system. This electrical output powers an electrolyser, specifically the Enapter AEM electrolyser [32], chosen based on the hourly production of the PV system so that the electrolyser can run. This electrolyser produces and stores hydrogen within a dedicated tank. Any excess electricity not consumed by the electrolyser is stored within a carefully selected lithium-ion battery. Subsequently, this stored hydrogen is effectively harnessed by the fuel cell. The selection of the fuel cell depends upon the quality of hydrogen generated by the electrolyser, with the AEM electrolyser ensuring hydrogen purity of 99.9%. To ensure seamless electrical conversion between AC and DC, a bidirectional converter is thoughtfully chosen.

The coordination of the entire system is managed through HOMER Pro's load-following dispatch strategy. This strategic approach guarantees that the generator produces just the requisite power to fulfill primary load demands. Secondary goals, such as the charging of the storage bank or the fulfilment of deferrable loads, receive precedence and are aligned with renewable power sources. Moreover, the generator's capacity can be augmented to supply power to the grid when economically advantageous.

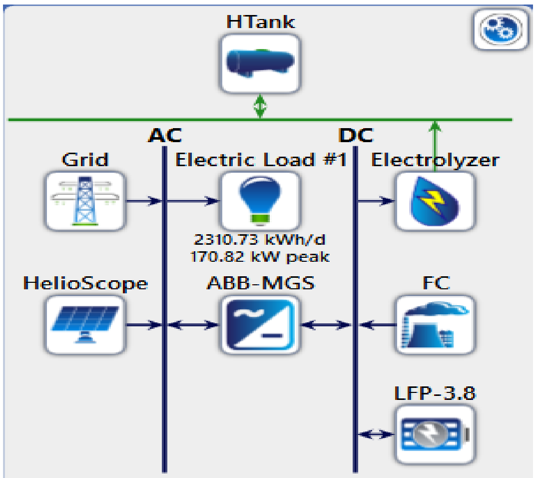

Figure 11: Design including Hydrogen Production. Homer pro

Using the HOMER Pro software's capabilities, a series of simulations are carried out to improve the system's performance. These simulations provide valuable information about the best ways to operate the system and the expected results. Consequently, a thorough evaluation is conducted to determine the feasibility and effectiveness of the solar PV hybrid energy storage system.

The second configuration that was tried includes a PV system designed in HelioScope, a battery, an externally supplied hydrogen fuel cell, a load, a bidirectional converter, a control strategy, and a grid connection. Similar to the previous design model, the PV system and the grid are connected to the AC bus, while the battery and fuel cell are connected to the DC bus line. For control dispatch, both the Homer load-following and Homer cycle-charging algorithms are evaluated to determine which dispatch algorithm works best in this configuration.

The Homer cycle-charging algorithm operates in such a way that whenever a generator needs to operate to serve the primary load, it operates at full output power. Surplus electrical production is directed towards lower-priority objectives, in order of decreasing priority: serving the deferrable load, and charging the storage bank, and the electrolyser [33]. Since there is no deferrable load and electrolyser whatever the surplus electricity goes into the battery.

Several considerations were taken into account when designing the above configuration. The capacity of the fuel cell has been chosen in a way that it cannot fully meet the peak demand. A fuel cell with a lower capacity has been chosen for the following reasons: if it were selected based on the peak power demand, it would be significantly larger and pose a financial burden on the project. To prevent this, the decision was made to ensure that at least 50% of the energy requirement is supplied by the fuel cell and PV system while the remaining portion comes from the grid. From the Homer Pro software library, a custom fuel cell with an efficiency of 56% is designed to operate using externally supplied hydrogen with a calorific value of 120 MJ/kg. At this stage of the project, no heat recovery from the fuel cell is considered; all the heat generated is lost. The Homer Pro software optimizes the size of the fuel cell to 80 kW by taking into account the specific characteristics of the generator, including its efficiency, capital cost, maintenance costs, and lifespan, to determine the optimal size that balances cost and performance.

On the other hand, the capacity of the battery has been determined based on the peak power demand (170.82 Kw). This ensures that the battery can independently handle the entire load for a specific duration. From the Homer Pro library, a 202-kWh lithium iron phosphate battery with a round trip efficiency of 95% is selected. The capacity of the bidirectional converter is chosen according to the battery's size, allowing it to manage the peak power drawn from the battery.

The size of the PV system remains consistent,63.4 Kw with the first configuration, limited by the available roof area.

A large number of simulations were performed to find a reasonable solution by varying the size of the components, both with and without certain components. Each result was then compared with the base system, which consists solely of the grid-connected system, in order to achieve the goals.

To analyse the Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and payback period, the HOMER Pro software serves as an invaluable tool. By inputting specific data into the software, accurate evaluations can be obtained, software uses following concept to find the results.

- Net Present Value**:** NPV is a financial metric used to assess the profitability of an investment or project. It compares the present value of cash inflows, which encompass income from grid sales, salvage value, and other forms of earnings, to the present value of cash outflows, which include Capital Expenditure, Operating Expenditure (OPEX), power and fuel prices, as well as other relevant costs, over the operational lifetime of the system. The software employs discounted cash flows to compute NPV.

$$NPV = \Sigma (CF_t / (1 + r)^{t}) \quad (1)$$

Where CF_t is the net cash flow at time t.

- Levelized Cost of Energy**:** LCOE signifies the cost per kWh of usable energy produced. It's calculated by dividing the total annualized cost of the system by the total electrical load served [34].

$$LCOE = \text{Total Annualized Cost} / \text{Total Electrical Load Served} \quad (2)$$

- Net Present Cost: NPC for a Component is the current value of all expenses associated with its installation and operation throughout the project's duration, subtracting the present value of all the income it generates during that time.

$$NPC = \Sigma (OPEX_t / (1 + r)^{t}) + \Sigma (CAPEX_t / (1 + r)^{t}) - \Sigma (Income_t / (1 + r)^{t}) \quad (3)$$

Where,

t-time period in years.

r- discount rate.

For precise results, specific data must be fed into the software: nominal discount rate, expected inflation rate, project lifetime, and costs associated with each system component. In this study, a nominal discount rate of 5.5% [35], an expected inflation rate of 6.8% [36], and a project lifetime of 25 years have been utilized. Furthermore, the accompanying table showcases detailed information regarding the cost components associated with the system:

Table 1: Cost associated with components.

Component	Price (£)	Capital cost (£)	Replacement cost (£)	O&M Cost (£/year)
Grid	0.2748 £/KWh	10000	0	0
Solar PV	400 £/Panel	77600	70000	1000
Battery	200 £/KWh	161600	140000	0
Fuel cell	1840 £/KW	147200	144000	648.24
Converter	131.5 £/KWh	26300	25000	1000
Hydrogen	2 £/Kg	0	0	73532

These calculations offer crucial insights into the economic feasibility and viability of the proposed system, facilitating well-informed decision-making and project planning.

5. RESULTS AND DISCUSSION

Various technologies and designs were tested, resulting in several simulated configurations. Among these, two configurations received the most attention. The first configuration involves the production of hydrogen through an electrolyser. This hydrogen is then stored in a dedicated tank and subsequently utilized by a fuel cell to generate electricity. The motivation behind investigating this approach lies in its renewable nature; it has the potential to significantly reduce the carbon footprint associated with the system. However, a project constraint comes into play with this configuration. The HOMER PRO software optimizes the arrangement in a manner that ensures the best possible outcomes. Specifically, the software aims to ensure that the electricity generated by the photovoltaic (PV) system is primarily utilized to meet the load demand, rather than being channelled to run the electrolyser, normally the electrolyser receives only surplus electricity. Pushing the electrolyser's operation would necessitate a substantial increase in the size of the PV system, which is unfeasible due to limitations imposed by the available roof area.

This constraint on PV sizing has led to the exploration of an alternative configuration. In this second approach, the hydrogen required for the fuel cell is procured externally and supplied to the fuel cell, preventing the need for components like hydrogen storage tanks and the electrolyser. It is important to note, however, that, unlike the first configuration, this approach introduces a certain level of carbon footprint associated with the externally sourced hydrogen.

While initial investigations and a review of existing literature indicated that the first configuration appeared to be a viable option, software simulations at this stage of the project have revealed a different reality. In light of the project's constraints and objectives, the first configuration, despite its renewable appeal, has been found to be suboptimal. The complex interaction between energy production, load requirements, and system limitations has driven the project toward the second configuration as the more suitable choice.

The PV panel for the Wilfred Brown building was designed using Helioscope software and optimized for maximum efficiency. The monthly electricity production based on available irradiance is shown in Figure 12, which demonstrates that during the summer months, a large amount of sunlight is available, leading to increased electricity production. In contrast, in the winter months, electricity production is lower due to reduced solar radiation. The PV system designed contains 194 panels with a total capacity of 63.4 kW, which is able to produce 59,156 kWh of electricity annually. This constitutes about 7% of the annual requirement.

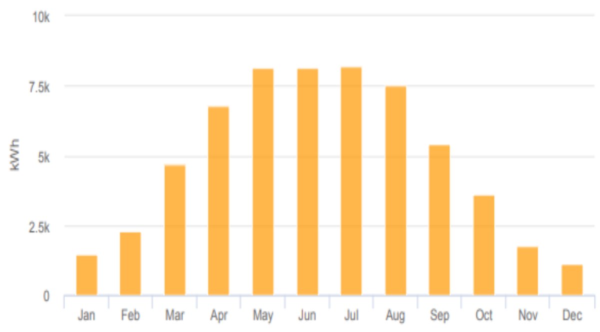

Figure 12: Monthly Electricity production from PV.

The suitable configuration, which is the second one, is shown in Figure 13. It includes the PV system designed in Helioscope, an 80-kW fuel cell, four 202-kWh batteries, a 200-kW bidirectional converter, a load, and a grid connection.

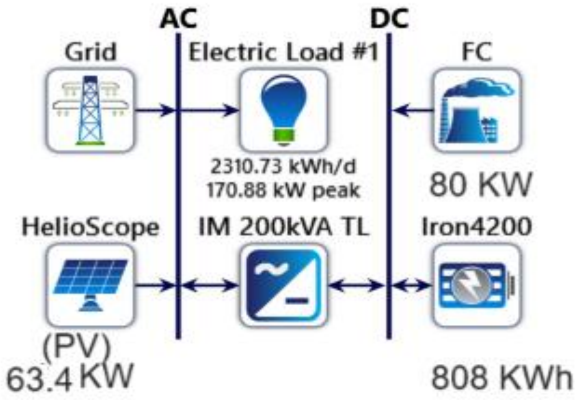

Figure 13: Hybrid System Configuration where hydrogen is externally supplied. Homer pro

886,844 kWh of energy is produced by the system. Out of this, 78.2% is generated by the fuel cell, 6.84% from the PV system, and the remaining 15.1% from the grid annually. The annual load requirement is 843,123 kWh. How this load is met each month from a mixture of energy is shown in the Figure 14. From the figure, it can be seen that during the summer months, PV production is higher due to the available sunlight, which helps reduce the electricity purchased from the grid. On the other hand, during the winter months, PV production is lower, resulting in an increase in the purchase of grid electricity to meet the load. Furthermore, fuel cell output does not vary significantly throughout the year.

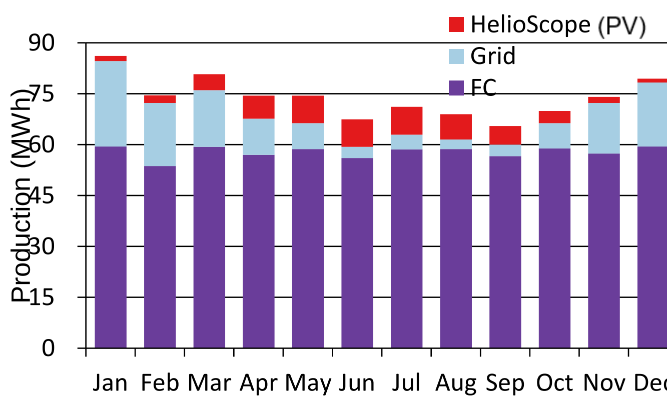

Figure 14: Electrical load supplied by a hybrid power system consisting of photovoltaics, fuel cells, and the grid. Homer pro

The homer cycle charging algorithm works in such a way that whenever there is an excess energy available from PV or fuel cell it is used to charge the battery, which has an autonomy of 6.7 hours. This means that in the event of a grid outage, if the PV and fuel cell cannot handle the peak load, the battery will supply power for 6.7 hours. To prepare for this worst-case scenario, a deliberately high battery capacity is chosen. With this configuration, approximately 25,253 kWh of electricity are sold to the grid at a unit price of £0.15 per kWh.

5.1. Carbon Footprint and Environmental Analysis

The carbon footprint associated with the base case that is grid only system is found out first which is equal to,

Carbon footprint= Total energy consumption* footprint associated with a unit of electricity (4)

Carbon footprint= 843,123kWh *0.207Kg CO2/KWh =174526.25 Kg CO2

The unit carbon footprint associated with each component is shown in Table 2.

In the presented table, a comprehensive comparison between the carbon footprints of various components in the base case and the proposed case is outlined.

Table 2: Carbon footprint Associated with components.

Componenet	Unit CO2 Equivalent	consumption/ Production/ capacity	Total CO2 Equivalent (Kg)
Grid	0.207 Kg CO2/KWh	133998 KWh	25993.672
Solar PV	0.050 Kg CO2/KWh	59156 KWh	2957.8
Battery	60 kg CO2/KWh	808 KWh	48480
Converter	0.05 kg/kw	200 KW	10
Fuel cell	24.2 Kg CO2/ Kw	80 Kw	1936
Hydrogen	0.025 Kg CO2/KWh	36766 Kg	919.15
Total CO2 emission			80296.622
CO2 Emission from base case			174526.25
CO2 Emission savings			**94229.628**

The base case involves a carbon footprint of 174526.25 kg CO2, while the proposed case exhibits a total carbon footprint of 81888.536 kg CO2, resulting in a substantial reduction of

94229.628 kg CO_2. This noteworthy reduction is primarily attributed to the strategic implementation of environmentally friendly alternatives in the proposed case.

Specifically, the base case components include a grid, solar PV, battery, fuel cell, and hydrogen, each with their respective carbon footprints and associated consumption/production/capacity figures. In the proposed case, a thoughtful combination of these components is introduced, capitalizing on low-carbon technologies. Notably, the substitution of conventional energy sources with a higher carbon footprint, such as the grid, is minimized in Favor of sustainable alternatives like solar PV and hydrogen. This shift towards greener options, characterized by lower carbon footprints, contributes significantly to the overall carbon footprint savings.

Over the span of 25 years, the annual carbon footprint savings of 94229.628 kg CO_2 accumulated to a total of 2355.74 metric tons of CO_2. This extensive reduction in carbon emissions underscores the long-term environmental benefits of transitioning from a conventional energy mix to a more sustainable and low-carbon configuration.

5.2. Economic Analysis

The project economics, such as the simple payback period and levelized cost of electricity, can be determined using HOMER Pro software. By inputting the costs associated with each component shown in Table 1 into the HOMER software, the necessary results are generated.

In the analysis, let's start by looking at the simple payback period. This refers to the time it takes for the designed system to earn back its initial cost through annual savings, which in this case is 8.01 years. The Net Present Cost (NPC) for the designed system is £5.66 MILLION. NPC helps us understand if the investment is profitable considering the changing value of money over time. The Return on Investment (ROI) is 8.7%, indicating that the designed system can generate positive returns over time. The initial investment for the system is £416,000.

When comparing these figures with the base case, notable improvements emerge. The NPC for the designed system £5.66 million is lower than that of the base case £6.83 million, highlighting its potential to generate more positive cash flows throughout the project's lifespan. The higher initial cost of the designed system £416,000 is due to the various components involved in the project compared to the base case £10,000.

Moreover, the designed system's Levelized Cost of Electricity is lower at £0.221/KWh, in contrast to the base case's LCOE of £0.275/KWh. This signifies that the designed system is more efficient in producing cost-effective electricity over the long term. To sum up, the designed system demonstrates improved financial performance. Its shorter payback period, lower NPC, and lower LCOE when compared to the base case all underscore its economic viability and potential for sustainable returns on investment.

5.3. Peak shaving

In the proposed hybrid energy system configuration, peak shaving was not achieved despite of having solar PV, a fuel cell, batteries, and the grid in the designed system. The solar PV system supplied energy during the day, charging the battery. When there is demand, the battery discharged stored energy to smooth load requirement. If forcefully tried to achieve peak shaving it will be at the expense of payback period going from 8.01 years to 18.88 years. To avoid this at this stage of project more weightage is given to payback period than peak shaving.

6. CONCLUSION

In conclusion, this dissertation extensively explored the design and evaluation of a solar PV hybrid energy storage system for a UK community building, focusing on Brunel University's Wilfred Brown Building. After thorough analysis and simulations, a suitable design developed.

The building's electricity consumption data were accurately characterized through Excel software, enabling the creation of a reliable energy demand profile.

Utilizing Helioscope software, an efficient solar PV system with a 63.4-kW capacity and 194 panels was designed, capable of fulfilling around 7% of the yearly energy requirement.

For the integration of the solar PV hybrid energy storage system, HOMER Pro software was employed to model and optimize configurations. After a thorough investigation, the second configuration in which hydrogen is externally supplied proved more viable due to project constraints and strategic considerations. This arrangement combined solar PV, batteries, a fuel cell, and bidirectional converters, operated through cycle charging dispatch strategies to minimize emissions, optimize consumption, and enhance economic efficiency.

The analysis and simulations yielded insights into the environmental and economic aspects. Carbon footprint analysis showed significant emission reduction with the proposed configuration, achieving about 53.99% annual reduction compared to the grid-only system, aligning with sustainability objectives.

Economically, the designed system showcased improved performance with a payback period of 8.01 years. Additionally, the system's levelized cost of electricity was lower at £0.221/KWh, in contrast to the base case's £0.275/KWh. These results supported the economic viability of transitioning to renewable energy, ensuring positive cash flows and cost-effective electricity in the long run.

This study revealed the technical feasibility of a solar PV hybrid energy storage system and also emphasized its potential to reduce carbon emissions and provide economic advantages. Through the combination of innovative technologies and advanced modeling tools, this research contributes to the evolving knowledge in achieving sustainable energy solutions and a greener future.

7. RECOMMENDATION AND FUTURE WORK

The study aims to reduce the carbon footprint associated with building energy consumption, learning to use both the Helioscope and Homer Pro software from scratch, in order to create a photovoltaic (PV) system model and conduct simulations on Homer Pro involving all system components, proved to be a time-consuming process. Multiple iterations were conducted with and without certain components varying their capacity and with different control strategies to get the desired results. Due to the limitation of time, the possibility of a custom controller using MATLAB link was not explored. Furthermore, the combined heat and power potential of fuel cells must be explored to meet the heating requirement of the building thereby increasing the overall efficiency of the system with further reduction in carbon footprint.

In terms of project expansion,

- Scalability and Integration: Based on the results of this project assess the possibility of expanding the scope of the project into neighbouring buildings. Moreover, with the increased capacity of PV panels onsite hydrogen generation can be considered.
- Advanced Energy Management**:** Investigate advanced energy management techniques, such as predictive analytics and artificial intelligence, to optimize the operation of the hybrid energy system. This could involve dynamic load scheduling and more sophisticated control algorithms.
- Technological Advancements**:** Stay updated on advancements in solar PV, energy storage, and related technologies. Investigate how emerging technologies like high-efficiency perovskites tandem PV panels, energy-dense batteries, and improved conversion efficiency could impact system design and performance.
- Long-Term Sustainability**:** Conduct long-term studies to assess the durability and performance degradation of system components. Investigate the system's sustainability over decades and explore potential upgrades or replacements of key elements.

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Appendix A
Extended Literature Review

Given the rising demand for energy and the urgent need to reduce greenhouse gas emissions, renewable energy sources have become an essential solution. Our research specifically focuses on solar PV systems, as they have shown great potential for clean energy production. Our objective is to install a solar PV hybrid energy storage system for a community building in the UK. Solar photovoltaic (PV) technology has seen significant progress since the first silicon-based solar cell was invented in 1954, with world record efficiencies of 23.3% for multi-crystalline Si cells, 26.1% for single crystal Si cells, and 26.7% for Si-based heterostructure solar cells. However, Si-based single-junction solar cells have reached a bottleneck as they approach the Shockley-Queisser limit of 29% efficiency. To address this, researchers are exploring tandem solar cells such as the perovskite/Si two-terminal tandem solar cell, which achieved an overall efficiency of 14.3% in 2015 and could potentially reach a PCE of 32% with further optimization [1]. The cost of solar PV systems has gone down significantly over the years, the recent increase in input prices since 2021 has caused a change in the usual trend. According to a report from IRENA, the worldwide average cost for large solar PV projects dropped by about 80% between 2010 and 2020, reaching a cost index of 49.9 by 2020 [2]. However, in 2021 and 2022, prices went up significantly (51.9 and 53.3 respectively) due to disruptions in the supply chain. Fortunately, in 2023, the prices have fallen back to 49.4 after a nearly two-year period of higher prices [3]

Solar PV systems need ongoing maintenance and operation to make sure they perform their best. Operational expenses (OPEX) include costs related to maintenance, monitoring, and running the system. In Europe, the average OPEX for large-scale systems has been around $10 per kilowatt per year. Looking at historical data from a European Union member country, it's been found that OPEX went down by 85% between 2005 and 2017, reaching $9 per kilowatt per year. This data indicates that as solar PV capacity doubles, there's a noticeable decrease of around 15.7% to 18.2% in OPEX [2]

One limitation of solar PV systems is that their energy output is intermittent and greatly dependent on weather conditions. Standalone photovoltaic power systems typically include energy storage devices, such as lead-acid batteries or any other technologies, to address the imbalance between supply and demand caused by the intermittent nature of solar energy [4].

Among the array of established battery technologies accessible for energy storage system (ESS) applications, lithium-ion (Li-ion) batteries are widely acknowledged for their role in bolstering the grid due to their exceptional attributes: high energy density, efficient energy efficiency (EE), and extended cycle life. Given these inherent characteristics, Li-ion batteries offer a well-suited platform for integrating ESS with renewable energy sources. This integration facilitates the storage and optimal utilization of generated electricity, all at a favourable cost [5].

However, the sustainable and enduring advancement of this application hinges upon the market's capacity to regulate battery costs, a trend that is on a positive trajectory thanks to economies of scale and enhancements in production technology. Projections suggest that the system price could attain €200/KWh by 2035 [6], paving the way for further evolution in the subsequent years. This evolution contributes to enhancing the viability of Li-ion-based ESS applications within both the European and global energy markets.

However, the limited cycle life of lead-acid batteries can raise operational costs. To resolve this, energy storage systems (ESS), such as hydrogen gas storage, have been proposed as a viable solution to store renewable energy in a transportable and accessible manner. The stored energy can be converted back into electrical power when required, which can improve energy security, combat climate change, and add value to energy systems [7]. ESS technologies, including lithium-ion batteries, proton-exchange membrane reversible fuel cells, and reversible solid oxide cells, can be integrated into standalone photovoltaic systems [8]. These technologies play a significant role in balancing energy supply and demand, reducing energy costs and carbon emissions, and enhancing building resiliency. Supercapacitors, lithium-ion batteries, fuel cells, and flywheels are all distinguishable ESS models with different mechanisms, structures, and modes of operation. One of the primary challenges facing ESS is system aging, which can decrease their performance and increase energy storage costs [8]. Therefore, it is crucial to develop strategies to mitigate system aging and extend the cycle life of ESS to improve their cost-effectiveness and long-term performance. However, none of the ESS technologies can fulfil both power and energy densities at the same time. To overcome this issue, the integration of hybrid energy storage systems (HESS) with PV power generation has become increasingly important. HESS provides several benefits, such as balancing generation and demand, improving power quality, flattening PV intermittence, and regulating frequency and voltage in building energy management systems. Ideally, HESS has two types of storage, one for high energy storage (HES) and the other for high power storage (HPS), where HES fulfills long-term energy demand, and HPS handles power transients and fast load fluctuations. Therefore, energy storage systems are necessary to integrate PV power generation into building energy management systems by improving power quality, system stability, and flattening PV fluctuations [9]. Various hybrid energy storage systems can be combined to perform different functions in renewable energy applications. Renewable energy applications can utilize different combinations of hybrid energy storage systems, with the SC/battery, battery/SMES, flywheel/battery, battery/FC, SC/FC, FC/flywheel, and CAES/battery being the most frequently used types according to studies [10]. A hybrid energy storage system (HESS) is an effective approach that combines two or more energy storage technologies with supplementary operating characteristics to overcome the limitations of individual technologies.

Alkaline Water Electrolysis (AWE) is a well-established method for hydrogen production, with extensive commercial use. A liquid electrolyte solution, often an alkaline water solution containing around 30% potassium hydroxide, hosts a pair of electrodes. These electrodes are divided by a gas-tight diaphragm, unless a solid electrolyte is employed. Passing electricity through the electrodes initiates water oxidation at the anode, producing hydrogen ions and oxygen gas. Reduction of water to hydrogen gas and hydroxide ions takes place at the cathode. The hydrogen and oxygen gases are then extracted, with hydrogen gas dried and purified to 99.9999% purity post-process. AWE exhibits a hydrogen production rate of 0.25 to 760 Nm3/h, with purity maintenance relying on water conductivity below 5 μS/cm. Operating at temperatures between 70°C to 90°C and pressures of 1-30 bars, AWE's efficiency averages 60-70% [11]–[13]. Its lifespan spans around 50,000 hours and boasts a lower CAPEX range of 500 – 200 USD/kW, making it widely used in industry, yet less suited for rapid response integration with renewables [14], [15]

Proton Exchange Membrane (PEM) Electrolysers utilize solid polymer electrolytes requiring noble metal catalysts due to electrolyte acidity. PEM's anodic oxidation generates oxygen gas and hydrogen ions, which combine at the cathode to yield hydrogen gas. Operating at 50-80°C and 70 bars, PEM achieves high efficiencies (80-90%) and close to 100% H2 purity, ideal for dynamic integration with renewables. A key constraint is higher capital cost, ranging from 1400 to 2100 USD/kW, attributed to noble metal use and polymer electrolytes. Challenges include low durability due to rapid stack degradation [13], [15].

Solid Oxide Electrolysers (SOEs) operate at 750-850°C using yttria-stabilized zirconia electrodes and ceramic electrolytes. Electrolysis of steam yields hydrogen and oxide ions, achieving efficiencies near 100% due to high operational temperatures, yet limited lifespan (20,000 hours). With low current density (0.2 to 210 A/sq.cm) and pressure requirements of 1-5 bars, SOEs are in early research stages, currently available at 100 kW to 1 MW scales with high capital costs exceeding 2000 USD/kWh. Their potential lies in co-electrolysis of CO2 and water vapor for synthetic fuel production [12], [15]

Anion Exchange Membrane Electrolysers (AEM) are a developing technology aiming to employ alkaline anion exchange membranes as solid electrolytes. Operating at higher temperatures than PEM, AEM could offer benefits such as reduced corrosion and compactness. Current research, however, highlights membrane instability at elevated operating temperatures [16].

Instead of producing the hydrogen on-site, hydrogen can be purchased. Grey hydrogen, the most common and economical form, is derived from natural gas through steam reforming, a process that separates hydrogen from the gas. However, this method releases greenhouse gases which are not captured or stored [12]–[14]. Blue hydrogen, produced similarly to grey hydrogen, involves capturing and storing carbon dioxide emissions underground, rendering it a more environmentally conscious alternative[14]. On the other hand, green hydrogen is generated by employing renewable energy for water electrolysis, a process that doesn't emit greenhouse gases. Though the most environmentally friendly option, green hydrogen is also the costliest [14].

Fuel cells function as devices capable of transforming the chemical energy stored in fuels into electrical energy. These cells can operate using various fuels like hydrogen and hydrocarbons such as methanol and ethanol. Hydrogen, in its pure state, is the preferred choice due to its higher electro-chemical reactivity. These fuel cells have diverse applications spanning distributed power systems, auxiliary power units, portable devices, and propulsion systems. Their compatibility with renewable sources is enhanced when on-site production of fuels, like hydrogen, is undertaken. In a fuel cell setup, fuel enters through the anode while the oxidant enters via the cathode. An electrolytic membrane divides the anode and cathode, allowing only the ions generated at the anode to pass. Fuel cells that function at lower temperatures necessitate the incorporation of a catalyst alongside the electrolyte to expedite reactions. At the anode, hydrogen splits into hydrogen ions and electrons. The hydrogen ions traverse the electrolyte to combine with oxygen and electrons at the cathode, resulting in water formation. The electrons at the anode travel through an external circuit to the cathode, generating electricity. When hydrogen is utilized as the fuel, the sole by-products are water and heat. In the case of hydrocarbon fuels, CO2 is also produced [17].

In recent years, there has been a growing focus on the development of Smart Energy Communities (SECs), which are intelligent local energy communities that aim to achieve sustainability in energy, environmental, and social aspects. These communities are designed to address the challenges of sustainable energy systems by considering energy consumption in different sectors and the socio-economic impacts. SECs are a collection of energy utilities that operate in a specific area and are used by end-users to meet their energy needs through cooperative approaches, promoting renewable sources and intelligent energy management. The development of local energy resources not only helps reduce energy consumption and carbon emissions but also provides benefits in terms of employment, training, and citizen participation. SECs are being developed at different levels of aggregation, from individual buildings to districts and cities [18]. In conclusion, the literature review highlights the significance of renewable energy sources, particularly solar PV systems, in meeting the increasing demand for energy while reducing greenhouse gas emissions. It is clear that the development of hybrid energy storage systems plays a crucial role in enhancing the performance and efficiency of the solar PV system. The literature review provides insights into various types of hybrid energy storage systems that are most frequently used in renewable energy applications. However, choosing the appropriate combination of hybrid energy storage systems is dependent on various factors such as hybridization targets, storage costs, geolocation, and storage space availability. The findings of this literature review will serve as a basis for the design and configuration of an effective solar PV and hybrid energy storage system for the specific community building in the UK, aimed at promoting energy flexibility, reliability, and sustainability.

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Appendix-B
PV System Design Using Helioscope

PV system for the building designed using Helioscope software. Figures explaining the various factors of the design attaches below,

Components

Component	Name	Count
Inverters	IQ7X-96-x-240 (Enphase)	194 (62.1 kW)
AC Branches	1/0 AWG (Aluminum)	10 (459.6 m)
Module	SunPower, SPR-E20-327 (327W)	194 (63.4 kW)

Figure 15: Components included in the Design from the Helioscope report.

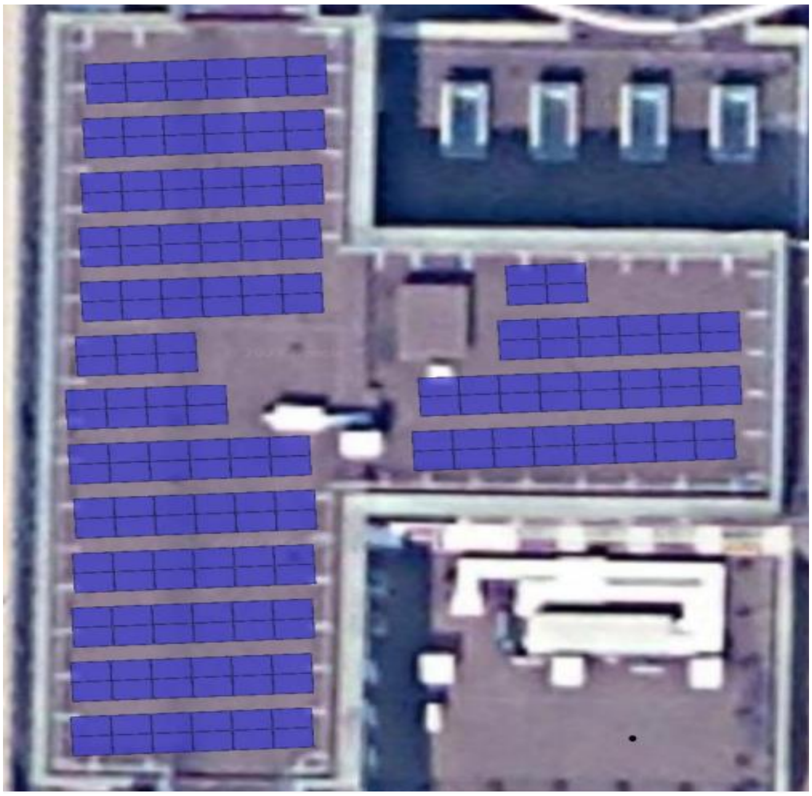


Figure 16: Solar panel layout from the Helioscope report.

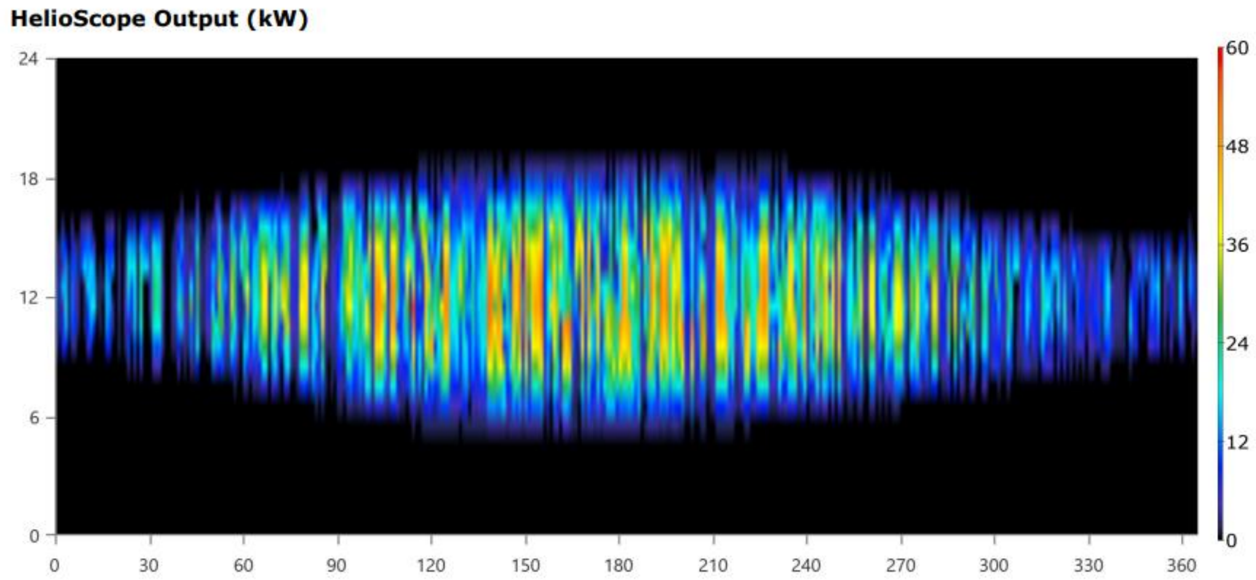


Figure 17: DMAP of annual electrical production using PV from Homer Pro report.

Annual Production

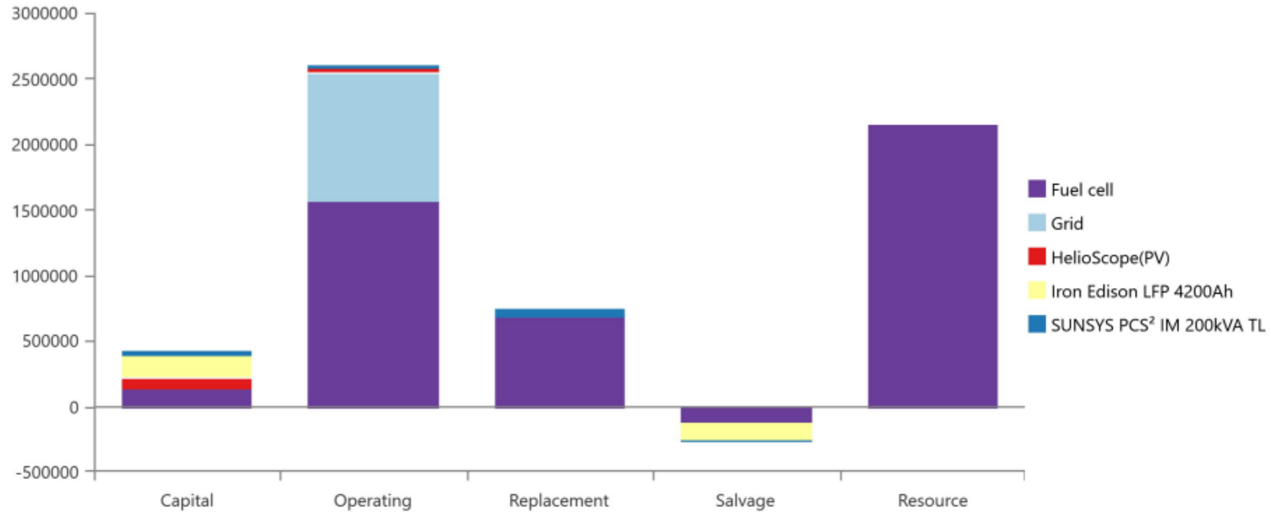
	Description	Output	% Delta
Irradiance (kWh/m^2)	Annual Global Horizontal Irradiance	986.2	
	POA Irradiance	1,125.4	14.1%
	Shaded Irradiance	1,051.4	-6.6%
	Irradiance after Reflection	1,013.8	-3.6%
	Irradiance after Soiling	993.5	-2.0%
	Total Collector Irradiance	**992.6**	**-0.1%**
Energy (kWh)	Nameplate	62,981.2	
	Output at Irradiance Levels	62,004.3	-1.6%
	Output at Cell Temperature Derate	61,207.5	-1.3%
	Output After Mismatch	61,172.8	-0.1%
	Optimal DC Output	61,172.8	0.0%
	Constrained DC Output	61,189.2	0.0%
	Inverter Output	59,438.6	-2.8%
	Energy to Grid	**59,156.1**	**-0.5%**
Temperature Metrics			
	Avg. Operating Ambient Temp		14.0 °C
	Avg. Operating Cell Temp		19.4 °C
Simulation Metrics			
		Operating Hours	4561
		Solved Hours	4561

Figure 18: Annual electricity production report from Helioscope report.

Appendix-C
Cost Summary Of the Design

The economic analysis of the entire project can be conducted using Homer Pro software. Based on the input values associated with each component and also considering the discount rate and inflation values, Homer software provides valuable insights into cost summaries, net present costs, and cumulative cash flows in comparison with the base case.

Cost Summary



Net Present Costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Fuel cell	£147,200	£1.57M	£688,088	-£121,262	£2.16M	£4.45M
Grid	£0.00	£972,179	£0.00	£0.00	£0.00	£972,179
HelioScope(PV)	£77,600	£29,429	£0.00	£0.00	£0.00	£107,029
Iron Edison LFP 4200Ah	£161,600	£1,250	£0.00	-£137,558	£0.00	£25,292
SUNSYS PCS² IM 200kVA TL	£29,600	£29,429	£65,011	-£18,336	£0.00	£105,704
System	£416,000	£2.60M	£753,099	-£277,156	£2.16M	£5.66M

Figure 19: Cost Summary and Net present cost from Homer pro report.

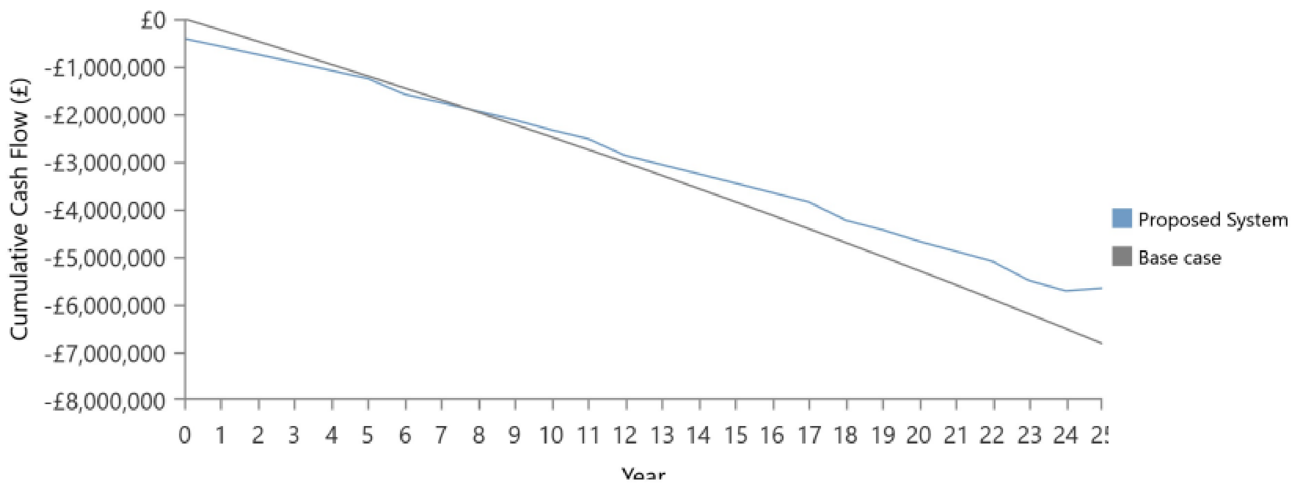


Figure 20: Cumulative cash flow on comparison with base case from Homer Pro report.

Appendix-D
Battery Performance

Battery is an important component of the design. The statics of the battery and the annual state of charge of the battery are depicted in the attached figure 21.

Iron Edison LFP 4200Ah Statistics

Quantity	Value	Units
Autonomy	6.70	hr
Storage Wear Cost	0.0523	£/kWh
Nominal Capacity	806	kWh
Usable Nominal Capacity	645	kWh
Lifetime Throughput	2,745,792	kWh

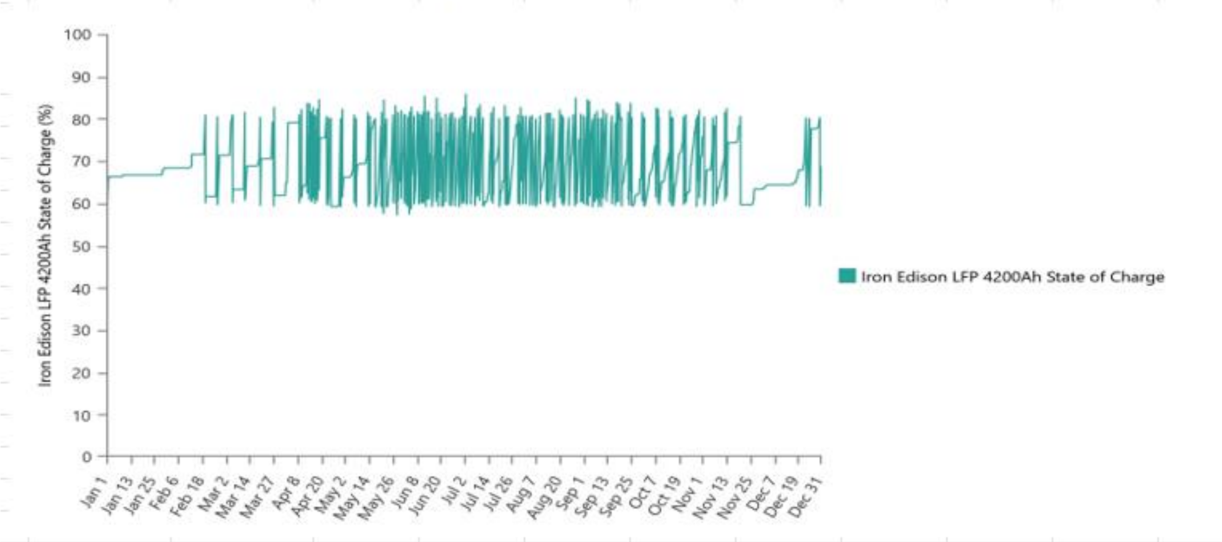


Figure 21: Annel performance of the battery from Homer Pro report.

Appendix-E
Grid Usage

Even after the design of a solar PV hybrid energy storage system for the community building, the grid remains an essential component of the design configuration for smooth operation. Approximately 133,998 kWh of electricity is annually purchased from the grid, while 25,253 kWh of electricity is sold back into the grid. The energy purchased and sold to the grid is illustrated in the form of a Dmap in Figure22.

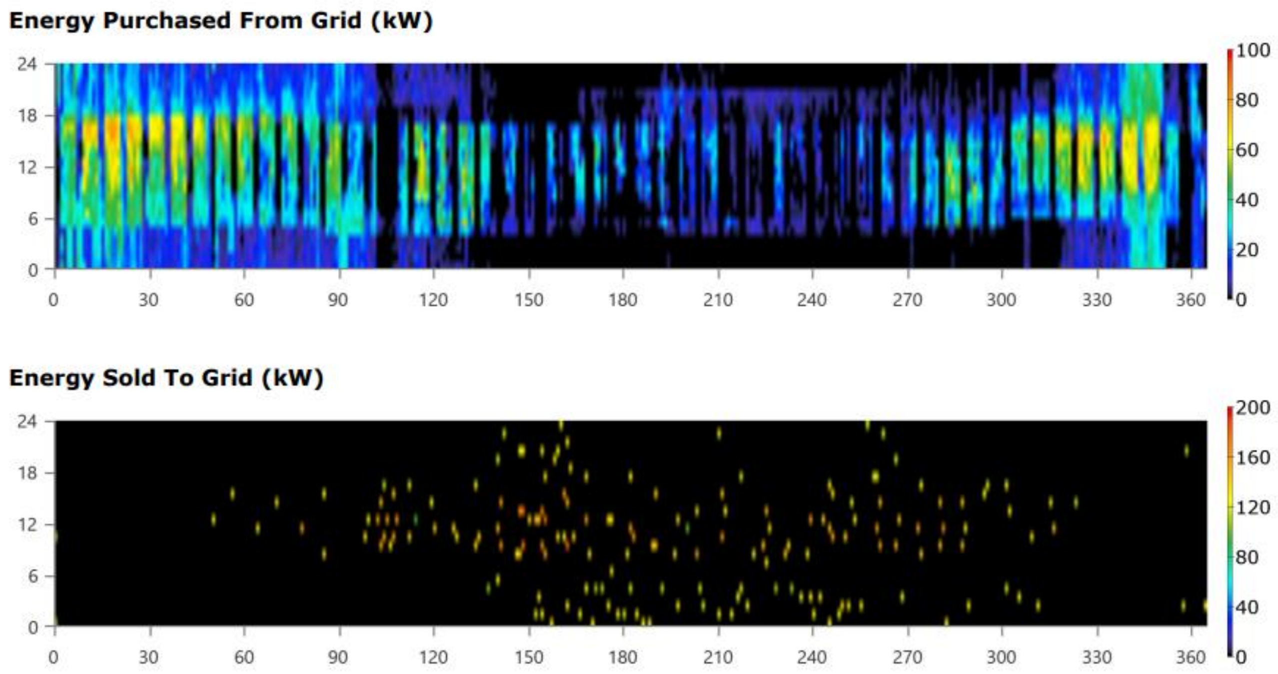


Figure 22: Electricity purchased and sold to grid from Home Pro report.

Appendix-F
Fuel cell and Fuel Summary

Figure 23 deals with the characterisation of the fuel cell and the fuel consumption details.

Generator: Fuel cell (External Hydrogen Supply)

Fuel cell Electrical Summary

Quantity	Value	Units
Electrical Production	693,690	kWh/yr
Mean Electrical Output	79.2	kW
Minimum Electrical Output	40.0	kW
Maximum Electrical Output	80.0	kW

Fuel cell Fuel Summary

Quantity	Value	Units
Fuel Consumption	36,766	kg
Specific Fuel Consumption	0.0530	kg/kWh
Fuel Energy Input	1,225,518	kWh/yr
Mean Electrical Efficiency	56.6	%

Fuel cell Statistics

Quantity	Value	Units
Hours of Operation	8,760	hrs/yr
Number of Starts	1.00	starts/yr
Operational Life	5.71	yr
Capacity Factor	99.0	%
Fixed Generation Cost	8.96	£/hr
Marginal Generation Cost	0.106	£/kWh

Fuel cell Output (kW)

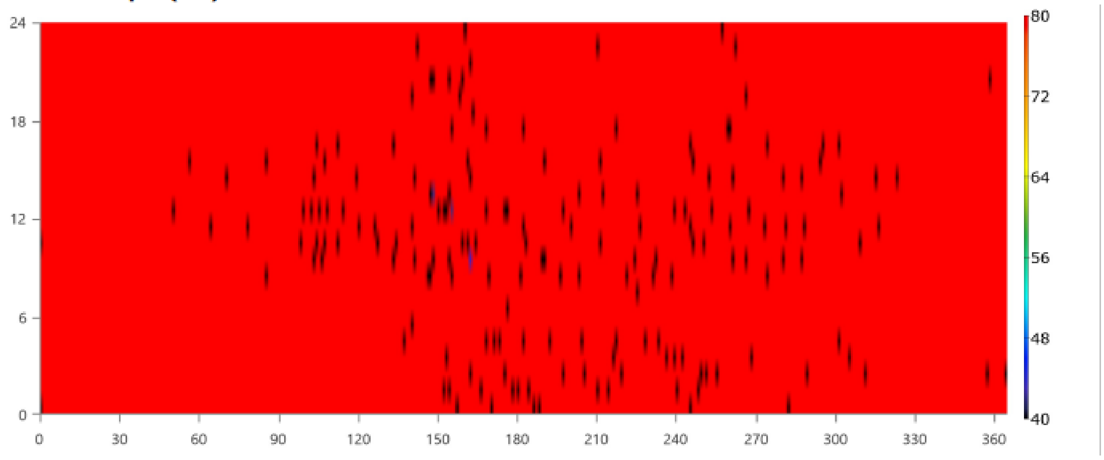


Figure 23:Fuel cell and fuel summary from Homer pro report.

Appendix-G
The cost and carbon footprint of each component

Table 3: Cost and carbon footprint associated each component with reference.

Component	Price (Pounds)	Capital cost (Pounds)	Replacement cost (Pounds)	O&M Cost (Pounds)	Cost Reference	Unit CO2 Equivalent	CO2 Equivalent Reference
Grid	0.2748	10000	0	0	[1]	0.194 Kg CO2/KWh	[2]
Solar PV	400	77600	70000	1000	[3]	0.050 Kg CO2/KWh	[4]
Battery	200	161600	240000	0	[5]	60 kg CO2/KWh	[6]
Fuel cell	1840	147200	144000	648.24	[7]	24.2 Kg CO2/ Kw	[8]
Converter	131.5	26300	25000	1000	Homer Pro	0.5 Kg/Kw	
Hydrogen	2	73532	0	0	[9]	0.025 Kg CO2/KWh	[9]

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Appendix-H
Project Proposal

1. Introduction

Electricity is vital for modern society and the economy. However, using coal and oil to generate electricity emits harmful greenhouse gases and pollutants, which threaten human health and the environment. Adhering to international agreements, such as the Paris Agreement, is crucial for limiting global warming to less than 1.5C compared to pre-industrial levels. The EU's "Fit for 55" package aims to reduce greenhouse gas emissions by 55% until 2030 compared to 1990 levels [15], [60]. To support the transition to a cleaner and sustainable energy future, renewable energy resources are essential. These include solar PV, solar thermal, wind, hydro, biomass, geothermal, ocean waves, and tides. Solar PV is significant due to its modularity, easy installation, mature technology, and low operating cost.

Solar PV technology has advanced significantly since the invention of the first silicon-based solar cell in 1954. Single-junction Si-based solar cells have reached their maximum efficiency, and researchers are exploring tandem solar cells such as the perovskite/Si two-terminal tandem solar cell. This achieved 14.3% efficiency in 2015, 29.5 % in 2020 and could potentially reach 32% with further optimization [37]

PV systems for energy generation are affected by environmental factors like solar radiation, wind speed, and temperature. However, the intermittent nature of renewable energy (RE) generation makes it challenging to integrate PV systems into the power grid to meet demand. To address this issue, energy storage systems (ESS) are used to regulate power profiles and smooth out the intermittent power produced from RE resources. Lead-acid batteries are commonly used as energy storage devices in standalone PV power systems to compensate for the supply-demand mismatch caused by the nature of solar energy. Unfortunately, their short cycle life increases the operating costs of PV power systems. To mitigate this issue, a hybrid energy storage system combining supercapacitors and batteries has been proposed. This approach can reduce operating costs and improve the efficiency and reliability of PV power systems, making them more practical for widespread adoption.

The adoption of solar PV and hybrid storage systems by communities and individual buildings not only provides self-sustainability and reliability of electricity, but also enables the creation of smart energy communities. By generating their own electricity and reducing reliance on grid electricity, these communities can optimize their energy usage, reduce costs, and contribute to a more sustainable future.

This dissertation aims to develop a clean energy production and hybrid storage concept for a community building on a geographical island in the UK. The study will use a systematic methodology, including data collection and analysis, and will be guided by relevant literature in the field. The project will begin with a literature review on solar PV and energy storage systems to identify the most suitable technologies and designs for the building. The system's design will then be optimized for maximum energy production and storage efficiency using HOMER and Helioscope or Polysun software to simulate performance under different conditions and configurations. The project will also evaluate flexible services, such as demand response and peak shaving, to improve system effectiveness and efficiency. The recommendations will be based on modelling and analysis and will be useful for implementing and operating the solar PV and hybrid energy storage system in the community building. This approach has the potential to impact energy security, climate change, and community development by promoting energy flexibility, reliability, and sustainability.

2. Background And Literature review

Research focuses on solar PV systems as a solution to rising energy demand and greenhouse gas emissions. The objective is to install a solar PV hybrid energy storage system for a UK community building. Solar PV technology has achieved impressive results, including tandem PV panels with 29.5% efficiency [37]. However, solar PV systems have the limitation of intermittent energy output, heavily reliant on weather conditions.

Standalone photovoltaic power systems use energy storage devices, such as lead-acid batteries, to address solar energy's intermittent supply and demand imbalance [15]. However, lead-acid batteries' limited cycle life can increase operational costs. To solve this, energy storage systems (ESS), such as hydrogen gas storage, are proposed as a viable solution for renewable energy storage in a transportable and accessible manner. The stored energy can be converted back into electrical power when needed, improving energy security, combating climate change, and adding value to energy systems [41]. ESS face challenges with system aging, which can reduce performance and increase energy storage costs [17]. Hence, developing strategies to mitigate system aging and extend ESS cycle life is crucial to improve their long-term performance and cost-effectiveness.

Hybrid energy storage systems (HESS) are increasingly important in integrating PV power generation into building energy management systems. HESS offers benefits such as balancing generation and demand, improving power quality, flattening PV intermittence, and regulating frequency and voltage. Ideally, HESS has two types of storage - high energy storage (HES) for long-term energy demand and high power storage (HPS) for power transients and fast load fluctuations. Energy storage systems are essential to enhance power quality, and system stability, and flatten PV fluctuations. Various hybrid energy storage systems such as SC/battery, battery/SMES, flywheel/battery, battery/FC, SC/FC, FC/flywheel, and CAES/battery can be combined for different functions in renewable energy applications [43].

HESS combines multiple energy storage technologies to overcome their individual limitations, with one storage unit for high power demands and the other for high energy demands. Coupling methods include direct DC-coupling, bidirectional DC/DC-converter coupling, and two DC/DC-converter coupling, with the parallel converter topology being the most common. HESS can improve power quality, system stability, and balance energy supply and demand [61], [62].

Smart Energy Communities (SECs) are intelligent local energy communities promoting renewable sources, cooperative approaches, and intelligent energy management. They reduce energy consumption, carbon emissions, and provide employment, training, and citizen participation benefits. SECs are developed at different levels, from individual buildings to districts and cities [50].

The literature review highlights the importance of solar PV systems in meeting energy demands while reducing emissions. Hybrid energy storage systems improve solar PV system efficiency. Different factors affect the choice of hybrid energy storage systems, such as location, cost, and storage space. This review informs the design of an effective solar PV and hybrid energy storage system for a UK building, promoting energy flexibility, reliability, and sustainability.

3. Aim And Objective

The aim of this project is to develop a solar PV and hybrid energy storage system that focuses on reducing the carbon footprint associated with the energy consumption of the building.

1. Conduct a literature review on solar PV and energy storage systems to identify the most appropriate technologies and designs for the specific community building and geographical island.
2. Develop a model using HOMER and Helioscope software to simulate the performance of the solar PV and hybrid energy storage system under various conditions and configurations.
3. Conduct an economic analysis of the project.
4. Evaluate the potential for flexible services, such as peak shaving, to enhance the effectiveness and efficiency of the energy system.
5. Provide recommendations for the implementation and operation of the solar PV and hybrid energy storage system in the specific community building based on the results of the modeling and analysis.

4. Methodology

1. A literature survey will be conducted using various platforms such as Science Direct, Google Scholar databases, Research Gate, and international energy agencies to investigate solar PV, hybrid energy storage systems, and smart energy communities. Relevant literature will be chosen by analyzing the title, keywords, abstract, article content, and the journal's primary subject of interest.
2. Energy consumption data for the specified building will be gathered by accessing utility bills, typically provided by utility companies on a regular basis, either monthly or quarterly. The concerned authority

or building owner/operator will be responsible for providing access to the utility bills or other energy consumption data sources for assessment purposes.

3. The irradiance and temperature data for the location of the building will be acquired through the software RETSCREEN.

4. The software primarily utilized will be Helioscope or Polysun and HOMER for conducting software simulations. Helioscope enables the identification of suitable areas for mounting photovoltaic arrays and facilitates the mechanical design of the PV system using defined parameters. It further conducts shading analysis, computes energy yields, and generates detailed reports encompassing crucial details such as system capacity, overall production, losses, and performance ratio. HOMER optimizes the design of solar PV and hybrid energy storage systems for smart energy communities by determining the optimal configuration of system components (e.g., solar panels, batteries, inverters) to maximize energy production, efficiency, and reliability.

5. The economic analysis will incorporate the following elements related to the installation of a solar PV and hybrid energy storage system: the installation costs of the solar PV and hybrid storage system, which will be obtained from the manufacturers' information and SPON's pricing book; the operational and maintenance costs of the system; and the energy generated from the solar PV system. The analysis can also be performed using software such as HOMER.

6. The environmental analysis will assess the carbon footprint associated with each component used in the solar PV and hybrid storage system. This will include an evaluation of the emissions generated during the production, transportation, and disposal of the components. Additionally, the analysis will estimate the amount of electricity produced from the proposed system, which will offset the amount of electricity that would otherwise be purchased from the grid. By comparing the carbon emissions from the proposed system to the emissions generated by the grid, the analysis will determine the net environmental impact of implementing the solar PV and hybrid storage system.

5. Project Outcomes

1. A comprehensive review of solar PV and energy storage systems, identifying the most appropriate technologies and designs for the specific community building in the UK.
2. A model developed using HOMER and HelioScope software to simulate the performance of the solar PV and hybrid energy storage system under various conditions and configurations.
3. An optimized design of the solar PV and hybrid energy storage system for maximum energy production and storage efficiency, taking into consideration the specific needs and characteristics of the community building in the UK.
4. Reduction of the carbon footprint associated with the energy consumption of the building through effective integration of solar PV and hybrid energy storage systems.
5. An economic and environmental analysis of the project to assess the feasibility and sustainability of the solar PV and hybrid energy storage system.

6. Project Management

For a detailed breakdown of how the dissertation project is planned, See the Gantt chart,

GANTT CHART																																		
Project Start:	Wed, 01-02-2023																																	
	Month		FEB				MAR				APR				MAY				JUN				JUL				AUG				SEP			
	Week		W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4
Dissertation Timeline	**START**	**END**																																
Task																																		
Dissertaion Proposal	3-2-23	14-3-23																																
Literature Review	3-2-23	14-3-23																																
Collect Data	3-2-23	13-4-23																																
Analyze Data	1-4-23	30-5-23																																
Solar PV Software Simulation	1-6-23	22-7-23																																
Hybrid Enrgy Storage System Software simulation	2-6-23	23-7-23																																
Simulation Results Validation And Optimization	1-7-23	30-7-23																																
Dissertation Drafting	15-6-23	19-8-23																																
Dissertation Review and Rivisions	01-09-2023	18-09-2023																																
Dissertation Submission	20-09-2023																																	

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Project Management Review

In the initial stage of the dissertation, everything went according to the plan, including going through various journals from different sources, filtering and sorting them based on relevance and keywords, which was successfully completed until April 23. After that, examination dates were announced, and preparing for the exams took precedence. Specifically, from April 25, 2023, to May 19, 2023, exam preparation and exams were ongoing, during which the dissertation work was put on hold. Once the exams were over, attention turned towards the dissertation again. By that time, a significant amount of work had to be caught up. Based on the journals and articles collected, a rough extended literature was prepared and submitted to the professor. Timely meetings were scheduled with the guide to get the dissertation back on track. However, there were some delays due to the need to learn two software programs from scratch in order to proceed with the dissertation. The first software was Helioscope, which is essential for designing a solar PV System. Without completing the PV system design, it was impossible to move on to the next software. After going through the design guidebook and watching tutorial videos on YouTube, Helioscope software was learned, the PV system design was completed, and the production report was downloaded. According to the original project plan, PV software simulation and optimization were planned to be completed from 01-06-23 to 23-07-23. However, due to the delay and difficulty in learning the software, this stage took more time than anticipated and was completed during the period from 20-06-23 to 30-07-23. Once the PV system design was completed, the next software, Homer Pro, was immediately started. This software allows the integration of various technologies such as PV, battery, fuel cells, converter, and grid into the building. Learning this software was the most challenging part due to the lack of guidebooks and proper tutorial videos. Outreach was made to Ph.D. students to come up with some ideas about the software, and spending more time on software knowledge was needed to design the system. Finally, through various iterations, a design suitable for the required building was developed. Initially, learning and designing both software programs were planned simultaneously. However, due to the difficulty in learning both software programs at the same time and the requirement to input the report from Helioscope into Homer Pro, both software programs were learned in different time frames. To adjust the time, hybrid system design and validation of the results were done simultaneously. This task took place from 30-07-23 to 30-08-23. Once the simulation results were validated, the next step was to draft the report. The first draft of the dissertation was prepared from 31-08-23 to 06-09-23 and was submitted to the guide on 07-09-23. Based on the suggestion from the professor, alterations were made to the report. However, even with these delays, through effective time management practices and expediting the report drafting stage, it was possible to get back on track with the original project management plan. Figure 25 represents the modified Gantt chart of the project management, in which red colour represents the hold on the dissertation and yellow represents the actual dates of each task.

GANTT CHART																																		
	Project Start:	Wed, 01-02-2023																																
	Month		FEB				MAR				APR				MAY				JUN				JUL				AUG				SEP			
	Week		W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4
Dissertation Timeline	**START**	**END**																																
Task																																		
Dissertaion Proposal	3-2-23	14-3-23																																
Literature Review	3-2-23	14-3-23																																
Collect Data	3-2-23	13-4-23																																
Analyze Data	1-4-23	30-5-23																																
Extended literature review writing and submission	30-5-23	12-6-23																																
Solar PV Software Simulation	20-6-23	30-7-23																																
Hybrid Enrgy Storage System Software simulation	30-7-23	30-8-23																																
Simulation Results Validation And Optimization	15-8-23	30-8-23																																
Dissertation Drafting	31-8-23	6-9-23																																
Draft submission	6-9-23	6-9-23																																
Dissertation Review and Rivisions	11-09-2023	18-09-2023																																
Dissertation Submission	20-09-2023																																	

Figure 24: Modified Gantt chart.