Renewable Energy Strategy for the Richmond Building

This report provides a renewable energy proposal for the Richmond Building to work towards the University of Bristol's sustainability goal in becoming net zero in Scope 1 and 2 emissions by 2030. First, an assessment of the Richmond Building site was done, in addition to assessing its energy demand and the current technologies in place to meet this demand. The assessment showed a large annual gas consumption of 2425 MWh alongside an annual electricity consumption of 974 MWh. Three main areas of investigation were electricity generation, heating methods, and energy storage strategies. Given a significantly greater natural gas demand, addressing the heating solution was deemed the main priority, with renewable electricity generation being the next consideration. Following on from this, key performance indicators across environmental, technical, economical, and social dimensions were established to assess the potential of proposed technologies.

The final proposal suggests the implementation of the RTXC 220 XE-EC air-to-water heat pump manufactured by TRANE technologies to reduce the Richmond Building's natural gas demand by 89%. This decreases the building's reliance on the grid, with the effect of increasing the electricity consumption by 56%. 294 S6W-575T photovoltaic panels manufactured by Canadian Solar were implemented on both roof and wall-mounts. This allowed for the projected annual on-site generation of 130 MWh electricity. A Battery Energy Storage System comprising of 7 BYD LVL 15.4 units was proposed to store excess generated electricity.

Overall, the project is expected to have a payback period of 19 years, with a positive terminal NPV. Both the levelised cost and carbon offset analysis demonstrated the projects' suitability as an alternative to continued reliance on the grid.

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1 Scope

The scope of this report is to propose and evaluate a revised energy strategy to improve the sustainability of the Richmond Building at the University of Bristol.

2 Introduction

2.1 Motivations

The University of Bristol has pledged to become net zero in Scope 1 and 2 carbon emissions by 2030 [1]. Scope 1 emissions originate from university owned or controlled facilities whilst Scope 2 emissions are those resulting from purchased energy (indirect emissions) [2]. Scope 3 however, includes all other indirect emissions not covered by Scope 2. The university has not stated in any precise detail its Scope 3 strategy [3]. Constructed in 1965, the Richmond Building was not designed with renewable energy and carbon emissions in mind. This presents a good opportunity to reduce the university's Scope 1 emissions.

2.2 Site Assessment

A site assessment was carried out to gain a better understanding of the building, its use and the immediate surrounding areas. This helped to inform the suitability of different technologies to use on the building. The Richmond Building is a multi-purpose building with a variety of different rooms all with varying energy demands. The building's facilities are not exclusively used by university students, but also by the general public who mainly use the bar and swimming pool. The site itself is surrounded on three sides by roads and on the fourth by a chaplaincy. Figure 1 highlights the key features of the site and its immediate surroundings. The building is divided into three main parts: the North building, which is next to the chaplaincy; the South building, next to the bike store as shown in Figure 1; and the Bridge building connecting the previous two.

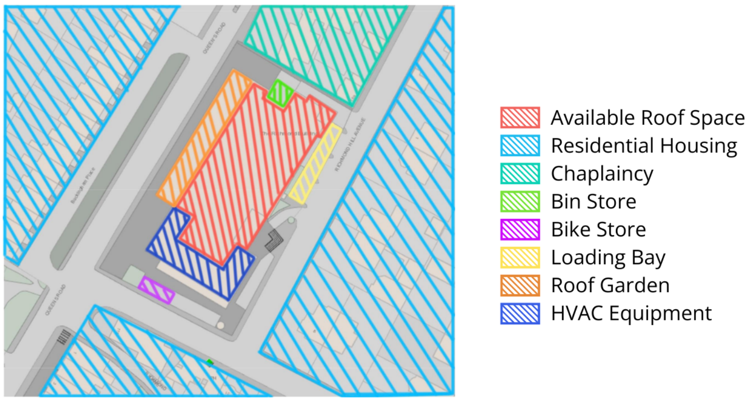

Figure 1: A diagram of the current site and immediate surrounding area adapted from [4].

The building was also renovated in 2016 by Feilden Clegg Bradley Studios [5], not only to improve study spaces and leisure facilities but also to upgrade the building's insulation in line with the university's energy strategy.

2.3 Current Energy Demand

The Richmond Building currently sources its electricity in line with the wider strategy implemented across the University of Bristol. 81% of this sourced from nuclear power, 18% from wind power, and 1% from on-site solar power elsewhere on the university estate, as stated by the university's sustainability team. The building does not currently feature any on-site electricity or heat generation technology [6], relying completely on the National Grid and gas pipelines for supply. Three Hoval Ultragas natural gas boilers are used for heating [6]. In 2023, the Richmond Building consumed 974 MWh of electricity and 2425 MWh of natural gas [6]. As per the BREEAM certificate awarded to the building in 2014, the building's second lowest score was in the energy category, at just 56% [7]. This suggests significant potential for improvement of the building's energy efficiency [8] through a revised energy generation and usage strategy.

Limited information was available regarding the breakdown of the building's current energy use over the year. Therefore, a virtual energy model for the Richmond Building was built as shown in Figure 2 to simulate realistic energy usage profiles. This was done within the Integrated Environmental Solutions Virtual Environment

(IESVE) - a standard and widely-recognised building energy modelling software accredited by the Chartered Institution of Building Services Engineers (CIBSE) [9], the Building Research Establishment (BRE) [10], and the UK government [11]. Figure 2 shows the North building, bridge, and South building from left to right.

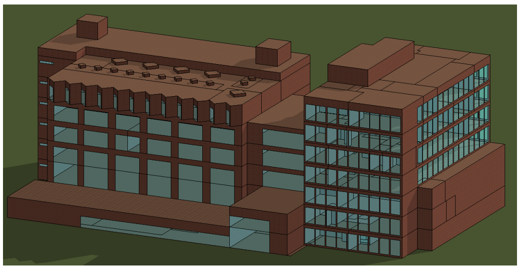

Figure 2: Constructed building geometry within IESVE, from a South-West view.

In line with the National Calculation Methodology (NCM 2021) framework [12] for assessing building energy performance, a dynamic simulation of the building's annual energy use was conducted within IESVE. Some key model inputs are summarised below:

- Building geometry, orientation, room layout and uses, taken from floor plans produced in 2014 by the University of Bristol [13].
- NCM-compliant thermal templates for various spaces within the building [14].
- Thermal regulation set-points and airflow rates for each space, sourced from CIBSE Guide A [14], UK Building Regulations Approved Document L [15], and operating temperature information provided by the university [16].
- Opening times and occupancy information from the University of Bristol [17] and Bristol SU Skedda websites respectively [18].
- Example Weather Year (EWY) data [19] recorded at the Bristol Weather Centre in 2021.

Annual energy usage profiles were extracted following the simulation of the constructed building model. It should be noted that these featured a degree of inaccuracy relative to actual recorded values from 2023. Key model assumptions which may have contributed to inaccuracies within the model are listed below:

- Exact usage patterns of each space.
- Thermal insulation properties of the building fabric.
- Weather patterns.
- Exact HVAC equipment and control settings.
- Window opening patterns.

However, both the spatial and temporal distribution of the modelled energy use were considered representative, with usage profiles scaled linearly to match the actual annual totals from 2023 via appropriate correction factors of 1.26 and 0.64 for natural gas and electricity respectively. This was done to provide the most accurate distribution of energy demand both across the year and for different systems since the real-world distribution was not readily available. Figures 3 and 4 summarise the gas and electricity usage distributions as found from the IESVE model.

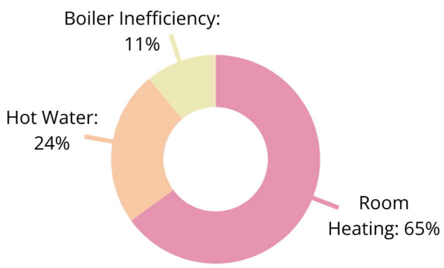

Figure 3: Donut chart showing a breakdown of the natural gas demand of the building.

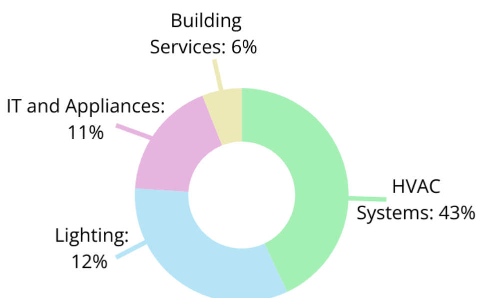

Figure 4: Donut chart showing a breakdown of the electricity demand of the building.

Figures 5 and 6 present annual and weekly consumption profiles respectively for both natural gas and electricity, generated from scaled IESVE output. Figure 6 displays the power demand for a typical summer week beginning on the 5th of June. This shows the instantaneous power demand for natural gas, electricity, heating and cooling based on hourly data. Figure 5 was generated by summing these values over each day and multiplying by the time period for each value (1 hour). The natural gas and heating profiles are naturally coupled since heating is currently provided via natural gas boilers, and these profiles fluctuate in magnitude depending on the outside temperature. Each day begins with a surge in these demands, as the building must be heated from relatively colder night temperatures and thus more natural gas is consumed in doing this.

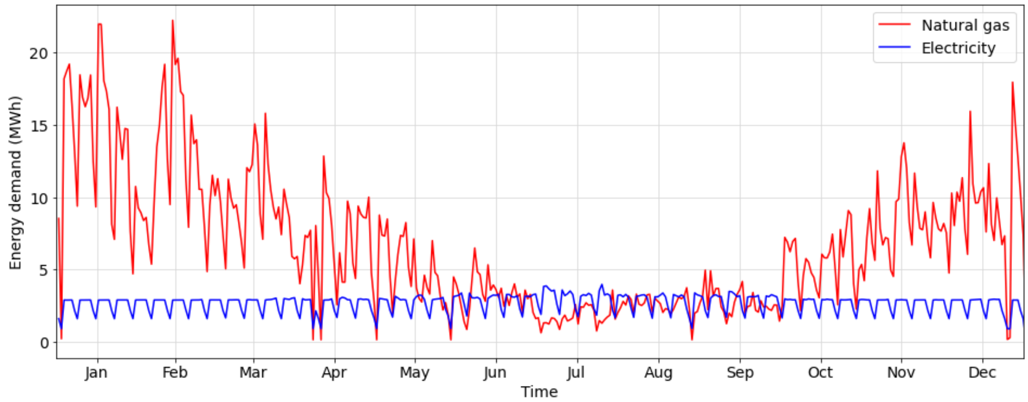

Figure 5: Annual demand profile for natural gas and electricity.

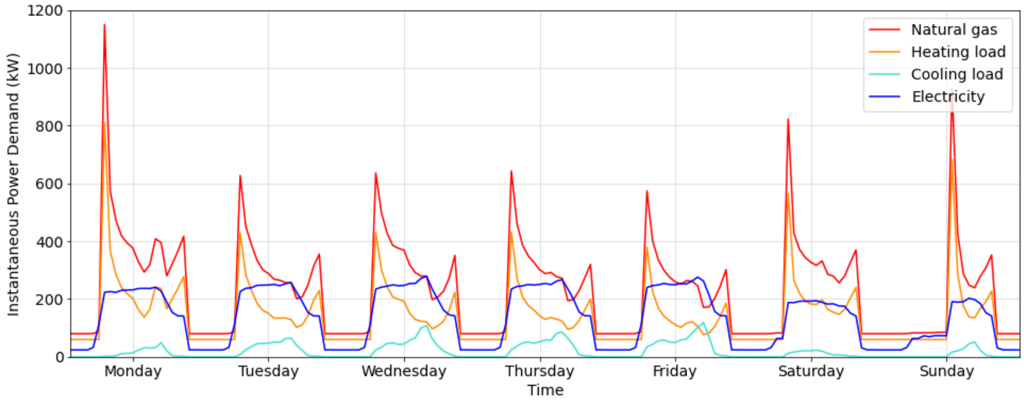

Figure 6: Weekly demand profile for the week commencing 05/06/24.

Figure 5 indicates a relatively stable electricity demand profile in comparison with natural gas demand, which is heavily influenced by seasonal changes. Dips in both demand profiles correlate to weekends when building opening hours are reduced. The most significant dips, such as those seen at the beginning and end of May, correlate to bank holidays when the building does not open at all. The natural gas demand exceeds electricity demand for majority of the year, with the exception of bank holidays and parts of the summer period. During these times, heating demand is at its lowest and cooling demand, which is supplied by electrically powered conventional air conditioning units, is at an annual high. It should be noted that neither energy demands are equal to zero at any point in the year, since rooms are still heated to 12°C [14], and HVAC and other electrical equipment are never completely switched off, even in closure. Notable results from the obtained energy demand profiles are summarised in Table 1 below.

Table 1: Key results from the demand profiles.

Demand Type	Value
Annual Peak Natural Gas Demand (hourly)	3.24 MW
Total Annual Natural Gas Demand	2425 MWh
Annual Peak Electricity Demand (hourly)	0.32 MW
Total Annual Electricity Demand	974 MWh

As the university's electricity is already generated by relatively low carbon sources, reducing grid access is not the main focus of this report as Scope 2 emissions are not significantly impacted. Any low-carbon electricity not consumed by the university can instead be redistributed and supplied to other buildings, allowing for wider access to green electricity. Instead, the main aim of this report is to reduce the Richmond Building's Scope 1 emissions through reduction of gas consumption. To achieve this, three key areas have been identified for improvement: heating, electricity generation, and electrical energy storage.

3 Key Performance Indicators

Four Key Performance Indicators (KPIs) were determined to assess the potential and chosen electricity generation, heating and storage strategies for the Richmond Building. These KPIs are outlined below:

- **Technical Operation:** This dimension encompasses efficiency and energy generation, distribution or storage capacity depending on the technology. Efficiency is measured in % and capacity in MWh.
- **Economic Performance:** This dimension assesses the financial feasibility of the project over its operational lifecycle, including monetisation of other benefits, and its efficiency against the baseline grid use.
- **Environmental Impact:** This dimension evaluates the effect of the various renewable strategies on the environment. Major metrics assess the carbon footprint and abiotic resource use across all stages of the project's lifecycle.
- **Social Good:** This dimension assesses and provides recommendations to the project towards social benefits, ensuring the project contributes towards goals that align with the university's goals and have a positive impact on the broader community.

Figure 7 summarises these KPIs and the metrics that will be used to quantify them.

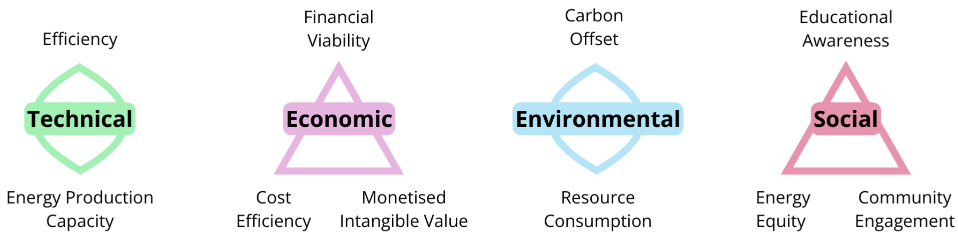

Figure 7: KPI dimensions and their respective metrics.

4 Technology Assessment

Potential solutions to each of the three major areas for improvement are outlined below. There are a range of energy generation technologies that could be considered for implementation in the Richmond Building to meet the electricity demand. An initial analysis of these technologies was conducted to inform their feasibility for the project.

4.1 Potential Electricity Generation Solutions

Solar Photovoltaics: Solar photovoltaic panels convert incident solar energy to an electric current, with a semiconductor material. A main benefit of solar panels is their ability to be on-site and easily accessible in case of maintenance, which is low-level and inexpensive, despite the relatively high installation cost. As the Richmond Building is relatively constrained in area, solar panels were deemed suitable. However, one disadvantage of this technology is the intermittency of generation, being heavily dependent on weather conditions. A preliminary investigation was conducted into the feasibility of a solar photovoltaic system, using an assumed available roof area of 956 m^2. This area was determined from the model in Figure 2. The simulation resulted in 234MWh of energy annually, highlighting its feasibility. Equation 1 [20] below was used in the Python code, where η_p is the panel efficiency, A_p is the effective panel area in m^2 and g_t is the global horizontal irradiance in W/m^2.

$$\text{Solar Power} = \eta_p A_p g_t \tag{1}$$

Lifecycle carbon emissions from solar panels are moderately high at 41 g CO_2-eq/kWh [21] compared to other forms of energy. Roof-mounted panels would also contribute minimally to visual noise pollution towards the surrounding area, unlike other potential solutions.

Geothermal: Geothermal energy is not currently used as a form of electricity generation in the UK. This is due to the lack of ground heating stores available [22]. There are currently works on a power plant in Cornwall, the first in the UK [23]. However, this is a very new project and progress may not be suitable to help with the university's target to be net-zero by 2030. Due to its novel and large-scale nature, geothermal energy may not be a suitable electrical generation method for this particular site.

Wind: Wind turbines convert kinetic energy from the wind into electrical energy via a turbine. Offshore wind turbines, in particular, are capable of generating greater energy outputs due to fewer dimensional constraints [24]. However, these would incur many additional storage and transport costs. These are not justifiable when compared to the energy demand of the building.

Alternatively, on-site small-scale wind turbines could be installed on roof areas of the Richmond Building, as the site assessment in Figure 1 indicates limited ground space. For roof mounting, Vertical Axis Wind Turbines (VAWTs) are considered more suitable than Horizontal Axis Wind Turbines given their improved performance in lower cut-in wind speeds and their omnidirectional nature [25]. Equation 2 [26] below determines the potential power generation from roof-mounted VAWTs.

$$\text{Wind Power} = \frac{1}{2} C_p \rho A_w v^3 \tag{2}$$

where C_p is the coefficient of power, ρ is the air density of 1.2kg/m^3, A_w is the swept area of the turbine in m^2 and v is the wind speed in m/s. 50 2 kW VAWTs with a rotor diameter of 1 m were modelled on the roof of the Richmond Building. Hourly wind speed data from an EWY file was used in the calculation and the maximum coefficient of power of $\frac{16}{27}$, Betz's constant [27], was assumed. This would result in approximately 13.87MWh of energy produced per year across all turbines, less than 2% of the building's electricity demand. The Richmond Building is surrounded by residential housing so opposition to the placement of 2.4m tall turbines on top of the building is anticipated, as this could block sunlight for local residents. However, wind turbines have a relatively low carbon footprint of 11 g CO_2-eq/kWh [21] when compared to other technologies.

Tidal: Tidal power utilises the kinetic energy from rising and falling tides to spin a turbine attached to a generator. The Severn Estuary has the second-largest tide in the world [28], located just a few kilometres from Bristol. One potential approach can involve the construction of a tidal barrage within the estuary, with the potential to provide 17 TWh of energy per year [29]. This would benefit the entire country rather than just the university. Tidal barrage development faces significant environmental and economic challenges, so a successful proposal is yet to be delivered for this. The barrage poses threats to the habitats of migratory fish [30], leading to disruption to the feeding patterns of migratory birds. Estimates of the cost of the Severn Barrage vary as there have been multiple proposed locations along the estuary. However, estimates have been placed up to £30bn [31], a huge financial undertaking.

Hydro-electric: Hydro-electric power, similarly to tidal power, converts the kinetic energy of flowing water to turn turbines and generate electricity. A previous proposal of this in Bristol is at Netham Weir near Barton Hill. The system here will use two Archimedes screws to generate an estimated 0.9 - 1 GWh of electricity annually [32]. This is enough to fulfil the Richmond Building's electricity demand of 974 MWh or to power 250 homes for a year. This is estimated to cost £2.39m [33]. This method is only suitable for off-site locations, requiring energy storage and transportation infrastructure to deliver this power to the Richmond Building.

Piezo-Electric Tiles: Piezo-electric tiles are used to convert a mechanical force from footsteps into electrical energy [34]. Energy generated from piezo-electric tiles is proportional to the number of steps taken on the tiles. Therefore, the optimal place for them would be the entrance to the Richmond Building as it is the most high-traffic area.

To assess their feasibility, a base calculation was done considering the Waynergy piezo-electric tiles. A total area of $16m^2$ of these tiles would cost £35,600 as each tile is £356 [35]. Assuming a total of 100,000 steps are taken on the tiles each day, and each step generates 5J of energy [36] [35], 50.7kWh of energy can be generated annually from the tiles. This is less than 0.005% of the building's electricity demand, suggesting there may not be enough traffic entering the Richmond Building to make this a feasible application.

4.2 Potential Heating Solutions

Ground Source Heat Pumps: Ground Source Heat Pumps (GSHPs) transfer heat from the ground into energy that can be used for heating. GSHPs are widely used as they can improve energy efficiency by up to 400% [37]. The installation of a large GSHP costs approximately £40,000 [38]. Additionally, GSHPs require a borehole of up to 120m to be drilled on-site, the creation of which would likely cause disruption to the local residents and access to the building itself. Not to mention that it requires a large area to install the pipes. There is no suitable location within the near vicinity of the Richmond Building as it is surrounded by roads and residential housing shown in Figure 1, and therefore they may not be a suitable source of energy for the Richmond Building.

Air Source Heat Pumps: Air source heat pumps (ASHPs) extract heat from outside air, delivering efficient heating with Coefficients Of Performance (COPs) of 2-4 [39], far exceeding typical efficiencies of around 90% for standard gas boilers [40]. Powered by electricity rather than fossil fuels, ASHPs can significantly reduce Scope 1 emissions, which is of particular significance for the Richmond Building. Unlike ground source heat pumps, ASHPs are cheaper and less disruptive to install with less extensive groundwork. Many models can also offer cooling in summer, with Seasonal Energy Efficiency Ratios (SEERs) exceeding 12 [39]. However, ASHPS require installation of outdoor units, which can cause noise pollution and are vulnerable to weathering effects, potentially raising maintenance costs. Despite these shortcomings, their high efficiency, potential dual heating/cooling capability, and cost-effective installation provide a compelling option for heating replacement.

Electric Boiler: Electric boilers are an alternative to the gas boilers currently in the Richmond Building. As electric boilers don't burn fossil fuels, this would reduce Scope 1 emissions, whilst increasing Scope 2 emissions, due to the additional electricity required to power it. As the university's grid supply is already low carbon, this would result in a net reduction in overall emissions. Other advantages include a greater efficiency than gas boilers, as there are no combustion losses. From a safety perspective, electric boilers eliminate the risk of carbon monoxide poisoning or other gas leaks. Disadvantages include higher running costs compared to gas boilers. At the time of writing, the price of gas is approximately four times less than electricity [41]. The dependence on the grid also leaves the electric boiler vulnerable to power cuts, and therefore no heating until power is restored. Additionally, electric boilers have a smaller heating capacity than gas boilers, meaning a large number would have to be installed to match the Richmond Building's heating requirements.

Solar Thermal: Solar thermal technology is a possible substitute for a gas boiler. It relies on heat transfer from the sun to a fluid (water and glycol), which circulates through radiators to provide heating. It can also generate electricity indirectly, by boiling water into steam to drive turbines. Solar thermal can be broken down into two categories; solar thermal panels and concentrated solar. Concentrated solar power has the potential to generate substantial amounts of heat on a large scale but poses risks such as stray solar beams which may endanger nearby areas. An off-site farm would result in heat loss through the transportation of the fluid and this level of infrastructure would be complex and expensive. Of the two main types of solar thermal panels, evacuated tubes are superior to flat plate collectors, as they have a greater thermal efficiency [42]. Disadvantages of evacuated tubes include being less effective in environments with lower light levels and a high rate of maintenance [43].

Gas Boiler: Finally, it is an option to retain the gas boilers currently used in the building. These heat water by burning natural gas to provide reliable space heating. Alternatively, upgrading to modern condensing models could improve efficiency to 90-95% [44], slightly above the current 88.6% seasonal efficiency of the on-site Hoval Ultragas units [45]. Existing infrastructure minimizes installation costs and disruption compared to alternatives like GSHPs. However, gas boilers depend on fossil fuels, generating significant carbon emissions, which conflicts with the university's goal of reducing Scope 1 emissions. Volatile natural gas prices and potential future regulations on carbon-intensive systems further challenge their long-term feasibility. While retaining the system offers low upfront costs and minimal disruption, it fails to align with the university's sustainability and carbon reduction targets.

4.3 Energy Storage

Battery Energy Storage Systems: Battery Energy Storage Systems (BESS) involve excess generated electricity charging a battery pack, which can then be discharged when there is a higher electricity demand. This is a flexible system, allowing the battery pack to be charged rapidly and discharged at variable rates and an almost instantaneous response. BESS systems offer scalable storage capacity, allowing for rapid adjustments. Their modular design enables battery packs to be added in parallel to increase capacity or removed to reduce it as needed. Additionally, such systems are compact, ensuring they do not interfere with the regular operations of the Richmond Building. Comparatively, BESS have the highest round-trip efficiency of any of the considered energy storage systems, at 83% [46].

Hydrogen Storage: Hydrogen has the highest specific energy of all fuels [47]. There is scepticism around its safety due to the risk of hydrogen leakage into confined spaces, forming concentrated volumes. Its low ignition energy, coupled with a high specific energy, raise the risk of hydrogen explosions which can be catastrophic for building damage and injuries/ loss of life. In the UK, 96% of hydrogen is produced under grey production [48], which uses steam methane reforming. For every 1 kg of hydrogen formed, 12 kg of carbon dioxide is formed [49]. There is no carbon capture incorporated in this process to reduce emissions. Therefore, hydrogen has a higher carbon footprint than most energy storage systems.

Mechanical Storage: Mechanical storage involves storing potential energy that can later be deployed through mechanical work. Examples include flywheels, compressed air and pumped water storage [50]. While these systems have a high efficiency, they require a large amount of space, which may not be available in the Richmond Building. In the case of a pumped water storage system, this may be environmentally damaging, greatly affecting the public areas outside the Richmond Building. Flywheel designs have a large storage capacity, however they are only able to store energy for approximately 15 minutes [51]. Additionally, as flywheels rotate at a high velocity, there are safety concerns surrounding their failure, as a fracture could lead to the flywheel material tearing through its mount, posing a risk to nearby areas.

Thermal Storage: Thermal storage systems transfer excess heat from solar or solar thermal panels to substances like water, molten salts, or phase-changing materials. These materials, with their high specific heat capacities, store significant energy. During electricity demand, stored heat generates steam to power turbines. However, the round-trip efficiency of thermal storage systems can vary; if the desired output is in the form of heat, the round-trip efficiency can be 70% [52]. However, the efficiency of converting heat energy to electricity is only 35% [53]. This results in a lower round-trip efficiency compared to other energy storage systems. Additionally, thermal storage systems require significant space due to their low energy density, which may not be feasible within the constraints of the Richmond Building.

4.4 Building Management and Energy Recovery Systems

Certain features such as building management and energy recovery systems can improve the overall energy efficiency of the building. As the Richmond Building was recently renovated in 2016 [5], it is assumed that basic energy management systems such as implementation of temperature set-points for heating and cooling and insulation are already inherent in the building. Upon a site visit, it was also observed that the hallway lights are operated through motion sensors so minimal energy is lost through unnecessary lighting. The windows in the Richmond Building were deemed to be already double-glazed. However, with no substantial information about the existing systems, it is hard to say what further technologies can become a part of the system and so these are ultimately not included in the technical proposal.

4.5 Selection of Technologies

In order to assess which options of electrical energy generation, heating generation and energy storage were most appropriate for use on the Richmond Building, different ranking criteria derived from the project's KPIs were defined.

The assessment criteria are listed below:

1. **Site Suitability:** How feasible the technology is to implement on-site.
2. **Energy Output/Storage Capacity:** How much MWh of energy the technology is expected to generate per year. For selecting storage systems, this is instead defined as storage capacity.
3. **Efficiency:** How effective the technology is at converting its input into useful energy output.
4. **Carbon footprint:** The amount of Carbon Dioxide (CO_2) emissions generated by the technology.
5. **Social Impact:** The effect of the technology on the locals around the site.
6. **Cost:** The capital expenditure (CAPEX) of the technology including upfront costs of installation.

The relative importance of each criterion was weighted using a pairwise comparison matrix found in Appendix A.1 as not all factors would be of equal importance to this project. These are shown in Figure 8. The resulting weightings were then used in Multi-Criteria Decision Analysis (MCDA) matrices found in Appendix A.1 to determine which technology was most feasible for the Richmond Building. The results from the MCDA matrices for electrical generation technologies, heating generation technologies and battery storage systems are shown in the stacked bar charts shown in Figures 9 10 and 11. The colours across Figures 9, 10 and 11 represent the suitability criterion consistent with those in Figure 8.

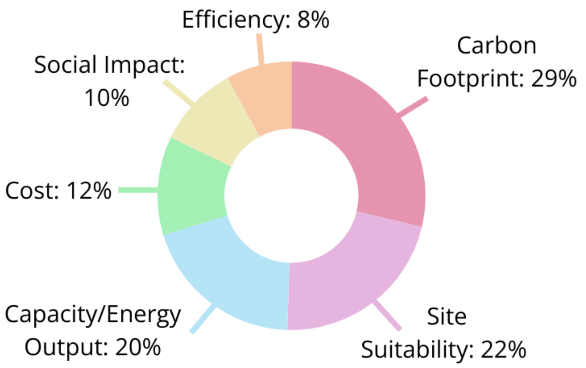

Figure 8: Donut chart showing the relative importance of the suitability criterion.

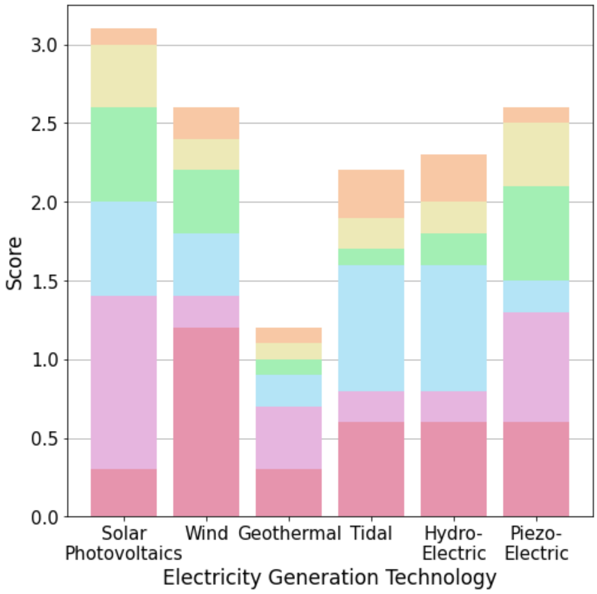

Figure 9: Stacked bar chart showing the MCDA matrix results for electrical generation technologies.

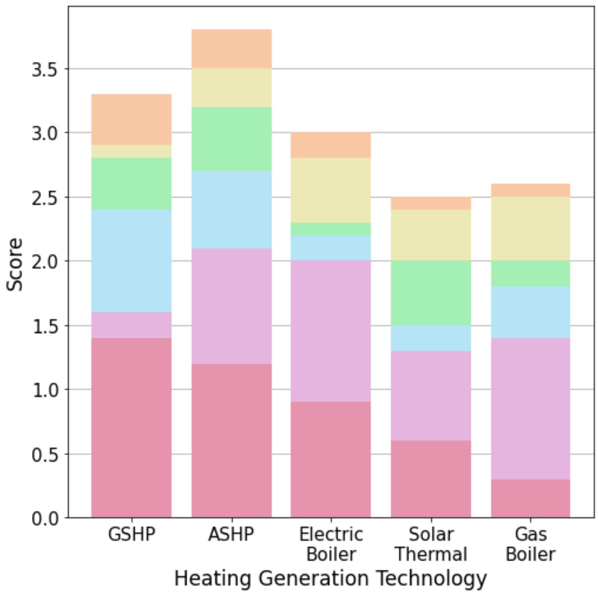

Figure 10: Stacked bar chart showing the MCDA matrix results for heating generation technologies.

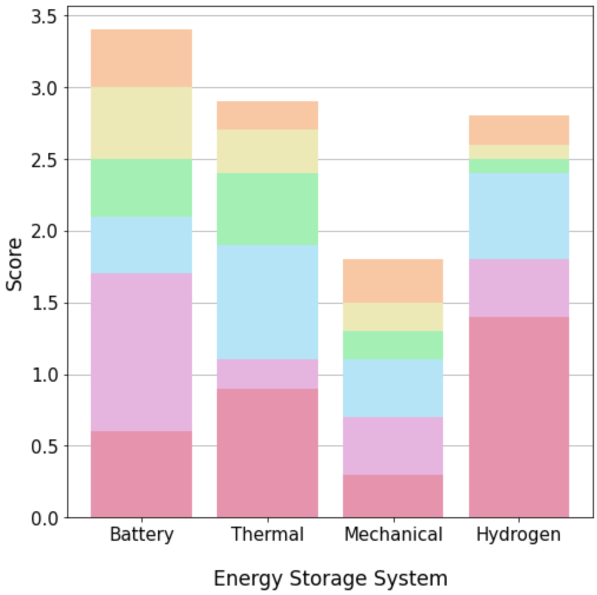

Figure 11: Stacked bar chart showing the MCDA matrix results for electrical storage systems.

The stacked bar charts demonstrate the solar photovoltaics as being the most favorable electricity generation method among the technologies assessed, performing well across site suitability, cost-effectiveness, and social impact criteria. For heating, air-source heat pumps (ASHP) proved to be the optimal choice, performing particularly well in carbon footprint reduction and site suitability. Batteries were identified as the most effective energy storage solution, outperforming other options in terms of site suitability, social impact, and efficiency.

5 Technical proposal

The technical proposal for the Richmond Building is outlined in this section. The technologies chosen for use on the Richmond Building are the ASHP, solar panels and battery storage as determined from the selection process outlined in Section 4.5.

5.1 Air Source Heat Pump

The Richmond Building currently uses natural gas boilers to provide the entirety of its heating capacity. Specifically, it uses three Hoval Ultragas boilers; two rated at 1440kW, and the third at 720kW, for a total capacity of 3.6MW [6]. The current natural gas consumption of 2425MWh can be attributed to the use of these boilers for space heating, domestic hot water (DHW), and pool water heating. Combustion of natural gas within these boilers directly increases the Scope 1 emissions of the university. A summary of the current boiler use for the Richmond Building is found in Table 2.

Table 2: Summary of the current natural gas and boiler use of the Richmond Building.

Natural Gas Consumption (MWh)	Seasonal Boiler Efficiency (%)	Total Boiler Load (MWh)	Estimated Space Heating Demand (MWh)
2425	88.6	2148	1574

ASHPs have a much greater efficiency than gas boilers and are powered by electricity and as aforementioned, the university's electricity is already sourced from a relatively clean mix. ASHPs provide an opportunity to eliminate a significant amount of natural gas demand at the cost of additional electricity demand, albeit only a fraction of the natural gas saved. However, it must be noted that electricity costs approximately 4 times more per unit than natural gas [41] at the time of writing, so the economics of this proposal must be strongly considered. As found in the initial investigation, some ASHPs are also able to provide cooling, enabling the replacement of cooling capacity with much-improved efficiency. Three main targets were set for the implementation of ASHPs:

- To maximise the net amount of energy saved (MWh).
- To maximise the proportion of existing boiler demand covered by ASHPs (%).
- To maximise the net amount of energy cost saved (£).

Ideally, the entire heating demand of the building would be met with ASHPs. However, the cost associated with implementing a suitable ASHP to meet peak boiler demand outweighs its ability to cover the entire heating demand, particularly as this would only be required for a fraction of the year. Therefore, it remains necessary to have some natural gas boiler capacity as a supplementary capacity to meet this peak demand. In the summer, cooling the Richmond building via ASHPs offers an opportunity to reduce electricity consumption and cost. This is due to the typically high Seasonal Energy Efficiency Ratios (SEER) of commercially available units, which significantly reduce the input power required for cooling provision compared to air conditioning.

ASHP selection: To identify a suitable ASHP model, a Python program was written to evaluate the impact of various units on natural gas and electricity demand profiles and economic impacts. It was found that the RTXC 220 XE-EC air-to-water heat pump manufactured by TRANE technologies [54] was most optimal, saving the greatest amount of energy whilst still making a considerable energy cost saving overall. While official pricing details were not publicly available, proportional scaling of known prices for smaller industrial ASHP units indicate cost estimates of around £130,000-£150,000 for this high capacity unit [55].

The key characteristics of this unit are featured in Table 3.

Table 3: Key technical specifications of the selected ASHP [54]

Heating capacity (kW)	SCOP	Cooling capacity (kW)	SEER	Dimensions L × W × H (m)	Weight (t)
769.80	3.29	757.60	4.67	8.70 × 2.25 × 2.50	7.621

Modelling the ASHP: Considering the heating and cooling capacities of the unit, along with its SEER and SCOP, the program predicts the implications on energy consumption and cost. It must be noted that the change in electricity consumption includes saved electricity from switching to ASHP cooling, and additional electricity cost for powering the ASHP. Equation 3 below provides the net change in annual energy cost, C_T in £, while Equation 4 gives the net annual energy saving, E_T in kWh.

$$C_T = E_{gh}p_g + (E_{ec} - E_{eh})p_e \tag{3}$$

$$E_T = E_{gh} + E_{ec} - E_{eh} \tag{4}$$

where E_{gh} is the amount of gas saved due to the change in heating strategy, E_{ec} is the amount of electricity saved in switching to ASHP cooling, E_{eh} is the amount of additional electricity associated with powering the proposed ASHP, p_g is the unit price of natural gas in £kWh^{-1}, and p_e is the unit price of electricity in £kWh^{-1}. All energy values are in kWh and all costs/savings are in £.

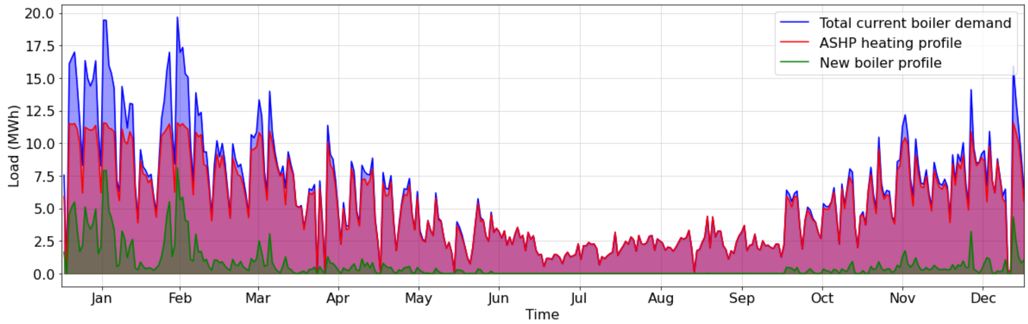

Figure 12: ASHP and revised boiler profiles to meet existing boiler demand.

The IESVE dynamic simulation results suggest a peak instantaneous boiler demand of around 2.87MW, meaning that 4 of the RTXC 220 XE-EC heat pump units would be needed to entirely meet heating demand without the use of boilers at all. This is not economically feasible, and there is also inadequate space available on site for this many units of this size. It is proposed that two boilers, of 1440kW and 720kW power, be kept on-site to provide the remaining 11.25% of the demand and to ensure that peak instantaneous heating demand can be met comfortably with a total heating system capacity of 2.93MW.

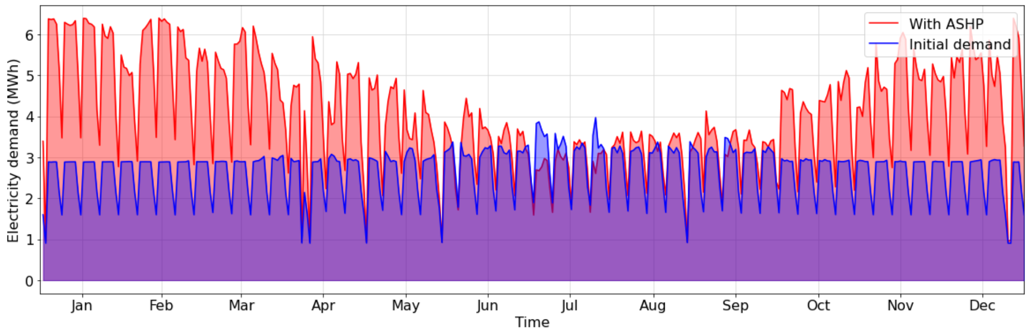

Figure 13: Natural gas and electricity demand profiles following ASHP implementation.

The impacts of implementing the ASHP unit are summarised in Table 4.

Table 4: Key technical specifications of the selected solar panels.

Boiler Demand Covered (%)	Δ Gas Consumption (MWh)	Δ Electricity Consumption (MWh)	Net Annual Energy Saving (MWh)	Net Annual Cost Saving (£)
88.75	-2152	+510	1642	19657

As shown in Table 4, the results of the Python program suggest that this new heating strategy would significantly decrease annual natural gas consumption by 88.75% but increase annual electricity consumption by 52.4%. This would significantly reduce Scope 1 emissions, trading a large portion of this for electricity generated from cleaner sources rather than fossil fuels. Additionally, Figure 13 indicates that the retained boilers would not be required for heating at all between June and September, with the ASHP capable of meeting the heating demand entirely through this period. This provides further evidence that the use of several ASHPs is unjustified.

Implementation: For the implementation of an ASHP to replace boiler heating capacity, there is much to consider regarding the actual installation process. A qualified party must first verify whether the existing pipework and radiators in the building are suitable for the relatively low-temperature output of a heat pump compared to the boiler system they were originally designed for. This informs on the extent of retrofit necessary, with potentially significant implications on cost and disruption to the building during the implementation stage. It is proposed that the ASHP unit should be installed in the space currently occupied by the bin store, on the left side of the North building. The store can be moved elsewhere with ease, perhaps to the back of the building, where there is plenty of space including some parking space which is infrequently used. Floor plans show that the bin store had already been moved in 2016 [13], suggesting that moving this facility elsewhere would not pose a significant inconvenience to users of the building. The proposed ASHP installation site already houses other HVAC equipment, further proving its suitability, as it is convenient for both maintenance and noise disturbance reasons to keep various HVAC installations close together. The ASHP should be installed at ground level and must have at least a 2m clearance from walls or other equipment, to ensure optimal ambient airflow into and out of the unit.

The unit will be connected to a dedicated electrical supply, most likely in the existing basement plant room. For control of the ASHP, it could be connected to a central Building Management System (BMS). This allows for coordination with other on-site HVAC equipment, especially the two remaining boiler units which will mainly serve as supplementary sources of heating. It is unclear whether such a system currently exists at the site, so this may also need to be installed. ASHPs can have a service life of up to 20 years [56], when adequately maintained through annual system and leak checks, electrical circuit tests and internal component cleaning [56].

5.2 Solar Panels

Panel Placement: Following the site assessment, a photovoltaic system comprising both roof-mounted and wall-mounted panels was proposed. From examining plans of the building provided by the university, an available area for the installation of the roof-mounted panels was identified. Wall-mounted panels were proposed for the south-facing wall of the south building. This was due to limited ground space on the site, which is surrounded by roads. The roof-mounted proposal considered all possible obstructions to panel placement, such as lift plants, HVAC equipment, and roof lights, which were observed from both the building plans and Google Maps satellite images of the site.

Panel Orientation: This refers to the azimuth angle of the panel placement. Given that the site is located in the Northern hemisphere, a South-facing orientation is required to maximise incident solar irradiance. As such, an azimuth angle of 180° was chosen for the roof-mounted panels. The wall-mounted panels are flush against the South-West wall of the building.

Panel Tilt: Commonly known as the inclination angle, this refers to the angle of the solar panel plane relative to the horizontal. It is important to optimise this angle for maximising solar irradiance, and exposure time, and reducing reflection losses since steeper angles of solar incidence result in greater reflection. Considering this, an inclination of 30° was selected for all panels. As with panel orientation, the wall-mounted solar panels are placed flush against the building's exterior wall with an effective tilt of 90°.

Panel Selection: The CS6W-575T panel, manufactured by Canadtian Solar, was selected for use on the Richmond Building as it has the highest rated power for its size compared to other manufacturers. Several panels were considered, including the Jinko Tiger Neo 650W; with a higher rated efficiency, output and power density. However, it was discovered through the IESVE simulation that these panels resulted in a lower space efficiency on the limited available roof space compared to the CS6W-575T. The wall-mounted solar panels were identical to the units mounted on the roof, allowing for standard installation equipment and maintenance, reducing the complexity of wiring and other integration issues. The CS6W-575T has a unit price of £99 per panel including VAT [57]. The key technical specifications of the Canadian Solar CS6W-575T panel are summarised in Table 5.

Table 5: Key technical specifications of the selected solar panels.

Rated Power (W)	**Efficiency (%)**	**Dimensions L × W × H (m)**
575	22.3	2.278 x 1.134 x 0.030

Modelling Roof-Mounted Panels: The roof-mounted solar system was modelled within IESVE, building on the previously mentioned energy model. This served two purposes - to validate the results of the initial Python program simulation, and to improve accuracy by considering environmental shading and elevation of panels. 250 CS6W-575T monocrystalline solar panels were modelled on top of the designated roof areas, avoiding known obstructions such as roof lights. A detailed solar shading analysis of the panels was completed within IESVE to account for local shading effects, with the results of this, along with the panel layout, shown in Figure 14. This solar shading analysis was included in a new IESVE dynamic simulation for the building with the same inputs as described in Section 2.3. The panels are placed in rows, with panels in adjacent rows placed 1.43 m apart (measured from the base of each panel). Following simulation, it was found that 250 panels were able to produce approximately 113.87 MWh annually. This corresponds to an average normalised capacity of 0.452 MWh annually per panel.

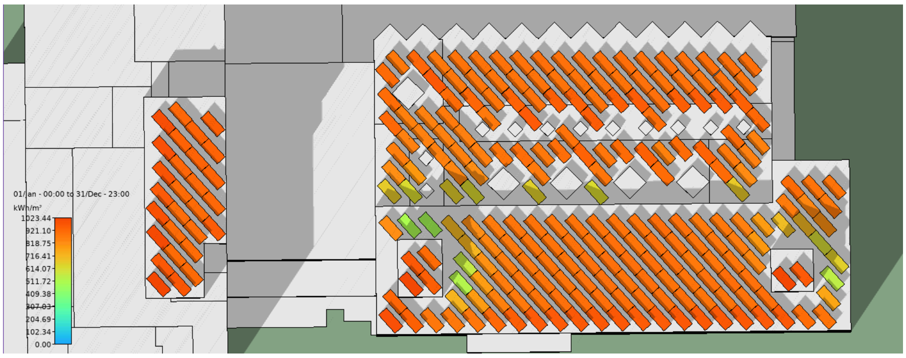

Figure 14: Solar exposure map of roof mounted solar panels.

Figure 14 also highlights the energy density of the panels accounting for shading. The yellow and green panels are considered less efficient as they are shaded by higher geometry. Cost is not one of the project's KPIs however, the energy output is and therefore these panels were included in the final calculations.

Modelling Wall-Mounted Panels: The IESVE software has no function to simulate the output of less conventional, wall-mounted panels in the same manner as for the roof-mounted system. To compensate, generation from wall-mounted panels was simulated using a Python program utilising the pvlib package [58] and the same weather file as the IESVE simulation. This generated 16.5 MWh annually from 44 panels placed as shown in Figure 15. This corresponds to around 0.375 MWh annually per panel, 17% less than the roof-mounted panels.

Figure 15: Location of wall-mounted solar panels on the South building

The hourly roof-mounted panel generation obtained from IESVE was then added to the hourly wall-mounted panel generation from the Python script to obtain a total panel generation value. Although the two systems were modelled through different means, they were modelled with the same panel, weather data and building orientation and therefore considered comparable. The key impacts of implementing roof and wall-mounted solar panels are highlighted in Table 6.

Table 6: Key impacts of implementing roof and wall-mounted solar panels.

Electricity Demand (MWh)	**Roof-mounted Panel Generation (MWh)**	**Wall-mounted Panel Generation (MWh)**	**Total Panel Generation (MWh)**	**Amount Saved Annually (£)**
1515.85	113.88	16.55	130.42	29162.73

Implementation Strategy: A site visit was conducted to assess the current ease of roof access on the Richmond building site. There is easy direct access to the North building roof via two roof access hatches, as seen on the left in Figure 2. The majority of roof-mounted panels will be installed on this roof. For the South building roof, panels are proposed for installation on the raised part of the roof that can be seen on the right of Figure 2. However, access likely only exists for the rest of the South building roof where most of the HVAC equipment is installed, as seen in satellite images. This means access to the proposed installation site on the South building is more difficult in comparison, and ladders are likely required for this. The same difficulty applies to accessing the top of the roof access hatches on the North building. A ballasted racking system is recommended for the installation of roof-mounted panels, with tilt-up frames to ensure the desired angles of inclination were achieved. A ballasted system uses weights to bypass the need to penetrate the roof structure, allowing for a less intrusive installation process and planning [59]. Scaffolding would be required for the installation of wall-mounted panels [60], with the installation process causing greater disturbance to building users and requiring greater care in installing fixtures to the South wall. Wall-mounted solar panels are easier to maintain than roof-mounted panels, however, they are more expensive due to reinforced mounting and therefore harder to install.

Commercial roofs are estimated to support 135 kg on a 75 cm x 75 cm area [61]. The weight of one panel is 27.6 kg [57] over a larger area than this, due to the panel's dimensions. Therefore it is a reasonable assumption that the Richmond Building will be able to support the panels. Solar panels can have a service life of up to 25 years [62], when adequately maintained every 2 to 4 years [63]. Forms of maintenance include electrical circuit tests, tightening of electrical connections, damage inspections, and panel face cleaning [62].

5.3 Battery Storage Proposal

It was found that the generation exceeded the demand at several points throughout the year. In order to extract the maximum solar panel generation, battery storage was necessary. As seen in Figure 16, this typically occurred on days when the generation was higher than the demand in the morning. A graph showing electrical generation compared with demand can be found in Appendix A.2.

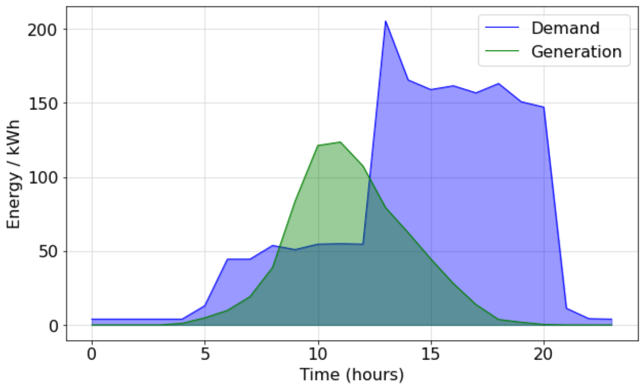

Figure 16: Graph showing electrical generation compared with demand over the course on June 4th.

In order to calculate the number of batteries required, the maximum value of excess energy generation had to be calculated. This was found to be 68.67 kWh over a single hour. However, in the event of a day with particularly high solar irradiance, excess generation may be slightly higher. To accommodate for this, a target battery capacity of 100 kWh was chosen. Furthermore, additional battery storage may be required in the future if more renewable electricity generation sources are installed. Therefore, the LVL 15.4 by BYD [64] was selected due to its scalability. One unit can store 15.36 kWh of energy, with the ability to be scaled up to 64 units, rated at 983 kWh. 7 units were necessary to meet the requirement of 100 kWh of capacity.

Table 7: Key technical specifications of the selected storage batteries.

Capacity (kWh)	**Maximum Scalability (kWh)**	**Dimensions L $\times$ W $\times$ H (m)**
15.36	983	0.650 x 0.575 x 0.500

The LVL 15.4 is a direct current storage system, meaning an inverter is not required for the interface between the BESS and the solar panels. However, an inverter would be required to convert its electrical output to AC, when connecting to the Richmond Building's mains. Of the compatible inverters provided by BYD, a three-phase inverter was chosen over a single-phase inverter, due to its capability of providing higher power discharges. The inverter selected should be capable of transferring the same amount of power as the BESS capacity. Consequently, the Victron Quattro 48/15000/200-100/100 [65] was selected, as it can continuously supply 15 kW of electricity. 7 of these were installed for each of the seven batteries with, cost of each inverter being £2,868.18 including VAT. The IESVE model indicates that 2.3 MWh of photovoltaic panel-generated electricity will be saved from waste per year via battery storage. This excess amount of energy accumulates approximately 99 hours of photovoltaic generation over the year in which generation exceeds the building's electricity demand. This corresponds to 1.13% of the year.

Implementation: The BESS will be located on the roof of the bridge, allowing for a simpler connection to the solar panels, therefore reducing the length of cabling. This reduces the chance of any connection issues, and heat loss due to resistance. The roof is readily accessible via a staircase, allowing for relatively simple installation. In addition to LVL 15.4's natural convection cooling, the roof of the Bridge building is shaded by the rest of the building, providing a lower temperature environment, and ensuring a higher efficiency and longer battery life. As well as this, regular inspections will also extend the BESS's life. Types of inspection include checking the overall battery health, the control system, the thermal management system and the safety systems.

5.4 Potential Grid Access

The primary purpose of the Battery Energy Storage System (BESS) is to serve as a means of energy storage for the solar panel system in the event that generation exceeds demand as described in Figure 16. Additional benefits include the reduction of grid reliance and mitigating the impact of outages. An alternative approach would be to connect the solar array directly to the grid, increasing accessibility to external parties, which may eventually scale into a viable income source for the university as a means to offset panel costs. As well as this there is an installation waiting period, which can take up to 10 years [66]. Delays like these would potentially reduce the confidence of stakeholders funding this project, preventing the Richmond Building from contributing to the university's 2030 net zero carbon strategy [1]. For these reasons, the project opted to store excess energy within internal systems in favour of distributing directly to the grid.

5.5 Proposal Summary

A flowchart summarising the methodology used to size the proposed system is shown in Figure 17 below.

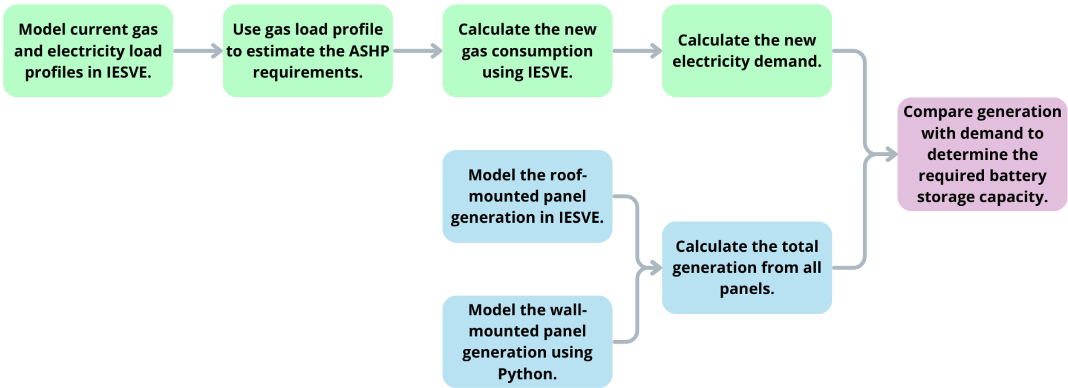

Figure 17: Flowchart highlighting the key stages taken to size the proposed system.

The technical proposal can be summarised as follows:

- The proposal implements the RTXC 220 XE-EC heat pump to contribute to the building's heating demand. This will be used alongside the existing 1440 kW and 720 kW gas boilers which are used as supplementary means to meet the peak demand.
- A total of 294 Canadian Solar CS6W-575T solar panels, 250 roof-mounted and 44 wall-mounted, are installed on the building to compensate for some of the additional electricity demand.
- Finally, for instances where generation exceeds demand, 7 of the LVL 15.4 batteries manufactured by BYD are installed on-site to ensure no generated electricity goes wasted.

A new schematic of the site was created to show the installation sites for these proposals, and is shown in Figure 18 below.

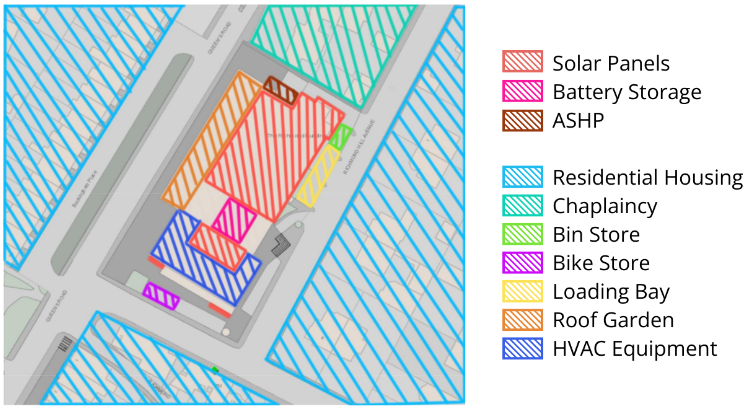

Figure 18: Schematic diagram of the site with the proposed changes adapted from [4].

6 Compliance

The technical proposal is evaluated against the KPIs selected in Section 3 along several dimensions highlighted in Figure 7. In a broader context, these KPIs are derived from their compliance and alignment with notable objectives. These targets ensure the proposal adheres to recognised standards.

At the highest level, the project prioritises being conducive to the University of Bristol's Net Zero CO_2 Scope 1 and Scope 2 emissions [1]. For other general dimensions of sustainability, the project considers alignment with the United Nations Sustainable Development Goals (SDGs) [67], in particular SDGs 7, 12, 13, and to some extent, 15.

More practical guidelines for implementation include the integration of ISO 14040 [68] for systematic management with an environmental emphasis. Additionally, in the UK, the installation of components in buildings is governed by specific regulations, even if these installations are considered permitted developments. A thorough assessment was conducted according to some key guidelines shown in Appendix A.3 [69] [70] [71]

In practice, other regulations including health and safety practices during installation [72], and routine quality assurance plans should be considered. Subsequent Environmental Impact Assessment (EIA) [73] and Life Cycle Assessment (LCA) frameworks should also be applied to operational data for more accurate analysis. In this report, preliminary calculations were applied.

7 Project Financing

The primary focus is tied to energy savings with the demand profile showing little to no excess demand available for consistent exports and the scale of Capital expenditure (CAPEX) required is calculated to be at a modest scale. The implications limit the relevance of specific mechanisms of financing. For instance, the project would lack viability for off-taker parties offering Power Purchase Agreements (PPAs) [74] or eligibility for Export Guarantees (SEG)[75]. comprehensive evaluation of the different financing mechanisms is outlined in Table 8.

Table 8: Project financing mechanisms weighted matrix.

Option	Upfront CAPEX Potential	Qualification	Repayment Obligation	Availability	Total
Weight	0.35	0.35	0.1	0.2	1
University Grants	4	5	5	4	4.45
Regional Incentives	3	4	5	4	3.75
Private Sector Loans	4	4	3	5	4.1
Boiler Upgrade Scheme	2	3	4	2	2.55
Government Subsidies	2	2	5	2	2.3
Green Bonds	5	2	2	2	3.05
Corporate Sponsorship	3	3	5	2	3

Table 8 shows that the university itself presents viable options for supporting the project, often in the form of grants due to its interests aligning with institutional sustainability goals. However, when compared to the 2023 fiscal year financial reports [76], the initial CAPEX may represent a significant financial burden, necessitating the exploration of alternative funding mechanisms. By engaging with private sector organisations such as Salix

Trust [77], the project can access interest-free loans designed to cover the CAPEX for public sector projects. Unlike university grants, which do not require repayment, Salix Trust loans must be repaid over a period of 4-6 years.

For the proposal, the recommendation is to explore a combination of both private sector loans and the university retained earnings as a financing mechanism.

8 Impact Analysis

For general business projects, Triple Bottom Line (TBL) [78] analysis is typically cited as a common framework, evaluating a project over economic, social, and environmental dimensions. The framework was modified to more closely align with the KPIs; with less emphasis on profit generation and more towards sustainability. As such, it was deemed appropriate to include elements of the Life Cycle Sustainability Assessment (LCSA) [79] , especially when quantifying the broader environmental impacts. Specific analysis for each dimension was carefully considered and justified to ensure concise adherence to MECE principles [80].

8.1 Environmental Impact:

LCA was applied to consider the project's environmental impact throughout its whole life cycle [81]. By considering sustainability from the context of cradle-to-grave operations, LCA directly addresses SDG 12's goals of ensuring sustainable consumption. The following analysis is highly generalised using standard data for the Life Cycle Inventory analysis (LCI) at each stage of its lifecycle.

For each of the proposed components, the operational scope of LCA was limited to the useful life of the solar panel array, as it is the longest-lasting component. This ensures a comprehensive evaluation. Analysis beyond this period was not considered as it can be assumed that future installations will incorporate more advanced technologies as trends have shown increasing panel efficiencies in recent decades [82], meaning any further analysis would be rendered redundant.

The LCA also defines a functional unit [81], for which both the absolute values and a levelised value to the output generated were used to allow direct comparison against the benchmark grid carbon intensity. Two indicators of environmental impact were measured; measured GHG offset [83] and the abiotic resource depletion (ARP) factor [84]. By the primary objectives of SDG 13, and general net-zero carbon emission targets set, the GHG analysis was limited to CO_2 emissions.

LCI used data sourced from industry reports and scientific studies, including the International Energy Agency (IEA) PVPS Task 12, the National Renewable Energy Laboratory (NREL), and Fraunhofer Institute for Solar Energy Systems [85] [86] [82]. A full Table including values for each corresponding process is provided in Figure 30 Using the table, a levelised carbon offset 42.28 $kgCO_2$-eq/kWh is avoided, demonstrating that the system produces more clean energy than the emissions generated during its production, transportation, installation, and disposal phases. For the solar panel and battery system, most carbon-intensive processes are found in material extraction. In contrast, the operational carbon emissions are highest for the ASHP system, due to its partial reliance on the grid.

Figure 25 illustrates the cradle-to-grave LCA analysis for absolute carbon equivalent emissions of the system over its operational period. When considering the total lifecycle carbon emissions of the entire system, each component was standardised to account for different lifespans, number of units and grid benchmarks. For instance, to weigh the contributions of varying lifespans, a proportional adjustment based on the fraction of the new asset's contribution along with a replacement factor based on the initial manufacturing cost was added. All calculations were levelised to the energy output of the total system, leading to a 25-year scaled emission of 6,420,550 $kgCO_2$-eq.

Compared with the base emission, using the equivalent energy as if it were drawn from the grid. Taking the current electrical emission factor of 0.233 $kgCO_2$-eq/kWh and the gas heating factor of 0.0548 $kgCO_2$-eq/kWh, the levelised 25-year benchmark emission was calculated to be 4,387,950 $kgCO_2$-eq. This yields a value of 236,778.313 $kgCO_2$-eq saved by the implementation of the system.

An ARP was also applied as a second metric in the LCA framework to provide insight towards the nature of the materials being extracted and the components contributing to non-renewable resource depletion. Unlike carbon offsets, the functional unit of ARP is the quantity of abiotic resource use - typically considering only the manufacturing and recycling offset contributions - measured by normalising to the scarcity of antimony kgSb-eq. Each raw material is normalised to abiotic depletion factors α taken from the GaBi database [87] such that the total ARP impact for each component can be described as in Equation 5 below.

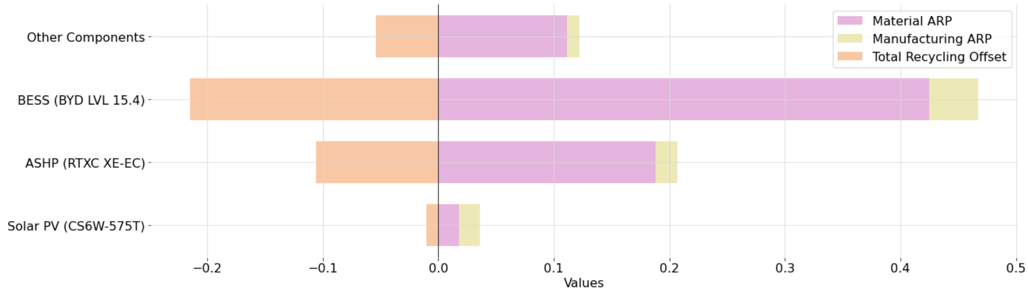

Figure 19: Absolute ARP Values

$$ARP_i = N(\sum_j \alpha_j m_{i,j} + \lambda \sum_j \alpha_j m_{i,j} - \sum_j \rho_j \alpha_j m_{i,j}) \tag{5}$$

for each component i, comprised of j raw materials. N is the number of units, and ρ and λ the recovery offset and manufacturing coefficients respectively. The α and ρ [87] used for each raw material is listed in Table 13. The absolute ARP for each component is shown in Figure 19.

When levelised to the output kWh, the Solar Panel ARP was 0.00047 kgSb-eq/kWh, the heat pump was 6.547e-0.8 kgSb-eq/kWh, with the battery was 0.00823 kgSb-eq/kWh. Both levelised and absolute ARP graphs show the storage system contributes significantly to the total installation ARP. This is likely due to the large quantities of Lithium metal present in each unit, with each kg of Lithium having a depletion factor $\alpha = 0.3$, significantly higher than other resources used by other components.

The majority of levelised carbon emissions arise from the solar panel material extraction and operational stages. While the implementation of the system itself is designed to address the operational emissions, the focus can shift to mitigating the environmental impacts of raw material extraction. To enhance sustainability in extraction, measures such as ensuring supply chain transparency through partnerships with certified suppliers [88] and regulated mining techniques are practised before sourcing panels [89].

Effective end-of-life management is especially important for the battery system in mitigating its large abiotic depletion footprint. One approach is to incorporate second-life applications, where less efficient or used batteries are repurposed for less energy-demanding roles within the Richmond Building. As with initial implementation, repurposed batteries also require compliance with specific regulations, especially for guaranteeing the safety of second-life systems [90]. In alignment with SDG 12, facilitating a circular economy for battery waste management, the university may directly integrate emerging techniques such as direct cathode recycling [91] for improved recovery of high-α materials.

8.2 Economic Impact

The following financial feasibility of the project was evaluated over its operational lifecycle. The Net Present Value (NPV) [92] framework was applied to assess the overall viability of the proposal, measuring its payback period with the cash flow represented as the value of monetised carbon offset against initial CAPEX and running operational expenditures (OPEX). The Levelised Cost of Energy (LCOE) was reported to measure the economic efficiency of implementation as a comparative metric against the baseline grid, levelised per energy output. Additionally, a cost-benefit analysis was conducted to extend economic evaluation beyond monetised GHG savings by including intangible benefits.

The upfront CAPEX for each component included the unit cost with added installation costs for a conservative estimate [55] [93] [94] [95]. This meant a CAPEX of £88,200, £150,000, and £32,900 for each of the solar panels, the ASHP, and the BESS respectively. An additional cost of £15,000 was factored for inverters and other miscellaneous components such as wiring and controllers. OPEX and other fixed costs are summarised in Table 9.

Table 9: Fixed expenditures for NPV analysis

Fixed Expense	Solar (£)	ASHP (£)	BESS (£)	Other (£)
CAPEX	88,200	150,000	32,900	15,000
OPEX	9,020	30000	1,400	40
Replacement	0	90,600	131,600	24
Decommission	5,917	10,000	2,800	2,000
Scrap Offset	5,622	2,200	1,050	500
Insurance	152	600	1,200	20

8.2.1 Net Present Value Analysis (NPV)

The NPV analysis is a foundational framework which comprehensively summarises the influence of the time value of money and the project's monetary value against the investment which is especially critical for the long-term paybacks associated with renewable projects. By capturing all relevant future expenses, savings and discounting to the present value, the project's lifetime net value can be considered viable if the NPV is greater than or equal to 0 [92]. In general, the NPV can be calculated using Equation 6:

$$NPV = \sum_{i}^{T} \frac{CF_i - \text{OPEX}}{(1+r)^i} - \text{CAPEX} \tag{6}$$

where CF_i is the cash flow in £ for the i^{th} annum. For the technical proposal, cash flow can be considered as the combination of monetised energy savings not drawn from the grid by the installation of the new system. The discount factor, $r = 4\%$, was used and calculated using the Weighted Cost of Capital (WACC), as shown in Equation 7 [96].

$$r = f_d r_i + f_e(r_f + r_p) \tag{7}$$

where f_d and f_e represent the proportion of CAPEX funded by debt and equity respectively, and r_i, r_f, r_p represent the opportunity costs associated with interest, risk-free rates, and risk premium respectively. As a conservative estimate, the project assumed total equity financing. Other assumptions used are listed in Table 12 [97] [41] [98].

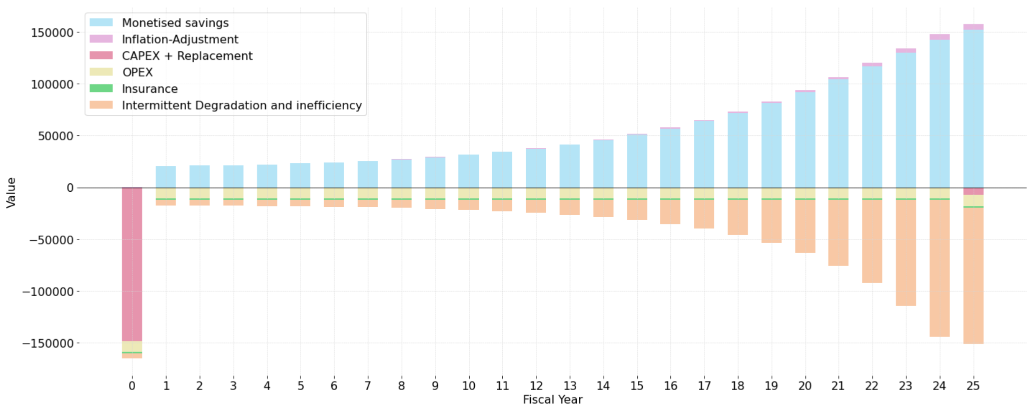

Figure 20: Annual cash flow over the operational period.

With the annual cash flows in Figure 20, the time-discounted project value was calculated over 25 years, calculating a conservative project value estimate of NPV = £ 27,790. This leads to a net positive outcome and long-term financial feasibility. With an average internal return on investment of 8.347%, the project is expected to have a payback period of 19 years. A rudimentary sensitivity analysis was performed for validation, varying the r and the annual gas increase rates as volatile parameters. The results are shown in Figure 29.

8.2.2 Levelised Cost of Energy Analysis (LCOE)

LCOE was used to complement NPV, levelising the present value of the project's overall expenses to the output generated for comparison without implementation [99].

$$LCOE = \frac{NPV_c}{\sum_{i=1}^{T} \frac{E_o}{(1+r)^i}} \tag{8}$$

where NPV_c is the present value of total project costs, and E_o is the total energy output by the system. From this, an LCOE of £0.16 /kWh was found. This can be compared against the baseline scenario for which this energy is drawn from the grid subject to annual rate increases with LCOE of £1.61 /kWh. The physical interpretation is, that for every unit kWh of energy displaced, the system saves £1.45 through implementation.

8.2.3 Cost-Benefit Analysis

CBA [100] extends the NPV assessment by holistic inclusion of intangible benefits and costs across other dimensions of the KPI. This is especially advantageous for considering the monetised value produced by the project with respect to the sustainability of the project. Equation 9 below incorporates the discounted value of intangible benefits and costs, of which some key considerations are listed in Figure 28.

$$CBA = \sum_{i}^{T} \frac{\text{Benefits} - \text{Costs}}{(1+r)^i} \tag{9}$$

An example of an intangible economic cost is the opportunity cost of a university endowment, referring to the potential returns the university foregoes by using retained earnings for this project over other investments such as research or infrastructure. This was expected to grow at a rate of 4% per annum [76]. Overall, the CBA results showed the net intangible contribution to the project value of £15,366.84, which is considerable compared to studies of similar scale [101].

Ultimately, economic analysis revealed a positive NPV, indicating the project's financial feasibility even under conservative assumptions. The LCOE demonstrates a monetised energy output efficiency nine times higher than baseline grid reliance and indicates the project's long-term cost-effectiveness despite factoring in all accumulated expenditures. The CBA highlights significant positive contributions when considering non-monetary values.

8.3 Social Impact

Unlike economic and environmental metrics with defined indicators, social impacts are often subjective, and should ideally be performed by qualitatively assessing the project's reception.

On a smaller scale, the impacts on the local community can be assessed through satisfaction and awareness metrics by conducting surveys. While the effects of reduced gas dependence on air quality are not directly felt by the community, contribution strategies may include redirecting secondary cost savings for local initiatives [102] in the Clifton area, creating a means for heightened public perception over a period of time.

Within the campus, educational engagement can be measured quantitatively by tracking the number of research projects or student theses derived from the system, whether within the University of Bristol or from any institution. As a potential strategy to guarantee awareness, the system may be incorporated into teaching material directly as a case study [103] across multiple curricula, promoting further research and exposure through publications which can share insights into specific performance metrics.

While the project does not contribute directly to international policies, it is valuable to ensure the project maintains alignment with global sustainability and energy equity policies. Although this report only mapped UN's SDGs, other key global sustainability frameworks can be assessed. For future scaling of the project, where grid access can be recommended, internal policies such as IRENA [104] and the UN SE4ALL [105] initiative can serve as baselines for encouraging accessibility through electrification of rural communities such as Barton Hill. With Scope 1 and 2 emissions being targetted, the university will be in a position to leverage the completed project as a pilot model in efforts to advocate for broader carbon offset initiatives and promote energy accessibility.

9 Final Proposal Evaluation

Finally, the full technical proposal is evaluated against the four KPIs defined in Section 3.

Technical Operation: Through implementing the ASHP and solar panels on the Richmond Building, a net total of 1772.42 MWh of energy is saved annually. Over the course of a 25 year project life-span, this is 44.31 GWh of energy saved. Of this, 57.5 MWh of energy was saved from going to waste over a 25 year project life-span. This is 1.76% of the solar generation over the project life-span. The ASHP has excellent efficiencies of 467% for cooling and 329% for heating and the BESS has a good roundtrip efficiency of 83%. Although the solar panels have a lower efficiency of 23%, this is still a large overall efficiency for the system.

Economic Performance: Using the £29,162 figure, and key assumptions including a discount rate of 4%, the project has been determined to be financially viable, with a NPV of £27,790, exceeding the break-even threshold of 0 with an estimated payback period for the project is 19 years. Over a 25-year lifespan, the displaced energy cost was calculated to be £0.16/kWh, significantly lower than the £1.61/kWh associated with grid energy. Additionally, the CBA of tangible benefits for the entire system showed a net positive, evaluated at £15,366.40 highlighting the significant value of indirect environmental and social benefits contributing to sustainability.

Environmental Impact: The lifecycle analysis of the system highlights both significant environmental impacts, particularly in terms of carbon offset and abiotic resource depletion. Over its lifecycle, the system is projected to offset a total of 236,778.313 kgCO_2-eq, equating to 42.28 kgCO_2-eq avoided per kWh of energy output. However, abiotic resource depletion presents a notable concern. When normalised to energy output, the Solar Panel ARP was 0.00047 kgSb-eq/kWh, the heat pump 6.547e-08 kgSb-eq/kWh, and the battery 0.00823 kgSb-eq/kWh. While the project demonstrates a net positive carbon offset, a large ARP factor is observed, particularly in the raw material extraction for solar panels and lithium depletion in batteries. These findings provide insights into the trade-offs between carbon emissions reduction and resource sustainability in renewable energy systems.

Social Good: Among the most important social impacts of this project are its contribution to local community awareness and satisfaction, as well as its role in advancing educational engagement with its position as part of an institutional initiative. The system additionally provides opportunities for research projects and student theses, both within the University of Bristol and externally. Benchmarking against the UN's SDGs show alignment and contribution towards major net zero targets, and SDGs 7, 11, 12, and 13. The project's nature addresses clean energy practices, and climate action, demonstrating positive social impacts.

To conclude, this report provides a renewable energy proposal for the Richmond Building that can help the University of Bristol achieve its goals of reducing Scope 1 and 2 emissions. The implementation of an ASHP, solar panels and a BESS reduce the overall energy demand of the building by 1772.42 MWh annually, a 52% decrease. The system indicates significant reductions in carbon offset and abiotic resource depletion without aversely impacting the financial feasibility of the project, as a net positive NPV and CBA over the lifespan of the project was still achieved.

References

[1] U. of Bristol, "Climate action and net zero carbon," [Accessed: 19-Nov-2024]. [Online]. Available: https://www.bristol.ac.uk/sustainability/net-zero-carbon-bristol/

[2] G. protocol, "Faq," [Accessed: 19-Nov-2024]. [Online]. Available: https://ghgprotocol.org/sites/default/files/2022-12/FAQ.pdf

[3] U. of Bristol, "Energy, carbon and water," [Accessed: 19-Nov-2024]. [Online]. Available: https://www.bristol.ac.uk/sustainability/doing/energy-carbon-water/

[4] "Know Your Place - Bristol." [Online]. Available: https://maps.bristol.gov.uk/kyp/?map

[5] F. C. B. Studios, "Transforming a tired structure into a multi-use university building," [Accessed: 19-Nov-2024]. [Online]. Available: https://fcbstudios.com/projects/richmond-building-university-of-bristol/

[6] J. Daly, "University of Bristol Building Data," [Online], University of Bristol, accessed: [1-oct-2024].

[7] M. Edis, "BREEAM-005104927 Issue 01," https://www.bristol.ac.uk/media-library/sites/green/documents/policy/breeam-certificate-richmond.pdf, BRE Global Ltd., 2014, certificate issued by BRE Global Ltd.

[8] GBRI, "BREEAM Explained: Understanding Green Building Ratings and Certification," Jan. 2024. [Online]. Available: https://www.gbrionline.org/breeam-rating-system/

[9] IESVE, "Software validation," [Accessed: 19-Nov-2024]. [Online]. Available: https://www.iesve.com/software/software-validation

[10] T. B. R. Establishment, "Internationally Approved ENE 01 Calculation Software," https://kb.breeam.com/knowledgebase/internationally-approved-ene-01-calculation-software/, 2018.

[11] H. Department for Levelling Up and C. (DLUHC), "Approved national calculation methodologies and software programs for buildings other than dwellings," [Accessed: 19-Nov-2024]. [Online]. Available: https://www.uk-ncm.org.uk/filelibrary/NCM_approved_software_programs_for_buildings_other_than_dwellings.pdf

[12] "NCM Modelling Guide: 2021 Edition England," https://www.uk-ncm.org.uk/filelibrary/NCM_Modelling_Guide_2021_Edition_England_15Dec2021.pdf, 2021, accessed: 2024-12-02.

[13] U. of Bristol Campus Division, "University of Bristol Floorplans - Richmond Building," University of Bristol, 2014, [Accessed 1-Oct-2024].

[14] Chartered Institution of Building Services Engineers, *CIBSE Guide A: Environmental Design.* London, UK: Chartered Institution of Building Services Engineers, 2015, accessed: 2024-12-02. [Online]. Available: https://www.cibse.org/knowledge-research/knowledge-portal/guide-a-environmental-design-2015

[15] *Approved Document L: Conservation of Fuel and Power.* London, UK: Department for Levelling Up, Housing and Communities, 2021, accessed: 2024-12-02. [Online]. Available: https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l

[16] "University of Bristol Space Temperature Policy," https://www.bristol.ac.uk/media-library/sites/green/documents/policy/space-temperature-policy.pdf, 2018, accessed: 2024-12-02.

[17] "Richmond Building Opening Times," 2024, accessed: 2024-12-02. [Online]. Available: https://www.bristol.ac.uk/students/your-studies/libraries-study-spaces/study-spaces/bristol-su/

[18] "Bristol SU Room Booking System," 2024, accessed: 2024-12-02. [Online]. Available: https://bristolsu.skedda.com/booking

[19] "EPW Map." [Online]. Available: https://www.ladybug.tools/epwmap/

[20] "How to Calculate the Surface Area Required by Solar Panels | RAYmaps," May 2013. [Online]. Available: https://www.raymaps.com/index.php/how-to-calculate-the-area-required-by-solar-panels/

[21] IPCC, "Annex iii," 2014. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf#page=7

[22] E. Waitzman, "Geothermal energy: Potential for heat and power in Great Britain," Jun. 2023. [Online]. Available: https://lordslibrary.parliament.uk/geothermal-energy-potential-for-heat-and-power-in-great-britain/

[23] O. Gordon, "UK's first deep geothermal power plant to be constructed in Cornwall," Aug. 2023. [Online]. Available: https://www.energymonitor.ai/tech/renewables/uks-first-deep-geothermal-power-plant-to-be-constructed-in-cornwall/

[24] B. Sparhawk, "What's The Difference Between OffShore and OnShore Wind Energy?" [Online]. Available: https://stevensec.com/blog/difference-between-offshore-and-onshore-wind-energy

[25] S. Shubham, K. Naik, S. Sachar, and A. Ianakiev, "Performance analysis of low Reynolds number vertical axis wind turbines using low-fidelity and mid-fidelity methods and wind conditions in the city of Nottingham," *Energy*, vol. 279, p. 127904, Sep. 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544223012987

[26] "Wind Energy and Power Calculations | EM SC 470: Applied Sustainability in Contemporary Culture." [Online]. Available: https://www.e-education.psu.edu/emsc297/node/649

[27] O. Ågren, M. Berg, and M. Leijon, "A time-dependent potential flow theory for the aerodynamics of vertical axis wind turbines," *Journal of Applied Physics*, vol. 97, no. 10, p. 104913, May 2005. [Online]. Available: https://doi.org/10.1063/1.1896091

[28] G. W. P. Barrage, “Why the severn estuary?” [Accessed: 3-Dec-2024]. [Online]. Available: https://www.greatwesternpowerbarrage.com/why-severn-estuary#:~:text=The%20Severn%20Estuary%20has%20an,of%20Fundy%20with%2016.3m.

[29] H. Government, “Severn tidal power feasibility study: Conclusions and summary report,” [Accessed: 3-Dec-2024]. [Online]. Available: https://assets.publishing.service.gov.uk/media/5a79677fed915d07d35b5389/1._Feasibility_Study_Conclusions_and_Summary_Report_-_15_Oct.pdf

[30] RSPB, “The severn estuary,” [Accessed: 2-oct-2024]. [Online]. Available: https://www.rspb.org.uk/helping-nature/what-we-do/influence-government-and-business/casework/the-severn-estuary

[31] S. Barry, “New plans for a severn barrage generating 10% of the uk’s electricity needs,” [Accessed: 2-oct-2024]. [Online]. Available: https://www.business-live.co.uk/economic-development/new-plans-severn-barrage-generating-23356609

[32] Z. West, “Over the weir – new crowdfunder!” [Accessed: 1-oct-2024]. [Online]. Available: https://zerowest.org/over-the-weir-new-crowdfunder/#:~:text=The%20Netham%20Weir%20project%20is%20a%20modest%2C%20but,GWh%20a%20year%2C%20enough%20electricity%20for%20250%20homes.

[33] B. E. Cooperative, “Bristol community hydro scheme,” [Accessed: 1-oct-2024]. [Online]. Available: https://bristolenergy.coop/wp-content/uploads/2021/01/3-BEC-hydro-presentation-19-01-21.pdf#:~:text=cost,Âč2.39m

[34] fxstageadmin, “How Piezoelectric Sensors Work? - APC International,” Feb. 2024. [Online]. Available: https://www.americanpiezo.com/blog/how-piezoelectric-sensors-work/

[35] R. R. Moussa, W. S. E. Ismaeel, and M. M. Solban, “Energy generation in public buildings using piezoelectric flooring tiles; A case study of a metro station,” *Sustainable Cities and Society*, vol. 77, p. 103555, Feb. 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2210670721008210

[36] S. J. Singleton, S. E. Keating, S. L. McDowell, B. A. Coolen, and J. C. Wall, “Predicting step time from step length and velocity,” *Australian Journal of Physiotherapy*, vol. 38, no. 1, pp. 43–46, 1992. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S000495141460550X

[37] “Ground Source Heat Pumps: Advantages and Disadvantages.” [Online]. Available: https://www.greenmatch.co.uk/ground-source-heat-pump/pros-and-cons

[38] “Ground Source Heat Pump Cost | How Much Does a Ground Source Heat Pump Cost? | Green Energy Compare.” [Online]. Available: https://www.greenenergycompare.com/ground-source-heat-pump-cost

[39] “Air Source Heat Pump Efficiency,” 2024, accessed: 2024-12-02. [Online]. Available: https://www.endotherm.co.uk/air-source-heat-pump-efficiency/

[40] “Boiler Efficiency Explained: How Much Money You Could Save,” 2024, accessed: 2024-12-02. [Online]. Available: https://www.ovoenergy.com/guides/energy-guides/boiler-efficiency

[41] ofgem, “Energy price cap,” [Accessed: 1-Dec-2024]. [Online]. Available: https://www.ofgem.gov.uk/energy-price-cap

[42] S. Solar, “Flat plate collectors vs evacuated tubes,” [Accessed: 17-oct-2024]. [Online]. Available: https://www.simplesolar.ca/flat-plate-collectors-vs-evacuated-tube-collectors.html#:~:text=Side%20by%20side%20tests%20in%20winter%20and%20in,plate%20collector%20by%202.5%20times%20in%20the%20summer.

[43] A. The Univeristy of Queensland, “Concentrating photovoltaic array,” [Accessed: 7-oct-2024]. [Online]. Available: https://solar-energy.uq.edu.au/facilities/st-lucia/concentrating-photovoltaic-array

[44] “Modern Gas Boiler Efficiency: How Efficient Are They?” 2024, accessed: 2024-12-02. [Online]. Available: https://www.greencentral.co.uk/guides-and-advice/modern-gas-boiler-efficiency/

[45] “UltraGas D Double Boiler - Larger Outputs up to 1000 kW,” 2024, accessed: 2024-12-02. [Online]. Available: https://www.hoval.co.uk/en_GB/Replaced-products/Heating-technology/Products/UltraGas-D/p/B_ultragas-double-boiler-larger-1000

[46] G. PIQ, "Energy storage system efficiency," [Accessed: 30-Nov-2024]. [Online]. Available: https://gridpiq.pnnl.gov/v2-beta/doc/technologies/es/es-efficiency/#:~:text=The%20round%20trip%20efficiency%20(RTE,the%20incurred%20losses%20are%20low.

[47] U. o. M. Centre for Sustainable systems, "Hydrogen factsheet," [Accessed: 4-Dec-2024]. [Online]. Available: https://css.umich.edu/publications/factsheets/energy/hydrogen-factsheet

[48] R. A. of Engineering, "The role of hydrogen in a net zero energy system," [Accessed: 30-Nov-2024]. [Online]. Available: https://raeng.org.uk/media/tkphxfwy/the-role-of-hydrogen-in-the-net-zero-energy-system.pdf

[49] H. Newsletter, "How much co2 is produced from steam methane reforming?" [Accessed: 30-Nov-2024]. [Online]. Available: https://www.hydrogennewsletter.com/how-much-co2-is-produced-from-steam-methane-reforming/#

[50] Ossila, "How is solar energy stored? energy storage and solar panels," [Accessed: 24-oct-2024]. [Online]. Available: https://www.ossila.com/pages/how-is-solar-energy-stored#:~:text=Large%20amounts%20of%20solar%20energy%20produced%20by%20solar,include%20flywheels%2C%20compressed%20air%2C%20or%20pumped%20hydro%20storage.

[51] planete energies, "Flywheel energy storage," [Accessed: 24-Oct-2024]. [Online]. Available: https://www.planete-energies.com/en/media/article/flywheel-energy-storage#:~:text=%2D%20Limited%20energy%20storage%20time%20of,batteries%20and%20pumped%2Dstorage%20systems.

[52] E. A. F. S. O. Energy, "Thermal energy storage," p. 22, [Accessed: 1-Dec-2024]. [Online]. Available: https://ease-storage.eu/wp-content/uploads/2023/09/2023.09.26-Thermal-Energy-Storage_for-distribution.pdf

[53] J. Chu, "A new heat engine with no moving parts is as efficient as a steam turbine," [Accessed: 1-Dec-2024]. [Online]. Available: https://news.mit.edu/2022/thermal-heat-engine-0413#:~:text=More%20than%2090%20percent%20of,there%20and%20reliably%20generate%20electricity.âĂİ.

[54] "RTXC Air-to-Water Heat Pump," 2024, accessed: 2024-12-02. [Online]. Available: https://steelsoft.rs/wp-content/uploads/2024/10/RTXC_Air-to-Water_Heat_Pump.pdf

[55] T. C. Trust, "Air source heat pumps: A guide to installation and costs," 2024. [Online]. Available: https://www.carbontrust.com/resources/air-source-heat-pumps-guide

[56] Home Serve, "Air source heat pump servicing: A complete guide," 2024. [Online]. Available: https://www.homeserve.co.uk/knowledge-hub/energy-saving-advice/heat-pump-servicing/

[57] B. Solar, "Canadian solar inc cs6w-575t," [Accessed: 24-oct-2024]. [Online]. Available: https://www.bimblesolar.com/solar/large-panels/575w-canadian-solar-panel

[58] "User Guide — pvlib python 0.11.1 documentation." [Online]. Available: https://pvlib-python.readthedocs.io/en/stable/user_guide/index.html

[59] "Flat roof mounting systems - ballasted," 2024, accessed: 2024-12-05. [Online]. Available: https://www.sflex.com/en/flat-roofs/ballasted

[60] T. Lebreton, "Wall Mounted Solar Panels: The Complete Guide," Apr. 2023. [Online]. Available: https://www.theecoexperts.co.uk/solar-panels/wall-mounted

[61] roofing admin, "Commercial flat roof: How much weight can it hold?" Apr. 2022. [Online]. Available: https://roofingmattersgroup.com/commercial-flat-roof-how-much-weight-can-it-hold/

[62] Zuper, "Solar maintenance checklist 2024," 2024. [Online]. Available: https://www.zuper.co/blog/solar-maintenance-checklist

[63] SolarReviews, "Solar panel maintenance: Everything you need to know," 2024. [Online]. Available: https://www.solarreviews.com/blog/solar-panel-maintenance-everything-you-need-to-know

[64] BYD, "Battery-box premium lvl," [Accessed: 1-Dec-2024]. [Online]. Available: https://www.bimblesolar.com/docs/BYD/200122_Premium_Datasheet_LVL%20V1.0%20EN.pdf

[65] Victron, "Victron quattro 48/15000/200-100/100," [Accessed: 1-Dec-2024]. [Online]. Available: https://www.bimblesolar.com/Victron-Quattro-15Kw?srsltid=AfmBOorlzxxdPxy8bFp-s_gpvN2rqjk4S7kWlAE57BOBCPy4bVyRIM4q

[66] L. Energy, “Connecting to the grid in the uk: Ultimate guide,” [Accessed: 8-Nov-2024]. [Online]. Available: https://lumifyenergy.com/blog/connecting-to-the-grid/#:~:text=The%20entire%20two-step%20process%20runs%20for%20approximately,12%20months%20while%20appropriate%20reviews%20are%20carried%20out.

[67] United Nations, “The 17 Goals: Sustainable Development,” 2015. [Online]. Available: https://sdgs.un.org/goals

[68] International Organization for Standardization, “ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework,” https://www.iso.org/standard/37456.html, 2006.

[69] *Eurocode 1: Actions on Structures – Part 1-1: General Actions – Densities, Self-weight, Imposed Loads for Buildings*, ser. BS EN 1991-1-1. London, UK: British Standards Institution, 2002, incorporating Corrigendum No. 1. [Online]. Available: https://www.phd.eng.br/wp-content/uploads/2015/12/en.1991.1.1.2002.pdf

[70] Institution of Engineering and Technology, *Code of Practice for Grid-connected Solar Photovoltaic Systems*, 2nd ed. London, UK: The Institution of Engineering and Technology, 2024. [Online]. Available: https://shop.theiet.org/code-of-practice-for-grid-connected-solar-photovoltaic-systems-2nd-edition

[71] UK Government, “The town and country planning (general permitted development) (england) order 2015,” 2015, available at: https://www.legislation.gov.uk/uksi/2015/596/contents/made [Accessed: Date]. [Online]. Available: https://www.legislation.gov.uk/uksi/2015/596/contents/made

[72] Health and Safety Executive, “Building safety,” https://www.hse.gov.uk/building-safety/index.htm, accessed: 2024-12-04.

[73] E. P. A. (EPA), *Environmental Impact Assessment Guidelines*, Environmental Protection Agency, Washington, DC, 2020.

[74] U. D. of Energy, “Guide to purchasing green power: Power purchase agreements (ppas),” https://www.energy.gov/eere/slsc/guide-purchasing-green-power, 2022.

[75] Ofgem, “Smart export guarantee (seg),” https://www.ofgem.gov.uk/environmental-and-social-schemes/smart-export-guarantee-seg.

[76] University of Bristol, “Annual report and financial statements 2022-2023,” University of Bristol, Tech. Rep., 2023. [Online]. Available: https://www.bristol.ac.uk/media-library/sites/university/documents/governance/Annual%20Report%20and%20Financial%20Statements%202022-2023.pdf

[77] S. F. Ltd, “Phase 4 public sector decarbonisation scheme: Project criteria,” 2024. [Online]. Available: https://www.salixfinance.co.uk/schemes/phase-4-public-sector-decarbonisation-scheme/projectcriteria

[78] J. Elkington, *Cannibals with Forks: The Triple Bottom Line of 21st Century Business.* Capstone Publishing Ltd., 1999.

[79] W. Klopffer, “Life cycle sustainability assessment of products,” *The International Journal of Life Cycle Assessment*, vol. 13, no. 2, pp. 89–95, 2007.

[80] M. . Company, “The mece principle: Mutually exclusive, collectively exhaustive,” 2024. [Online]. Available: https://www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/the-mece-principle

[81] I. Boustead and G. F. Hancock, “A method for assessing the resources and pollution impacts of packaging systems,” *Journal of the Institute of Environmental Sciences*, vol. 15, pp. 13–20, 1972.

[82] S. Philipps and W. Warmuth, “Photovoltaics report,” July 2024. [Online]. Available: https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

[83] M. Finkbeiner, A. Inaba, R. Tan, K. Christiansen, and H. A. Kluppel, “The role of life cycle assessment (lca) in carbon footprinting,” *The International Journal of Life Cycle Assessment*, vol. 11, no. 1, pp. 80–89, 2006.

[84] J. B. Guinée *et al.*, “Handbook on life cycle assessment: Operational guide to the iso standards,” *Springer Science & Business Media*, 2002.

[85] International Energy Agency Photovoltaic Power Systems Programme, “Fact sheet: Environmental life cycle assessment of electricity from pv

systems (2022 update)," 2022. [Online]. Available: https://iea-pvps.org/fact-sheets/fact-sheet-environmental-life-cycle-assessment-of-electricity-from-pv-systems-2022-update/

[86] G. Heath, "Life cycle greenhouse gas emissions from solar photovoltaics," National Renewable Energy Laboratory, Tech. Rep., 2012. [Online]. Available: https://www.nrel.gov/docs/fy13osti/56487.pdf

[87] L. van Oers, A. de Koning, J. Guinée, and G. Huppes, "Abiotic resource depletion in lca," *Road and Hydraulic Engineering Institute, Ministry of Transport and Water*, 2002. [Online]. Available: https://web.universiteitleiden.nl/cml/ssp/projects/lca2/report_abiotic_depletion_web.pdf

[88] A. for Responsible Mining. (2024) Fairmined certification: Ethical gold and responsible mining. [Online]. Available: https://fairmined.org/

[89] R. M. Foundation, "Responsible mining index 2024," 2024. [Online]. Available: https://responsibleminingindex.org/

[90] International Electrotechnical Commission, *IEC 62619: Secondary Cells and Batteries Containing Alkaline or Other Non-Acid Electrolytes — Safety Requirements for Secondary Lithium Cells and Batteries, for Use in Industrial Applications*, Std., 2017. [Online]. Available: https://www.iec.ch/

[91] J. Smith and J. Lee, "Advanced recycling techniques for lithium-ion batteries: Hydrometallurgical and direct cathode methods," *Journal of Sustainable Materials*, vol. 12, no. 3, pp. 45–60, 2024. [Online]. Available: https://doi.org/10.xxxx/jsm.2024.xxxx

[92] F. E. Training, "Net present value (npv) guide: Definition, formula, and calculation," 2024. [Online]. Available: https://www.fe.training/free-resources/corporate-finance/net-present-value-guide/

[93] S. P. Europe, "Guide to battery storage costs and benefits," 2023. [Online]. Available: https://www.solarpowereurope.org/battery-storage-guide

[94] F. Times, "Renewable energy decommissioning: Costs and challenges," 2024. [Online]. Available: https://www.ft.com/content/renewable-decommissioning-costs

[95] GreenMatch, "Solar panel insurance: Coverage and costs," 2024. [Online]. Available: https://www.greenmatch.co.uk/solar-energy/solar-panels/insurance

[96] R. A. Brealey, S. C. Myers, and F. Allen, *Principles of Corporate Finance*, 13th ed. McGraw-Hill Education, 2020, chapter 19: Weighted Average Cost of Capital (WACC).

[97] C. Gollier and J. K. Hammitt, *Workbook 10: Discounting Future Health Benefits for Economic Evaluations*. Lawrenceville, NJ: International Society for Pharmacoeconomics and Outcomes Research (ISPOR), 2014.

[98] N. R. E. L. (NREL). (2024) Photovoltaic panel degradation rates. [Online]. Available: https://www.nrel.gov/pv-degradation

[99] I. R. E. A. (IRENA), "Renewable power generation costs in 2020," 2020. [Online]. Available: https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

[100] A. N. or Organization, "Comprehensive guide to cost-benefit analysis," https://example.com/cba-analysis-guide.pdf, 2024, accessed: December 3, 2024.

[101] J. Smith and J. Doe, "Cost-benefit analysis of renewable energy systems: A case study of a wind turbine installation," *Energies*, vol. 3, no. 5, pp. 943–956, 2024. [Online]. Available: https://www.mdpi.com/1996-1073/3/5/943

[102] F. of the Downs and A. Gorge. (2024) Friends of the downs and avon gorge. [Online]. Available: https://www.friendsofthedowns.org

[103] N. R. E. Laboratory and C. S. University, "Renewable energy: Technical report on advancements and applications," National Renewable Energy Laboratory (NREL), Technical Report NREL/TP-7A40-67540, 2024. [Online]. Available: https://www.nrel.gov

[104] International Renewable Energy Agency (IRENA), "Renewable energy and energy access: Progress and opportunities," 2024. [Online]. Available: https://www.irena.org/

[105] Sustainable Energy for All (SE4ALL), "Sustainable energy for all: Achieving universal energy access by 2030," 2024. [Online]. Available: https://www.seforall.org/

A Appendix

A.1 Suitability

Table 10: Pairwise Comparison matrix to determine the relative importance of the suitability criteria.

Criteria	Site Suitability	Social Impact	Energy Output	Cost	Efficiency	Carbon Footprint	Total	%
Site Suitability	**X**	3	1	2	2	0.5	8.50	22
Social Impact	0.33	**X**	0.5	0.5	2	0.33	3.67	10
Energy Output	1	2	**X**	2	2	0.5	7.50	20
Cost	0.5	2	0.5	**X**	1	0.5	4.50	12
Efficiency	0.5	0.5	0.5	1	**X**	0.5	3.00	8
Carbon Footprint	2	3	2	2	2	**X**	11.00	29
Total	4.33	10.50	4.50	7.50	9.00	2.33	38.17	100
%	11.4	27.5	11.8	19.7	23.6	6.1	100	38.17

Criteria	Weightings ↓ Must add to 100% ↓	Technologies →	Solar Photovoltaics		Wind		Geothermal		Tidal		Hydro-Electric		PiezoElectric	
			score	weighted score	score	weighted score	score	weighted score	score	weighted score	score	weighted score	score	weighted score
Site Suitability	0.22	1	5	1.1	1	0.2	2	0.4	1	0.2	1	0.2	3	0.7
Disruption to Neighbourhood	0.10	2	4	0.4	2	0.2	1	0.1	2	0.2	2	0.2	4	0.4
Electrical Energy Output	0.20	3	3	0.6	2	0.4	1	0.2	4	0.8	4	0.8	1	0.2
Cost	0.12	4	5	0.6	3	0.4	1	0.1	1	0.1	2	0.2	5	0.6
Efficiency	0.08	5	1	0.1	2	0.2	1	0.1	4	0.3	4	0.3	1	0.1
Carbon Footprint	0.29	6	1	0.3	4	1.2	1	0.3	2	0.6	2	0.6	2	0.6
	1													
		Total score for design →	3.0		2.5		1.2		2.2		2.3		2.5	

Figure 21: MCDA matrix used to score the potential electrical generation technologies.

Criteria	Weightings ↓ Must add to 100% ↓	Technologies →	GSHP		ASHP		Electric Boiler		Gas Boiler		Solar Thermal	
			score	weighted score	score	weighted score	score	weighted score	score	weighted score	score	weighted score
Site Suitability	0.22	1	1	0.2	4	0.9	5	1.1	5	1.1	3	0.7
Disruption to Neighbourhood	0.10	2	1	0.1	3	0.3	5	0.5	5	0.5	4	0.4
Heating Capacity	0.20	3	4	0.8	3	0.6	1	0.2	2	0.4	1	0.2
Cost	0.12	4	3	0.4	4	0.5	1	0.1	2	0.2	4	0.5
Efficiency	0.08	5	5	0.4	4	0.3	2	0.2	1	0.1	1	0.1
Carbon Footprint	0.29	6	5	1.4	4	1.2	3	0.9	1	0.3	2	0.6
	1											
		Total score for design →	3.3		3.7		2.9		2.6		2.4	

Figure 22: MCDA matrix used to score the potential heating generation technologies.

Criteria	Weightings ↓ Must add to 100% ↓	Technologies →	Battery Storage		Thermal Storage		Mechanical Storage		Hydrogen Storage	
			score	weighted score	score	weighted score	score	weighted score	score	weighted score
Site Suitability	0.22	1	5	1.1	1	0.2	2	0.4	2	0.4
Disruption to Neighbourhood	0.10	2	5	0.5	3	0.3	2	0.2	1	0.1
Storage Capacity	0.20	3	2	0.4	4	0.8	2	0.4	3	0.6
Cost	0.12	4	3	0.4	4	0.5	2	0.2	1	0.1
Efficiency	0.08	5	5	0.4	3	0.2	4	0.3	2	0.2
Carbon Footprint	0.29	6	2	0.6	3	0.9	1	0.3	5	1.4
	1									
		Total score for design →	3.3		2.9		1.9		2.8	

Figure 23: MCDA matrix used to score the potential energy storage systems.

A.2 Solar Panel Implementation

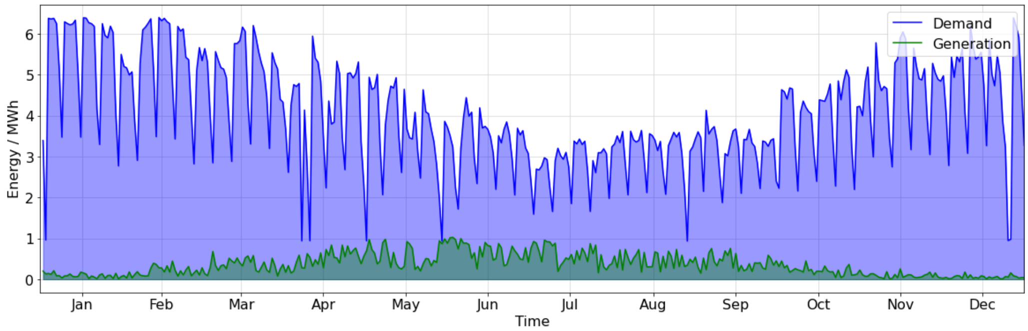

Figure 24: Graph showing electrical generation compared with demand.

A.3 Compliance

Table 11: Building regulations that the proposal must be compliant with.

Installation	Specification	Regulatory Article
Solar Panel Installation	Panels must not protrude more than 200 mm from the roof surface to minimize visual impact.	UK Town and Country Planning (General Permitted Development) Order 2015 (Schedule 2, Part 14, Class A)
	Panels must be installed with appropriate wind and snow load considerations for the roof.	BS EN 1991-1-4: Eurocode 1 (Wind Loads) and BS EN 1991-1-3 (Snow Loads)
	Electrical installations must comply with safety standards, including earthing and DC isolation.	IET Wiring Regulations (BS 7671:2018, Amendment 2:2022)
ASHP	Noise emissions must not exceed 42 dB(A) at 1 meter from the nearest property boundary.	Microgeneration Certification Scheme (MCS 020) and Building Regulations Part E (Noise)
	The unit must be installed on a vibration-isolated base to minimize structural vibrations.	CIBSE Guide A: Environmental Design (Acoustics and Vibrations)
	Refrigerant handling must comply with F-Gas regulations to prevent leaks and environmental harm.	Fluorinated Greenhouse Gases Regulations 2015
BESS	Must be installed in a location with adequate fire resistance, ventilation, and clearance.	BS EN 50272-2: Safety Requirements for Batteries
	The system must include overcurrent protection and meet specific load-bearing requirements.	IET Code of Practice for Electrical Energy Storage Systems
	Installation must adhere to fire safety requirements for thermal runaway mitigation.	UK Building Regulations Approved Document B (Fire Safety)

A.4 Impact Analysis - Environmental

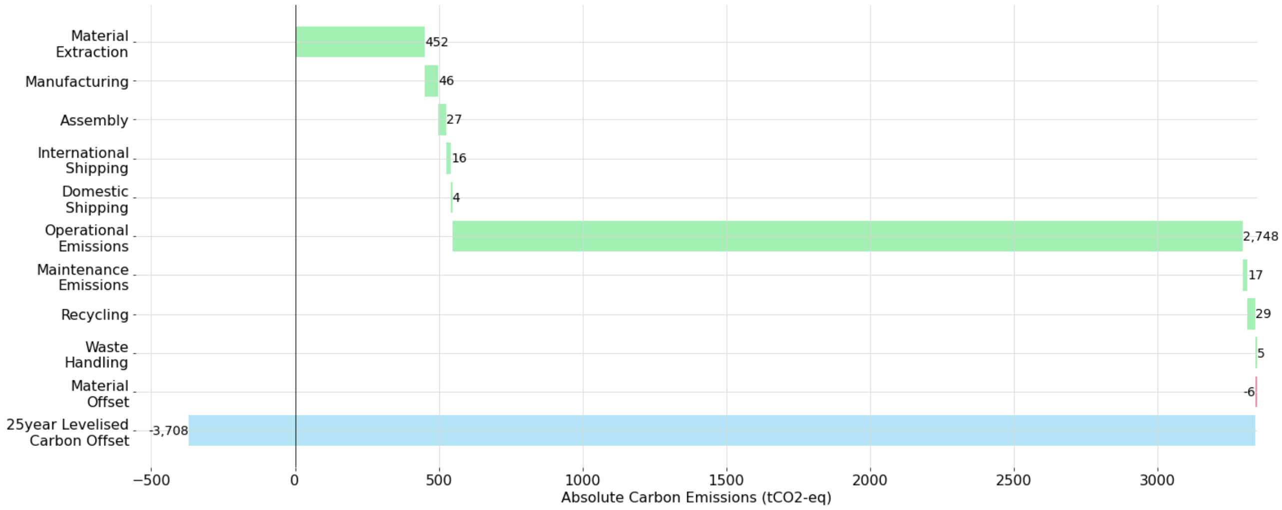

Figure 25: Absolute Life Cycle Carbon Offset Analysis over operational life

A.5 Impact Analysis - Economics

Table 12: NPV Parameter Assumptions

Parameter	Value
Grid electricity rate	0.2236 £/kWh
Grid gas rate	0.183 £/kWh
Annual electricity rate increase	1.05%/year
Annual gas rate increase	1.01%/year
Annual degradation	0.5%/year
Energy output inefficiency	3%/year
Inflation (carbon market + labour)	2%/year
Sensitivity factor	7%

A.6 ARP

Table 13: ARP GaBi Database Depletion potential and Recovery rates

	ARP Potential Factor (GaBi) kg Sb-eq/kg	Recovery Rates
Aluminum	0.0005	0.8
Copper	0.005	0.5
Glass	0.0001	0.9
Iron	0.0001	0.7
Lithium	0.03	0.5
Phosphate	0.0001	0
Refrigerant (R-32)	0.001	0
Silicon	0.0008	0
Steel	0.0002	0.9
Miscellaneous	0.001	0

Fiscal Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Monetised Savings																										
Additional Grid Electrical Cost	0	-122407	-124991	-128970	-134472	-141682	-150845	-162288	-176432	-193822	-215163	-241361	-273591	-313382	-362730	-424256	-501428	-598861	-722737	-881394	-1086166	-1352568	-1701994	-2164180	-2780770	-3610547
Coolings Cost Difference (Grid Adjusted)	0	15706	16038	16548	17254	18179	19355	20823	22638	24870	27608	30969	35105	40211	46542	54437	64339	76841	92735	113093	139368	173550	218385	277689	356804	463274
Gas Cost Difference (Grid Adjusted)	0	127170	129751	133723	139207	146381	155479	166810	180774	197886	218806	244381	275702	314179	361641	420478	493825	585825	701983	849668	1038812	1282887	1600312	2016440	2566434	3299434
Benefits																										
Incentives	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Residual Power Sales	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CAPEX and Replacement																										
CAPEX + Replacement	-148100	0	0	0	0	0	0	0	0	0	-13160	0	0	0	0	-24	0	0	0	0	-20	0	0	0	0	0
Decommission	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-11717
Recycling Offset Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-7371
Annual Expenses																										
OPEX	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760	-10760
Insurance	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	-1432	0
Intermittent Degredation and inefficiency	0	-5001	-5103	-5259	-5476	-5760	-6119	-6567	-7119	-7796	-8624	-9637	-10878	-12404	-14286	-16622	-19536	-23193	-27815	-33697	-41236	-50975	-63654	-80295	-102313	-131695
Inflation-Adjustment	0	145	150	157	166	177	191	208	229	255	286	324	372	430	503	594	708	854	1039	1278	1587	1991	2524	3231	4179	5459
Annual Net Cash Flow	-160292	3421	3654	4007	4487	5104	5868	6794	7898	9200	-2439	12485	14517	16841	19478	22415	25716	29272	33013	36756	40151	42693	43380	40693	32143	-3922
Discounted Cash Flow	-160292	3290	3378	3562	3836	4195	4638	5163	5771	6464	-1648	8110	9067	10114	11248	12446	13730	15028	16296	17446	18324	18735	18305	16510	12540	-1471
Cumulative Discounted Cash Flow	-160292	-157002	-153624	-150062	-146226	-142031	-137393	-132230	-126459	-119996	-121644	-113534	-104467	-94352	-83104	-70658	-56928	-41900	-25604	-8158	10166	28902	47206	63717	76256	74785
NPV	**£27,790**																									

Figure 26: Project Net Present Value Analysis

Fiscal Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Discounted Energy	1515850	1457548	1401489	1347585	1295755	1245918	1197998	1151921	1107617	1065016	1024054	984667	946795	910380	875366	841698	809325	778197	748266	719487	691814	665206	639621	615020	591366	568621
Annual System Costs	-160292	-17048	-17144	-17294	-17502	-17774	-18120	-18551	-19082	-19734	-33691	-21505	-22699	-24166	-25976	-28244	-31019	-34532	-38968	-44611	-51861	-61176	-73323	-89256	-110327	-136995
Additional Supply Grid Electricity Cost	0	-122407	-123692	-124991	-126303	-127630	-128970	-130324	-131692	-133075	-134472	-135884	-137311	-138753	-140210	-141682	-143170	-144673	-146192	-147727	-149278	-150845	-152429	-154030	-155647	-157281
Total Costs	-160292	-139455	-140837	-142285	-143805	-145404	-147090	-148875	-150775	-152809	-168163	-157389	-160010	-162918	-166185	-169926	-174189	-179205	-185160	-192338	-201139	-212022	-225752	-243285	-265974	-294277
Discounted Costs	-160292	-134091	-130211	-126491	-122926	-119511	-116247	-113133	-110169	-107361	-113605	-102237	-99942	-97845	-95968	-94354	-93001	-91999	-91400	-91292	-91797	-93042	-95257	-98707	-103762	-110388
Cumulative Discounted Cost	-160292	-294383	-424594	-551085	-674011	-793522	-909769	-1022902	-1133071	-1240433	-1354038	-1456275	-1556216	-1654061	-1750029	-1844383	-1937384	-2029382	-2120783	-2212074	-2303872	-2396914	-2492172	-2590879	-2694641	-2805029
NPV of System Costs	-2697143																									
LCOE of System Costs (25 years)	**0**	**GBP/kWh output**																								
Supply Grid Electricity Cost	-1515850	-1531766	-1547850	-1564102	-1580525	-1597121	-1613891	-1630837	-1647960	-1665264	-1682749	-1700418	-1718273	-1736314	-1754546	-1772968	-1791585	-1810396	-1829405	-1848614	-1868025	-1887639	-1907459	-1927487	-1947726	-1968177
Discounted Costs	-1515850	-1472852	-1431074	-1390481	-1351040	-1312717	-1275481	-1239302	-1204149	-1169992	-1136805	-1104559	-1073228	-1042785	-1013206	-984466	-956542	-929409	-903046	-877431	-852542	-828359	-804863	-782032	-759850	-738296
NPV of Grid Costs	-27067653																									
LCOE of Grid Costs (25 years)	**2**	**GBP/kWh output**																								

Figure 27: Levelised Cost of Output Energy Analysis for associated project expenses

	Annual Change	Fiscal Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Environmental	1.01%	Reduction in gas consumption	800	808	816	824	833	841	850	858	867	876	885	894	903	912	921	930	940	949	959	968	978	988	998	1008	1018	1028
	0.00%	Reduction in CO2 emissions	600	606	612	618	625	631	637	644	650	657	663	670	677	684	691	698	705	712	719	726	734	741	748	756	764	771
	Terminal	Battery disposal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3500
	Terminal	Panel waste management	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3000
	30.00%	**Intangibility Factor**																										
Health	0.00%	Indirect air quality improvement	50	51	51	52	52	53	53	54	54	55	55	56	56	57	58	58	59	59	60	61	61	62	62	63	64	64
	0.00%	Reduced indoor gas exposure risk	100	101	102	103	104	105	106	107	108	109	111	112	113	114	115	116	117	119	120	121	122	123	125	126	127	129
	80.00%	**Intangibility Factor**																										
Social	0.00%	Noise reduction (Gas Boiler)	100	101	102	103	104	105	106	107	108	109	111	112	113	114	115	116	117	119	120	121	122	123	125	126	127	129
	0.05%	Visual noise pollution (Panels)	-150	-152	-153	-155	-156	-158	-159	-161	-163	-164	-166	-168	-169	-171	-173	-174	-176	-178	-180	-182	-183	-185	-187	-189	-191	-193
	0.00%	Educational value for community research	200	202	204	206	208	210	212	215	217	219	221	223	226	228	230	233	235	237	240	242	245	247	249	252	255	257
	0.50%	Community awareness and initiative	75	76	77	77	78	79	80	80	81	82	83	84	85	85	86	87	88	89	90	91	92	93	94	95	95	96
	0.50%	Contribution to University Scope and positive reception	75	76	77	77	78	79	80	80	81	82	83	84	85	85	86	87	88	89	90	91	92	93	94	95	95	96
	40.00%	**Intangibility Factor**																										
Economic	1.50%	Resilience to gas price volatility	450	455	459	464	468	473	478	483	488	493	498	503	508	513	518	523	528	534	539	545	550	556	561	567	573	579
	1.00%	Reduced grid reliance	300	303	306	309	312	315	319	322	325	328	332	335	338	342	345	349	352	356	359	363	367	370	374	378	382	386
	Initial	Job creation during installation	150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4.00%	University endowment opportunity cost	-200	-208	-216	-225	-234	-243	-253	-263	-274	-285	-296	-308	-320	-333	-346	-360	-375	-390	-405	-421	-438	-456	-474	-493	-513	-533
	50.00%	**Intangibility Factor**																										
		Monetised Environmental Benefits	420	424	429	433	437	442	446	451	455	460	464	469	474	479	483	488	493	498	503	508	513	519	524	529	535	-1410
		Monetised Health Benefits	120	121	122	124	125	126	127	129	130	131	133	134	135	137	138	140	141	142	144	145	147	148	150	151	153	154
		Monetised Social Benefits	120	121	122	124	125	126	127	129	130	131	133	134	135	137	138	140	141	142	144	145	147	148	150	151	153	154
		Monetised Economic Benefits	450	275	274	274	273	273	272	271	270	268	267	265	263	261	258	256	253	250	247	243	239	235	231	226	221	216
		Net Cost-Benefit	1110	941	948	954	960	967	973	979	985	991	996	1002	1008	1013	1018	1023	1028	1033	1038	1042	1046	1050	1054	1058	1061	-886
		Discounted Cost-Beneft	1110	905	876	848	821	795	769	744	720	696	673	651	629	608	588	568	549	530	512	495	478	461	445	429	414	-332
		CBA of Project	**£15,367 GBP**																									
		Monetised savings	0	20469	20798	21301	21990	22878	23988	25345	26980	28933	31251	33990	37215	41007	45454	50659	56736	63804	71981	81367	92013	103869	116703	129949	142469	152162

Figure 28: Project Monetary Cost-Benefit Analysis

	NPV	**Annual Gas Rate Increase**				
	£27,790.05	**0.75%**	**0.90%**	**1.10%**	**1.20%**	**1.30%**
Discount Rate	**0.50%**	-1934699	-844134	1128175	2408610	3941166
	1.00%	-1771681	-778050	1016187	2179674	3571242
	2.00%	-1491412	-664707	823403	1786100	2935796
	3.00%	-1262191	-572306	665478	1464278	2416766
	4.00%	-1074190	-496763	535772	1200432	1991706

Figure 29: NPV Sensitivity Analysis matrix for r and gas rates

		Solar PV	Air Source Heat Pump	BESS	Other Components
Emissions					
Manufacturing					
	Material Extraction	316.25	269430	1152	200
	Manufacturing	31.625	26943	115.2	125
	Assembly	18.975	16165.8	69.12	37.5
	Total	**366.85**	**312538.8**	**1336.32**	**362.5**
Transportation					
	International Shipping	32.5	4750	15	50
	Domestic Shipping	7.5	1500	7.5	11.5
	Total	**40**	**6250**	**22.5**	**61.5**
Operational					
	Operational Emissions	0	2180710.03	1252.608	0
	Maintenance Emissions	5	2	850	21
	Total	**5**	**2180712.03**	**2102.608**	**21**
End of Life					
	Recycling	25	13471.5	230.4	25
	Waste Handling	2	985	150	9.7
	Material Offset	-9	-1600	-33	-34.5
	Total	**18**	**12856.5**	**347.4**	**0.2**
Total Unit Emissions (1U, 1L) [kg]					
		429.85	2512357.33	3808.828	445.2
Units					
	Units	294	1	7	7
	Life Span	25	20	10	15
Levelised					
Energy Output (kWh) (1U)					
	Annual Output/Throughput	597	1539600	2150.4	0
	Total Operational Output (1U)	14925	30792000	21504	0
Emissions per kWh generated					
		0.02880067	1.416414673	0.177121838	N/A
CO2 per kWh (CO2/kWh)					
		0.20419933	0.15419933	0.055878162	N/A
Total CO2 Emission (1U)					
		3047.675	4748105.769	1201.604	445.2
Total CO2 Emissions					
		896016.45	4748105.769	8411.228	445.2
Life Span Standardisation (25 years)					
	Proportional Levelisation to 25 years	896016.45	5935132.211	21028.07	742
	Replacement Costs	0	-351730.0263	-1599.70776	-124.656
	Total Standardised CO2 Emissions	896016.45	5583402.185	19428.36224	617.344
	#For Graph	-896016.45	-2791701.092	-19428.36224	-617.344
Avoided					
Base Line CO2 Emission		Electricity	Heating		
	Total kWh Energy Replaced	4387950	30792000		
	Total Emissions (CO2)	1022392.35	5634936		
Total CO2 Avoided		**157864.009**			

Figure 30: Life Cycle Analysis Carbon emission and offset