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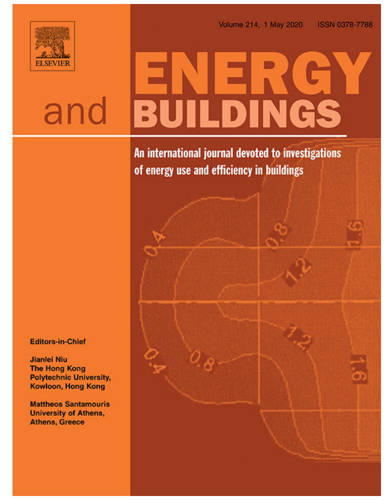

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Economic analysis of integrating photovoltaics and battery energy storage system in an office building

Guangling Zhao*, Joanna Clarke, Justin Searle, Richard Lewis, Jenny Baker,

Faculty of Science and Engineering, Swansea university, UK

Corresponding author email: guangling.zhao@swansea.ac.uk

Abstract

The concept of 'Active Building' refers to any building, such as factories, offices, homes, and other structures in the built environment, which are equipped to conserve, generate, store, and release energy in the UK. One such Active Building was built at Swansea University in the UK in 2018 and is currently used as a small office including well fare facilities.

The objective of this study is to analyse the economic performance of an Active Building, incorporating building-integrated photovoltaics (BIPV) and lithium-ion (Li-ion) batteries with real building operational profiles and metered energy load profiles. The cost covers the capital cost of 22 kWp BIPV and 110 kWh Li-ion battery, and electricity cost from the electric grid with two types of time of use electricity tariffs - South Wales (SW) time of use tariff and Red, Amber, and Green (RAG) rates, and the potential carbon cost of electricity supplied from the Wales electric grid and generated from the Active Building. Four battery operational strategies are designed, and battery status of charge and electricity flow are monitored.

The analysis is undertaken on the BIPV units with or without Li-ion batteries under various scenarios. The results show that the investment of BIPV units without Li-ion batteries can make a profit within the lifetime of BIPV in the current electricity market. However, the current Li-ion battery storage does not compensate for its capital cost from the reduced economic value obtained from the BIPV system when the electricity is curtailed. Even though the current economic analysis of the Active Building installing BIPV and battery is not convincing at the current capital price, this combination can enable the Active Building to be independent of the electric grid and to balance electricity demand and generation itself. The analysis will demonstrate the market conditions required to make these operational benefits cost-effective.

1 Introduction

More than 80% of total greenhouse gas (GHG) emissions are caused by energy production and energy users in the EU-27 in 2017 [1]. Although the EU building sector has shown a decrease in GHG emissions since 2005, due to the implementation of higher standards for new buildings, it still contributes around one-third of total energy-related GHG emissions [2]. The UK parliament passed legislation to cut the GHG emissions by 100% from 1990 levels by 2050 [3] and bring all UK's GHG emissions to net zero. Despite the fast development of renewable technology including photovoltaics (PV), the share of renewable energy worldwide is still small compared to that of fossil fuels [4]. To overcome this issue, there has been an increased emphasis on improving PV systems integrated with battery storage to increase energy resilience and reduce GHG emissions [5, 6]. The 'Active Building' concept refers to any building, such as factories, offices, homes, and other structures in the built environment, which are equipped to conserve, generate, store, and release energy in the UK [7]. The ‘Active Building’ concept promoted can help to reduce electricity losses during long-distance transmission and reduce GHG emissions from buildings compared to using electricity from the electricity grid [8].

Previous studies have focussed on the optimising of photovoltaic (PV) and battery storage systems [9,10]. In most practical scenarios, the size of the PV is constrained by the architecture of the building such as size, roof type, etc. The appropriate energy storage (Li-ion battery) size for PV has been proposed based on different factors such as self-sufficiency ratio and electricity bill minimisation using historical relative flat electricity tariffs [11]. The declininge cost of silicon PV [12] and increasing energy prices drive the application of energy storage to capture solar energy for later use within the building. In the UK, the early rooftop PV deployment was generally driven by government subsidised feed-in tariffs (FIT) [13], which gave a subsidy for electricity generated regardless of whether it was used by the consumer or not. In addition to the generation subsidy, there was also a ‘deemed export’ tariff which was not metered and assumed that 50 % of generated electricity was exported to the grid. This subsidy was ended for new contracts in May 2019. Smart Export Guarantees (SEG) started on the first of January 2020 and regulated a non-zero price for metered export [14]. Effectively energy distribution companies choose how much money to pay consumers for their exported electricity [15].

Economic analysis of installing roof PV and battery energy storage systems (BESS) has focussed more on residential buildings [16, 17]. Akter et.al. concluded that the solar PV unit and battery storage with smaller capacities (PV < 8 kW, and battery <10 kWh) were more viable options in terms of investment within the lifetime of PV and battery for residential systems. A similar conclusion was delivered by Zhang [18] modelling a PV-battery system on a residential building in Sweden, where the self-sufficiency ratio and net present value can increase with increasing battery capacity when the battery capacity is lower than 72 kWh. Logically PV and BESS was more economically viable with a higher electricity price [11]. The cost of carbon, i.e. a carbon price which charges emitters for greenhouse gases, was not considered in the mentioned references, but the cost of carbon should not be neglected as we move towards a carbon neutral society in 2050. Besides residential buildings, there is also a growing market for commercial buildings or offices using PV and BESS [19, 20]. In the US, where the incentives relied on state-level subsidies, the payback period of installed PV+ BESS for large consumers such as hospitals, schools, and large offices, could reach up to 10 years with a policy incentive in place [20]. In the UK, the process of retrofitting both existing UK commercial and residential buildings into nearly zero energy buildings is led by Department for Levelling Up, Housing and Communities [21]. The newer buildings with higher energy standards are relatively less challenging to retrofit than the older buildings.

This study analyses both the economic aspects of building integrated photovoltaic (BIPV) and BESS to emphasize the role of battery storage in the form of saving electricity costs, and the economic benefits of carbon reduction. A real load profile monitored, in an office building in South Wales, UK, since 2018 includes BIPV generation data and battery operation data. A particular contribution of the work lies in the use of hourly building load profiles, BIPV generation, and consumption profiles. The real hourly operation data of a lithium-ion battery system have been applied to analyse the battery energy throughput under two electricity tariffs. We explore the economic and technical impact of different battery operational strategies. It is expected that the results from this study will be useful not only for policy implications of energy tariffs but also to emphasise the benefits of energy storage to the distribution network. In this work, the economic analysis is performed on various scenarios considering different system configurations and electricity tariffs as detailed in the subsequent section. Section 2 provides detail about capital investments in the Active Building and the energy performance from July 2018 to May 2022. Section 3 presents key factors besides capital investment. Section 4 presents and discusses the results of economic analysis of the BIPV system with lithium-ion battery storage under different electricity tariffs, considering the real operational data of PV production and load.

2. System Description

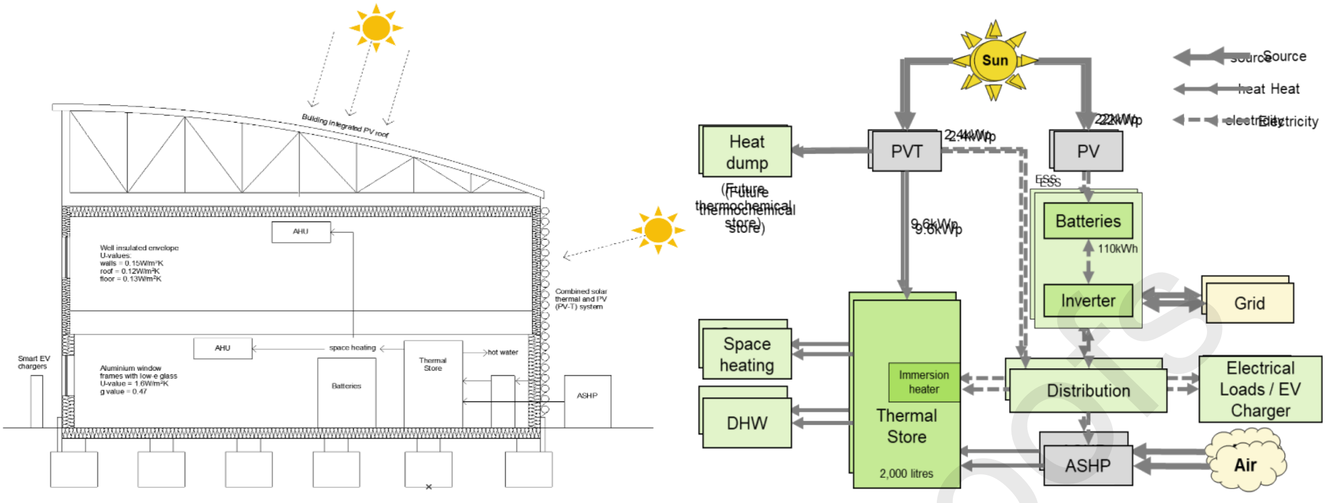
2.1 Active Building

The Active Office was constructed on Swansea University's Bay Campus in 2018 to demonstrate the application of the Active Building concept on a two-story office building. The building features a variety of low-carbon technologies, including a BIPV consisting of thin-film CIGS solar modules bonded to steel roof sheeting on a curved roof profile; a combined photovoltaic and photovoltaic thermal collector (PVT) array on the south elevation; electrical and thermal energy storage systems; electric vehicle charging; and extensive data monitoring, visualised through an energy dashboard located in the entrance foyer (Fig.1 (a)). The building is of volumetric modular construction, comprising 12 locally manufactured steel-frame modules, providing office accommodation for 35 people, meeting spaces, and ancillary accommodation within a total floor space of 376 m^2.

The office building is grid-connected and utilises BIPV panels and a BESS. The BIPV panels and battery packs are respectively connected to the direct current (DC) electric vehicle (EV) charger via three chargers of 7 kWh through inverters (Fig.1 (b)). The installed BIPV acts as the main generator of electrical energy. The power output from the BIPV is linked to the bi-directional DC/AC inverter through the common DC line, which is connected to the electric grid in Southern Wales through the university power grid. When the BIPV generation is higher than the electric power load, excess power can be directed either to the BYD Li-ion battery storage or to the electricity grid. When BIPV generation is less than the power load, the stored electricity and electric grid can meet the excess electrical load. The size of the BIPV array was determined by the physical size of the roof with wall mounted PVT modules providing further electric and thermal energy. The size of the BESS was specified to meet the maximum predicted one-day energy demand without importing from the grid. Characteristics and prices of the components in the energy system are illustrated in Table 1 below. To minimise the battery degradation and ensure there was always some stored energy in the event of grid cut-off, the battery operator chose to curtail the battery to stop discharging when state of charge (SOC) was less than 30%.

The BIPV has a curved form for architectural reasons and to demonstrate the potential of the new BIPV technology. As a new technology being produced in low volumes, it was more expensive (£1803/kWp) (Table 1) than silicon PV (£1078/kWp) installed in 2018 [12]. However, the BIPV panels also contribute to the roof fabric itself which can offset some cost. The costs presented in Table 1 are the actual values paid for components that had a short lead time, a protracted procurement process and were one-off orders. It is reasonable to expect in all cases that the costs will reduce significantly if the building was specified now and if silicon had been used rather than BIPV the cost of the PV would have been reduced by ~40%, although the curved form factor of the roof would not have been possible and extra costs would have been incurred in the roof covering and PV system support structure.

Even though the lithium-ion phosphate (LFP) battery is a mature technology and has been in the market for decades [22, 23], the cost has made it prohibitive to be used on a scale for grid energy storage. With increased manufacturing scale and market demand, Li-ion battery cost has decreased with battery prices reducing by 30% between 2018 and 2022, further cost reductions could also be achieved through increased buying power – for example by a house-builder or building contractor [24].



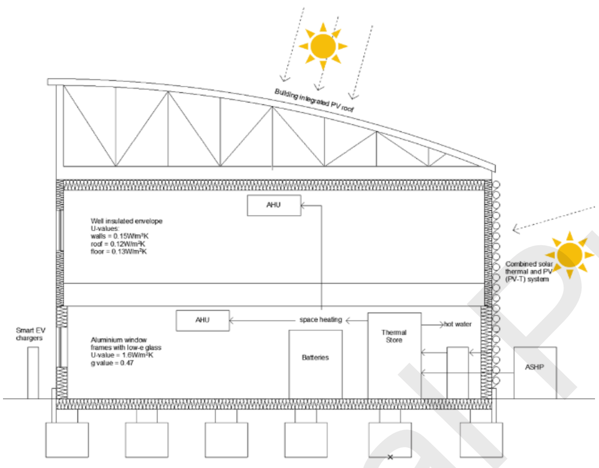


Figure 1(a) Cross Section through the Active Office (b) Stylised schematic and energy flow of Active Office

Table 1 Key parameters of installed equipment in active building

	Active office building (2018)
Solar PV	
Type	BIPV CIGS Curved roof
Size (kWp)	22
Cost (GBP)	39670
Lifetime (year) (warrantied)	25
Battery storage	
Type	BYD LFP battery
Capacity (kWh)	110
Lifetime (year) (warrantied)	10
Cost (GBP)	77537

2.2 Energy Performance

The energy consumption of the building includes electricity for heating/ventilation, office operation (including a small kitchen area), and all regulated and unregulated loads such as small power and EV charging. Figure 2 below describes the daily energy demand for electricity, heating, and EV charging in 2020. It shows the unbalanced solar energy generated and energy demand during different times of the year. The electricity generated from BIPV was higher in summer than in winter. In contrast, the energy demand was higher in winter, especially heating demand. The total demand for electricity, heat, and EV charging was 10 MWh, 7.9 MWh, and 4.0 MWh respectively in 2020, all of which were reduced from 2019, which had values of 15 MWh, 9.6 MWh, and 9.3 MWh respectively. The variation between 2019 and 2020 energy demands is mainly due to the COVID-19 lockdown since March 2020.

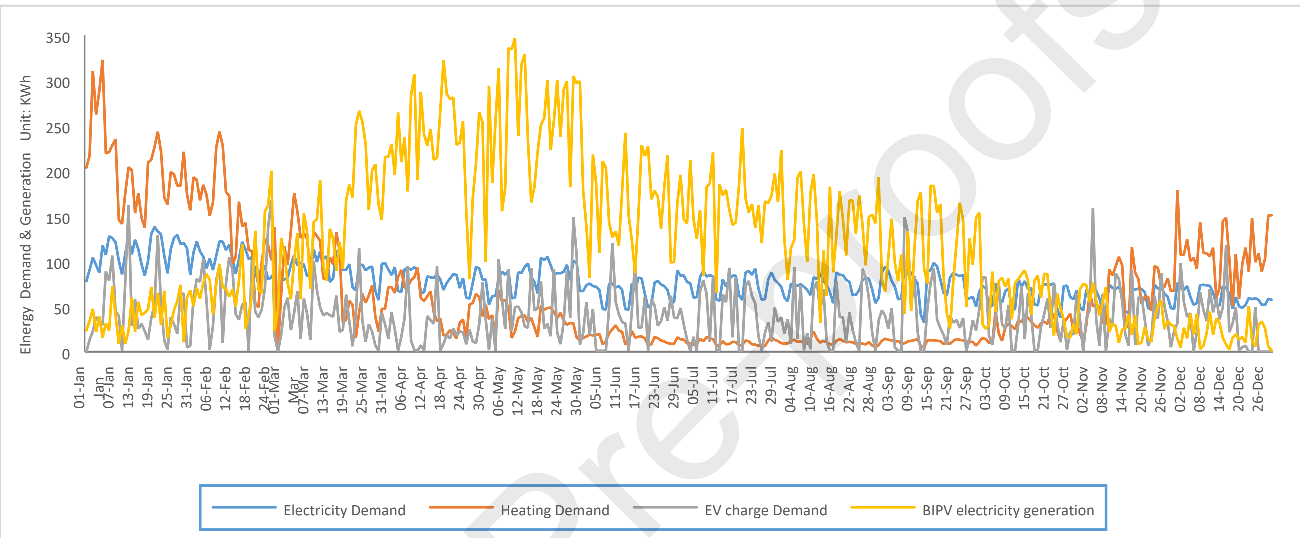


Figure 2 Energy demands and BIPV electricity generation in 2020

Figure 3 presents a typical demand and BIPV electricity generation for given days. The 22 kWp BIPV array can generate up to 15 kWh on a sunny day in winter, a 13 kWh on a cloudy summer day (Fig.3~~2~~), and up to 144 kWh on a sunny summer day on 15^{th} June 2020. Since the Active Office is a commercial building, operating typical office hours,~~'~~ the energy demands and PV electricity generation follow a similar trend with higher demand/generation during the day and low demand and zero generation during night-time. It is worth mentioning that the significant peaks in electrical demand are caused by EV charging during the working day f.x. 2^{nd} December 2019. The highest heating demand happens in the morning or the afternoon with lower electricity generation at the same time.

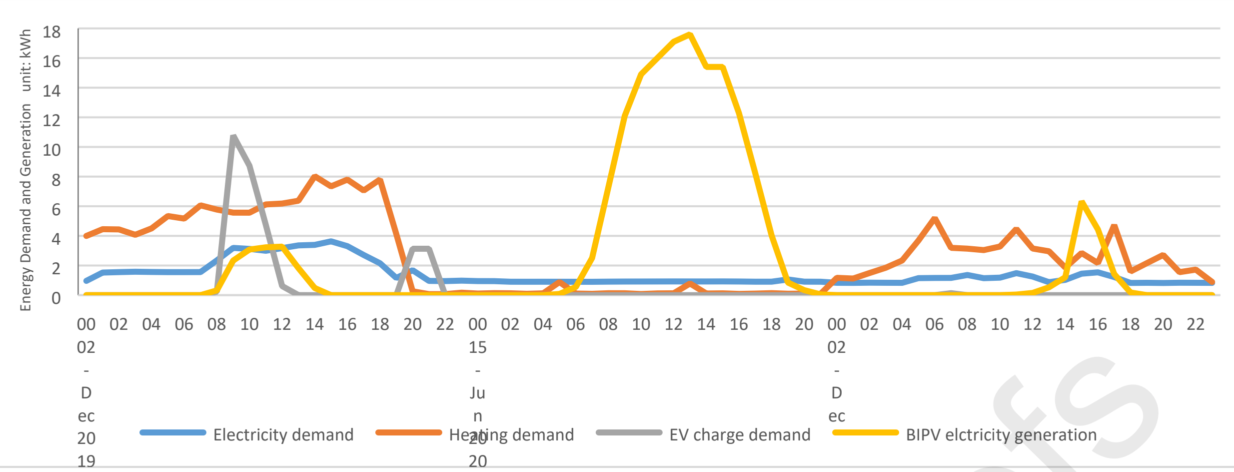


Figure 3 Energy demand and electricity generation during typical summer and winter days.

When the BIPV generation is higher than the electric power load, excess electrical energy goes to the EV chargers, and then to the battery pack, which stores energy for later use. In the summertime especially during the summer holiday period and COVID lockdown, when the energy demand is lower and the battery is full, the building will deliver electricity to the university campus or with the potential to sell the electricity to the Wales 'electric grid. In the wintertime, the BIPV receives less sunlight. This coupled with the fact that the energy demand of the building is increased requires a portion of the energy demand to be met by the electric grid via import through the electricity meter.

3 Method

3.1 Electricity cost

The retail price of electricity in the UK depends on several factors including client type, area, local electricity market, tax, etc.. In the UK, the tariff is comprised of a purchase tariff and an export tariff.

For the studied building, the electricity cost is calculated from energy consumption which is supplied by a BIPV + battery storage system in combination with two different time-of-use (TOU) electricity tariffs. One of the tariff schemes is based on the hourly dynamic pricing offered by Octopus Energy. The purchase tariff is called agile import tariff, and the export tariff is called agile outgoing/export tariff. This tariff was designed to give cheaper rates at off-peak times of the day or night when the demand is at its lower level. The export tariff is much lower than the consumer purchase price. The data covering July 2018 – May 2022 is given in the supplementary data file 1. The Active Office is in South Wales, so the historical import and export electricity price is taken from Octopus Energy of Southern Wales after March 2019. The price for exporting electricity to the grid is fixed to be 5.24 p/kWh before March 2019 [13].

The second electricity tariff is called Red, Amber, and Green tariff (RAG), which is the large electricity consumer tariff (Table 1). This is a typical RAG tariff available to commercial enterprises during the dates specified by EDF energy [25]. The customer export tariff is the same price as the import tariff. This is because the Active Office can offset electricity use of the rest of the Swansea University campus, effectively acting as a community grid. The hourly share of electricity demand in each settlement period is split between Monday-Friday including bank holidays and Saturday-Sunday.

Table 1 RAG Tariff available to public sector bodies

Time Bands and electricity price			
Periods	**Red Time Band**	**Amber Time Band**	**Green Time Band**

Monday to Friday	17:00 to 19:30	07:30 to 17:00 19:30 to 22:00	00:00 to 07:30 22:00 to 24:00
Weekends		12:00 to 13:00 16:00 to 21:00	00:00 to 12:00 13:00 to 16:00 21:00 to 24:00
Price (2018-2021) p/kWh	15.4	9.5	9.0
Price (2022) p/kWh	19.4	13.5	13.0

3.2 Carbon cost

The carbon emissions associated with the energy supply from an Active Building is determined by the upstream carbon emissions and total electricity generated or stored or delivered by the devices throughout the lifetime. Life cycle assessment (LCA) is employed to calculate the embodied emissions from the BIPV and lithium-ion battery storage. The operation of renewable-based electricity generation and energy devices installed in the building is considered carbon neutral. The carbon emissions from BIPV are due to upstream primary resources/materials used to manufacture them, which is based on a previous study [26]. The carbon emissions from LFP battery pack is based on Liu [27]. The emissions from the Active Office is based on previous work [8]. Calculation of the reduction in CO_2 emissions in terms of overall energy demand and generation, and grid independency is crucial for both existing as well as new 'Active Buildings' in the future. The carbon emissions of the grid electricity are based on the national grid ESO [28]. The cost of carbon emissions is set to be 46.4 £/t CO_2e according to higher scenarios of the UK policy proposal [29].

3.3 Battery operation strategy

The aim of installing the Li-ion battery was to increase energy resilience/self-consumption and to reduce energy bills by maximising self-consumption of electricity generated from BIPV.

Four operational strategies have been used during the period analysed to manage the interactions between the electrical grid, BIPV, and LFP batteries.

- Strategy 1 is the default operation, where energy consumption from the BIPV is prioritized, before the Li-ion batteries, and last, by the electrical grid, and any surplus generation that cannot be stored in the batteries is exported at the time of generation.
- Strategy 2 is economic operation, where the battery is charged at lower grid electricity cost and discharged at higher electricity cost.
- Strategy 3 involves targeting a fixed import/export power based on an estimated energy surplus or deficit over a defined period; thus reducing variation in import/export over short periods, and helping to stabilise the grid.
- Strategy 4 uses a fixed rate of charge/discharge based on the current state of charge and historic generation and consumption.

4 Result and Discussion

Utilising the described Active Building the financial performance of the building was examined. Four steps of examining factors that affect electricity bills are carried out in the results. Section 4.1 considers BIPV installed in the office without battery storage. Section 4.2 calculates the economic effect of using battery storage together with BIPV. Section 4.3 expands on this by comparing different operational strategies detailed in section 3.3. Finally, section 4.4 covers the impact of introducing a carbon price to the system.

4.1. Economic performance of BIPV system with different electricity tariffs

To understand the contribution of each component within the Active Building energy system (including exports and EV charging) to the operational cost, the BIPV is analysed without battery storage. Fig. 4a presents the monthly electricity cost of the Active Building energy system with only installed BIPV from July 2018 to May 2022. In the wintertime, the energy cost can be 10 times higher than in the summer months, due to higher energy demand and lower BIPV generation. Figure 4b gives the BIPV generation and electricity demand data at monthly intervals for this same period.

The monthly energy bills using the university RAG tariff are lower than the SW tariff. One of the reasons for this is the different price of the outgoing electricity price from the Active Building to the electric grid. In the SW tariff based on Octopus, the price of exporting electricity to the grid is lower than the price of importing electricity from the grid. In the RAG tariff, the price of sending electricity to the grid is the same as the price of buying electricity, because the university effectively acts as a 'microgrid' where electricity is shared behind the meter. Whilst in all months (except Feb 2020) the RAG tariff is beneficial, the differential becomes much more significant at the end of 2021. This is because the industrial RAG tariff did not see the same immediate increase in electricity price compared with the SW tariff which passed price rises directly onto the consumer.

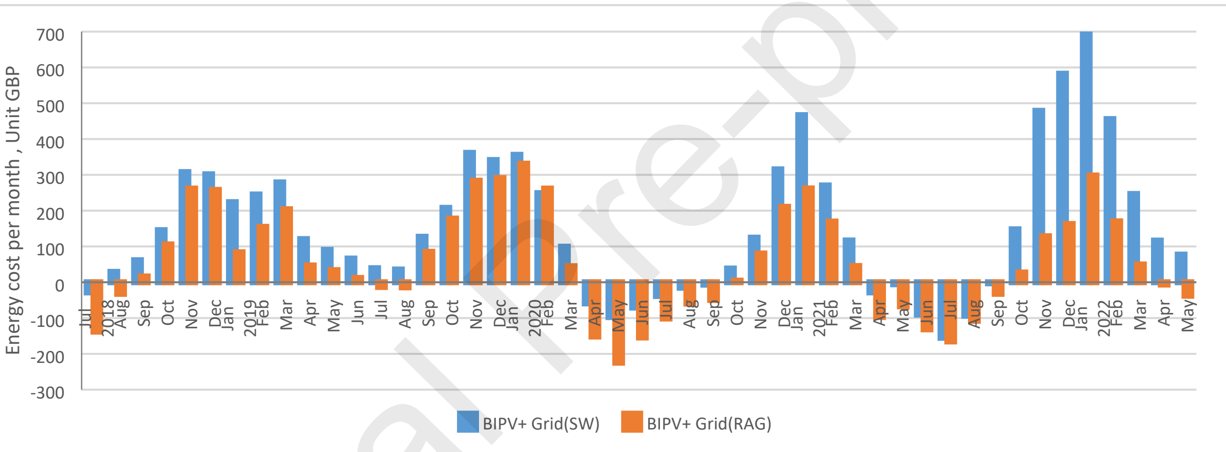


Figure 4a. Total monthly energy cost from Active Building System with exporting electricity to the grid from July 2018 to May 2022.

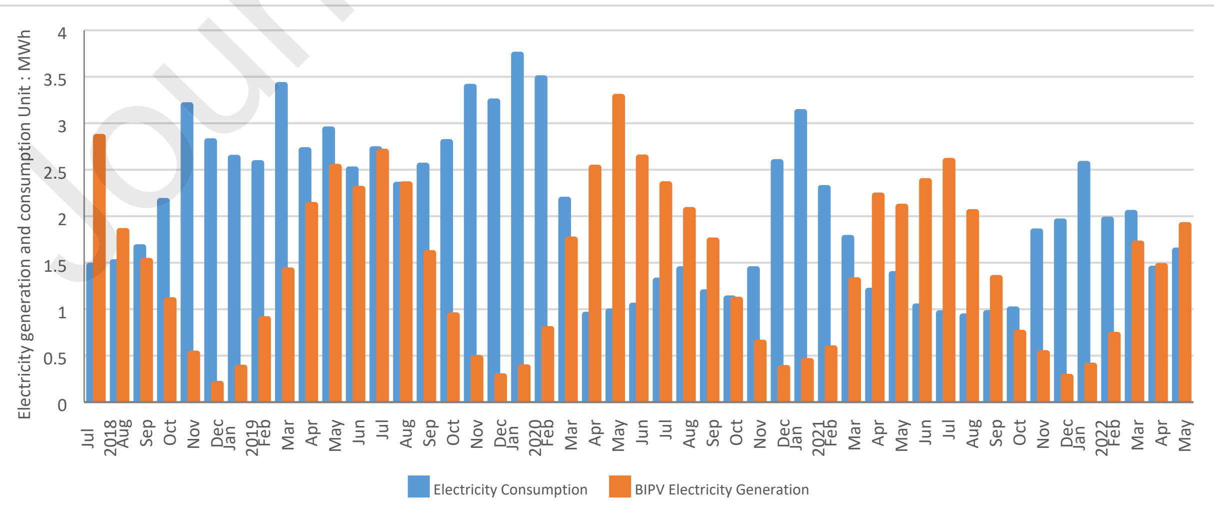


Figure 4b Comparison of monthly electricity consumption of the Active Building System (including EV charging) to PV generation.

Fig. 5 presents the monthly cost of the Active Building installing BIPV without exporting electricity to the grid from July 2018 to May 2022. Whilst some of this data was collected during the COVID pandemic lockdown, the building systems and heating were left running to enable the building operation to continue to be evaluated. Energy demand slowly came back after September 2020, when staff and students resumed occupation of the campus. The monthly energy bills using the university RAG tariff are lower than the SW tariff. One of the reasons is the different prices of the outgoing electricity price from the Active Building to the electric grid. During the COVID lockdown, which started in March 2020, the energy demand had decreased dramatically. This was mirrored by a reduction in electricity price on the dynamic SW tariff, whereas the RAG tariff was fixed. This is the only period where the dynamic the SW tariff was a lower cost monthly for the Active Office operation without a battery. In the SW tariff based on Octopus, the price of exporting electricity to the grid is lower than the price of buying electricity from the grid. In the RAG tariff, the price of sending electricity to the grid is the same as the price of buying electricity because the university effectively acts as a separate 'grid' where electricity is shared behind the meter.

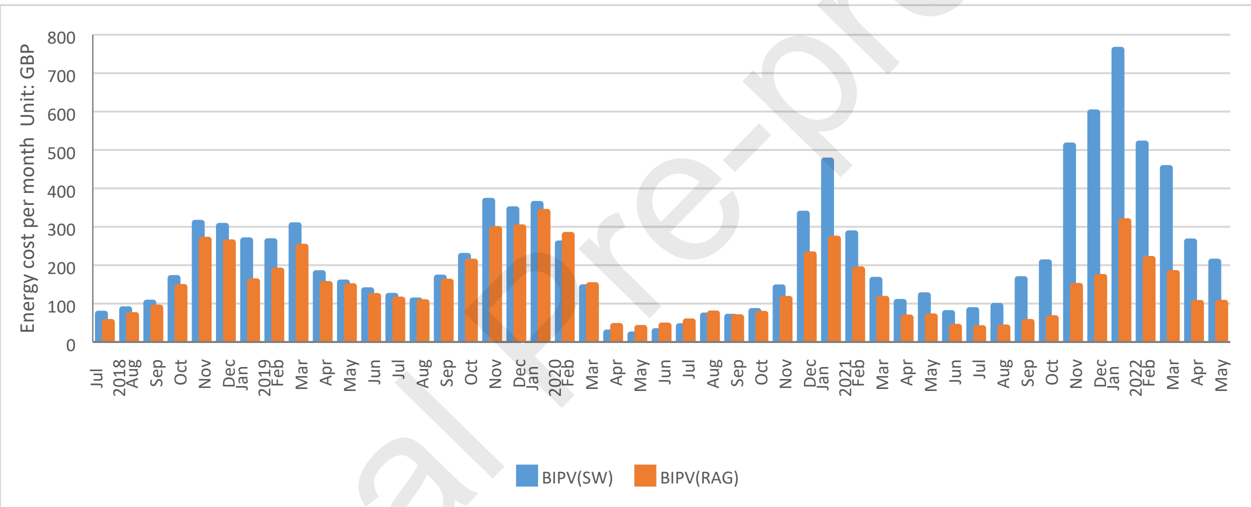


Figure 5. Total monthly energy cost from Active Building System without exporting electricity to the grid from 2018 to 2022

The payback time of installing BIPV is calculated based on two scenarios: BIPV+ Grid with exporting electricity to the grid, and BIPV without exporting electricity to the grid. Three-time baseline periods (T1, T2, and T3) are chosen as a baseline annual energy cost. The three periods represent differences in electricity price from the grid and electricity demand due to the COVID and inflation. A simple payback method is used rather than discounted enable comparisons given the volatile period of financial costs/inflation. The payback times are the result of annual solar insolation, rate of self-consumption, and energy price.

With the SW tariff, the payback time of installing BIPV with exporting of electricity to the grid decreased from 27.4 years in T1 to 7.1 years in T3 (Table 2). When the installed BIPV can sell excess electricity to the grid, the payback time of BIPV is within its lifetime span in the two considered electricity tariffs. With the SW tariff, the payback time of BIPV can decrease to 7.3 years, due to the high energy price. With the RAG tariff, the payback time is shorter than the SW tariff in T1 and T2. However, it becomes much longer in T3, where the electricity price is significantly higher from the SW tariff than it is from the RAG tariff. When the BIPV electricity is not compensated financially for exporting to the grid, there is barely any financial benefit of installing BIPV, with payback times in some scenarios exceeding 67 years as shown. The warrantied lifetime of BIPV is 25 years guaranteeing 80% of the original performance [30].

Table 2 The payback time of installing a BIPV unit: years

Time	Baseline period	BIPV+Grid (SW)	BIPV+Grid (RAG)	BIPV (SW)	BIPV (RAG)
T1	01/06 2019 - 31/05 2020	25.8	20.4	40.0	44.5
T2	01/06 2020 - 31/05 2021	25.0	23.4	46.4	67.6
T3	01/06 2021 - 31/05 2022	7.3	21.9	21.4	55.8

Figure 6 presents the average electricity unit cost for each month over four years. The unit electricity cost is lower in the RAG Tariff than the SW tariff, following the same trend as the total monthly electricity cost. January has the highest electricity costs, which were 14.3 p/kWh, 8.9 p/kWh, 14.5 p/kWh 25.9 p/kWh from 2019 to 2022 respectively (Fig.6). The electricity cost is negative between April and September from 2019 to 2021, since the financial gain from exporting excess BIPV is higher than the cost of buying grid electricity in those months.

Due to Covid 19, the UK started a national lockdown in March 2020, and energy demand in the UK significantly decreased. Whilst people were no longer working in the office, the office heating and ventilation were left in operation to continue assessing building performance. Occupancy by May 2022 has still not returned to the pre-COVID level, since the university was still encouraging hybrid working. As the electricity generated from BIPV was not affected in the lockdown, the average monthly energy use is lower in 2020 than that in 2019. This was followed by inflation in 2021, as seen in Table 1 for the RAG tariff and supplementary data sheet no 1 showing the SW tariff. The use of BIPV reduced the maximum average monthly unit cost incurred by the office to 30 p/kWh from 35 p/kWh of the SW tariff (Supplementary 1). The electricity cost from RAG tariff was lower than the SW tariff, demonstrating how larger energy consumers can be economically protected compared with the individual small energy consumer.

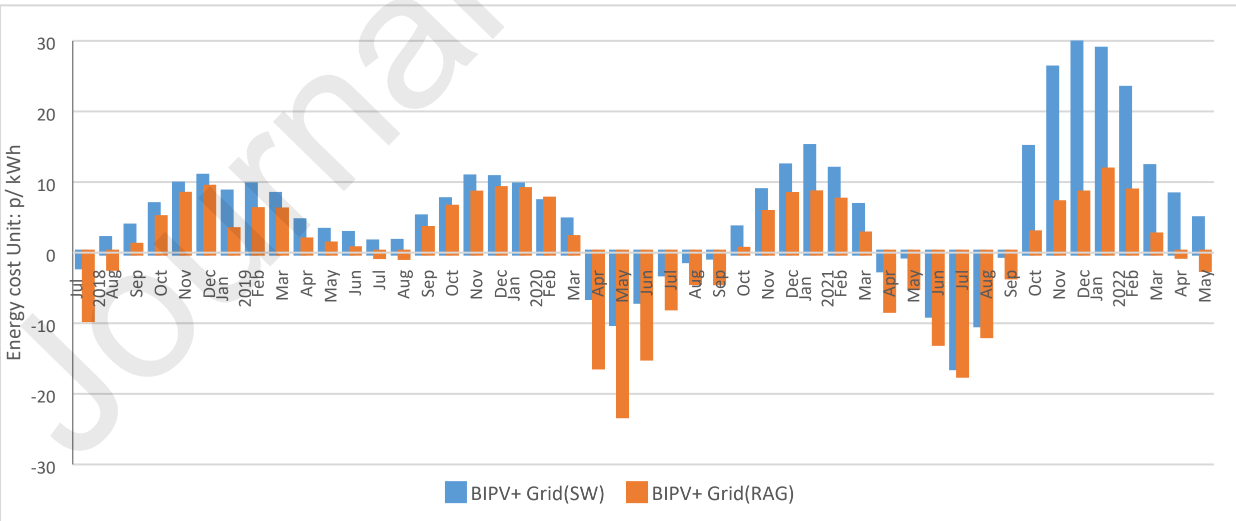


Figure 6 The average unit monthly energy cost from Active Building System Unit: p/kWh

4.2 Economic performance of BIPV system with battery storage

Having presented in section 4.1 the cost benefit of BIPV without a battery storage, the economic effects of adding an LFP battery to the system are analysed. The average monthly cost of the Active Building with BIPV and LFP battery installed is presented in Fig. 7. In both analysed electricity tariffs, the total monthly energy cost in 2019 is highest among the monitored years. This is partly due to the COVID lockdown, which led to a change in the energy demand profile after April in 2020, as shown in Fig. 4b.

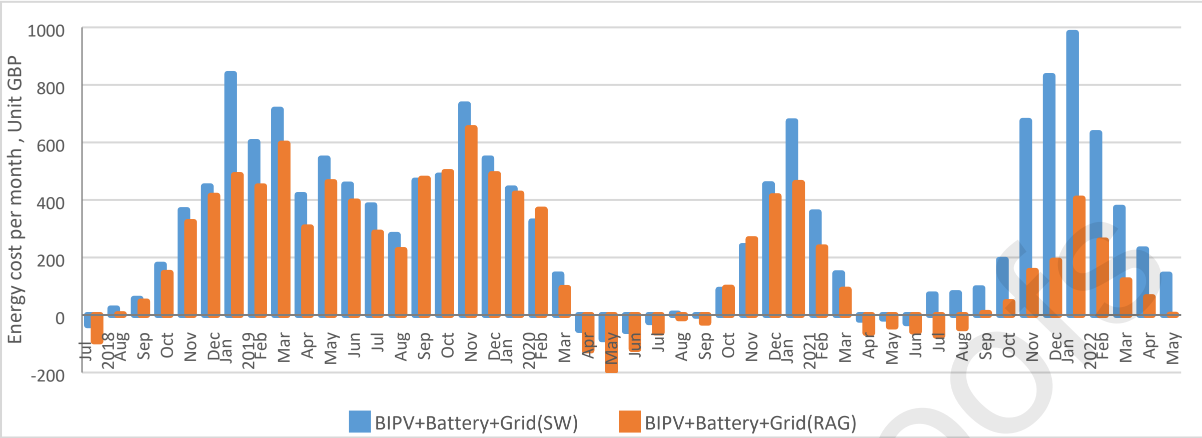


Figure 7 Monthly Energy cost from Active Building System with LFP battery storage Unit: GBP

It is interesting to note that whilst the RAG tariff is usually the lower cost, especially when there is an excess of electricity from the BIPV (e.g. summer), occasionally in the winter of 2019/2020 this trend reversed with the lowest costs seen using the dynamic SW tariff even though the battery operation was not optimised for the SW tariff differences. From mid-2021 to May-2022 electricity supply from SWT became significantly more expensive with monthly operating costs up to three times the price of the RAG tariff.

To analysis the benefit of adding the LFP battery to the BIPV system, the average monthly electricity costs utilising BIPV and LFP battery storage are compared with electricity costs using BIPV only, without exporting electricity to grid for RAG tariffs, where the battery operation strategy are developed (Figure 8). The positive number means there is a higher energy cost from BIPV+ battery than using only BIPV. The results show that in the winter months the energy bills are higher with an installed battery compared to operating without a battery. The exception to this is the summer of 2019. Investigating the data further, the battery becomes economically beneficial at times when the PV generation is higher than the electricity consumption of the building, Fig. 4b. The summer of 2019 had higher consumption than predicted when the building was designed, due to uncontrolled EV charging, which reduced during the COVID19 lockdown and subsequent years. This highlights the need to understand the effect of new electricity demands on building operation and ensure that there are systems in place to manage them for the best economic outcomes.

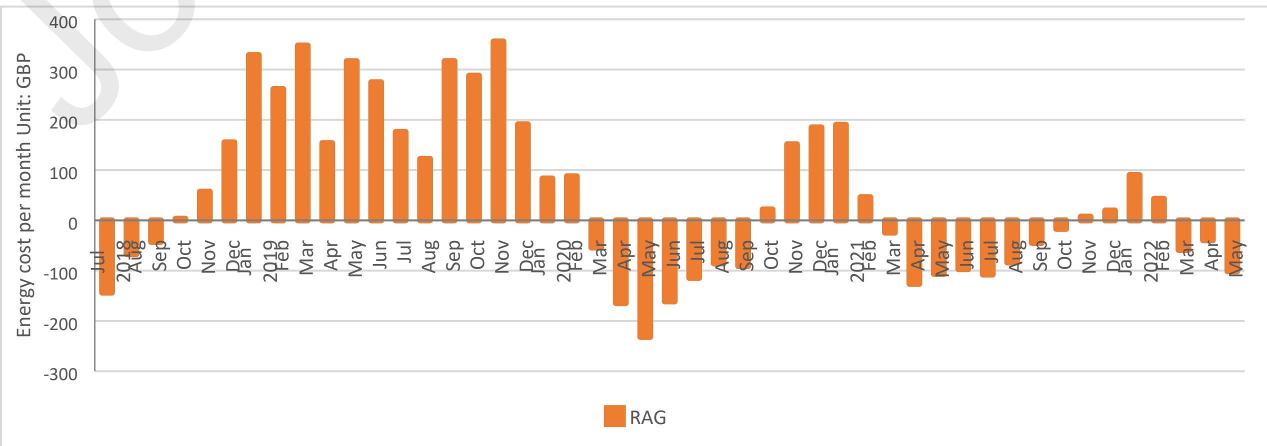


Figure 8 Monthly cost benefit of using a battery versus BIPV only, positive values indicate a cost of using the battery. Unit:GBP

When we consider the battery capacity investment, the payback time in the scenarios considered can take more than 100 years in the current electricity market using a battery capital cost from 2018. Since the lifetime battery is predicted to be significantly less than this [31], there is no economic gain by installing lithium-ion battery for energy storage. Besides the high current capital investment of stational battery storage, the reason is the small price differences of time of use in RAG tariff. Electricity price from red period is only 6 p/kWh more than the green period, amber is only 1 p/kWh more than the green period.

4.3 Technical performance of the battery system.

For a PV system, the performance can be easily calculated by comparing the insolation received by the panels to the electricity output. Higher electricity yields result in improved economics of the BIPV system, and lower environmental impacts. The economic performance of the battery is dependent upon the price gap between buying and selling, as well as the round-trip efficiency (RTE). The RTE of the battery is also not static - like PV it can be affected by temperature but it is also affected by charge rate, and energy throughput (due to parasitic losses, such as acting as a UPS) [32].

The strategies were chosen by the battery operator based on the RAG tariff. Strategy 1 was the default setting. The aim of strategies 2-4 was to utilise all the PV followed by buying at a low price during the 'green' period and selling at a higher price – ideally during the peak 'red' period. The cost-benefit of the energy storage is given in equation 1.

$$\frac{\text{Buy Price}}{\text{Round Trip Efficiency}} - \text{Selling Price} = \text{cost / benefit of storage} \quad (1)$$

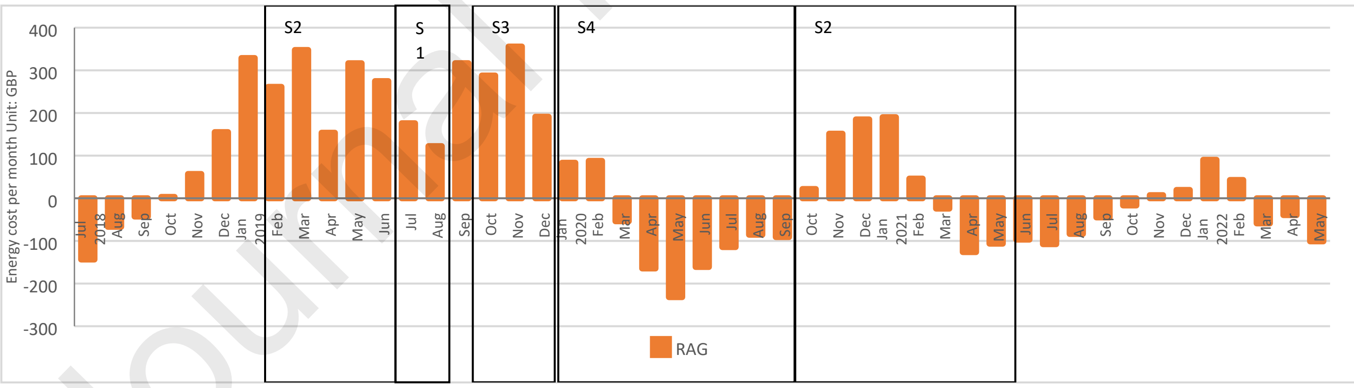


Figure 9 Monthly cost benefit of using a battery versus BIPV only, with the four operation strategies (S1-S4)

Due to variations in energy usage from both the uncontrolled EV charging in summer 2019 and then the COVID lockdown in 2020, coupled with large variations in tariff prices, it is not possible to draw specific conclusions about the cost effectiveness of different energy strategies. This data will be used in future work to validate a model which will calculate the best operational strategy depending upon whether economic or environmental performance is being optimised. One important factor when calculating storage performance is the RTE of the battery. This is difficult to measure on a transient basis but will be affected by charge/discharge rate, temperature, inverter and other system losses and parasitic drains, such as the battery being used as an uninterruptable power supply (UPS) [33].

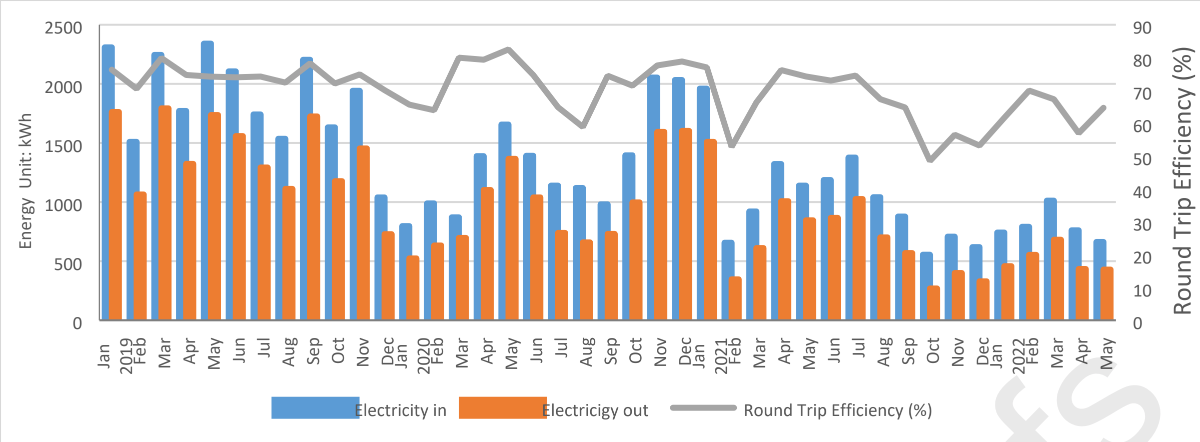


Figure 10 Battery round-trip efficiency compared with energy input / output from the battery.

The RTE, Fig. 10, for the battery is calculated based on the monthly incoming and outgoing energy. There will be some minor inaccuracies when the state of charge is different at the beginning to the end of the month. The RTE has an average of over 70-80% for the operation in 2019, but this drops in 2020, mirroring the reduction in energy throughput (Fig. 11). This is expected since the draw to keep the battery operating as a uninterruptible power supply (UPS) will be unchanged, meaning that a greater proportion of stored energy is used up in battery standby, reducing measured efficiency.

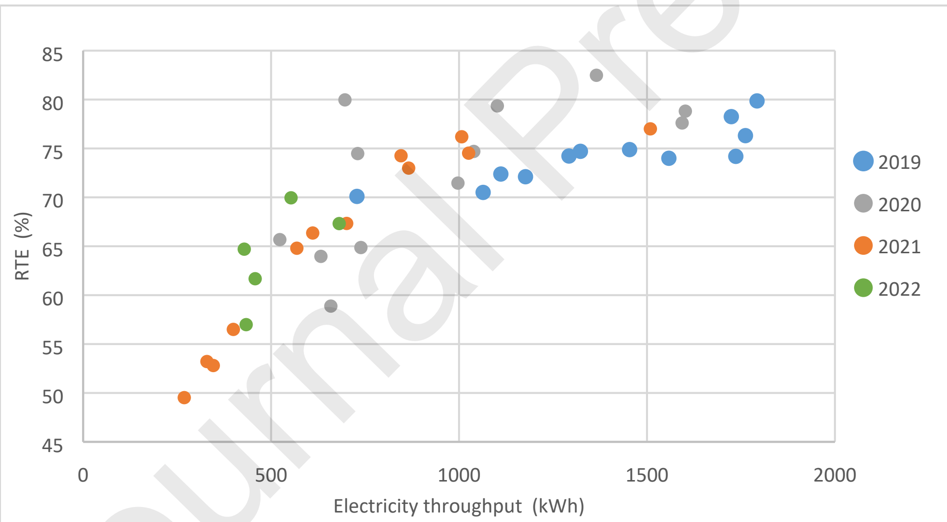


Figure 11 Battery round-trip efficiency with the change of electricity throughput

When buying at the green tariff and selling at the red tariff (2019-2021 numbers), an RTE of 58% is required to break even in operational costs. An RTE of 70 % gives a benefit of 2.5 p/kWh. If the battery is charged in the red band and then discharged during the amber band, then an RTE of 95% is needed to break even on operational cost. In all the strategies trialled, whilst the intention was to discharge during the red time and charge during the green time, during times of high load the battery could be discharged during the amber time band, resulting in an addition operational cost of 3.3 p/kWh, giving a resulting electricity cost of 12.3 p/kWh compared with 9.5 p/kWh drawing directly from the grid. This is because the control system did not differentiate between economically beneficial storage (supplied by the BIPV) and non-economic storage (stored from the grid and discharged in the amber band). The price change to the RAG tariff in 2021 makes energy storage less beneficial, with a RTE of

67 % required to break even on operational costs charging in the green period and discharging in the red period.

4.4 Environmental cost of BIPV and BIPV with battery storage system

The potential consequences of adding carbon costs to the energy bill are discussed in three scenarios of the grid only, BIPV + grid, and BIPV + battery + grid from 2019 to May 2022 (Fig.12). The carbon cost accounts for no more than 10% of energy cost in all three scenarios. The BIPV + grid only has the lowest carbon cost. The highest carbon cost comes from electricity grid in the monitored months except November/ December 2019 and November 2020, where the BIPV + battery + grid has the highest carbon cost – indicating that the battery is not only giving an economic detriment in these months but a GHG detriment too. Even though the objective of battery storage is to increase electricity consumption from BIPV, the carbon cost increased with installing a battery system, compared to without a battery. One reason is energy loss during the process of charging the batteries and delivering electricity to the building. The other reason is the batteries are charged from the grid, which can be seen in November and December 2019, where carbon cost from BIPV + battery + grid is the highest. When we consider carbon cost in the energy bills, the shortest payback time of BIPV reduces from 7.3 years to 7.0 years.

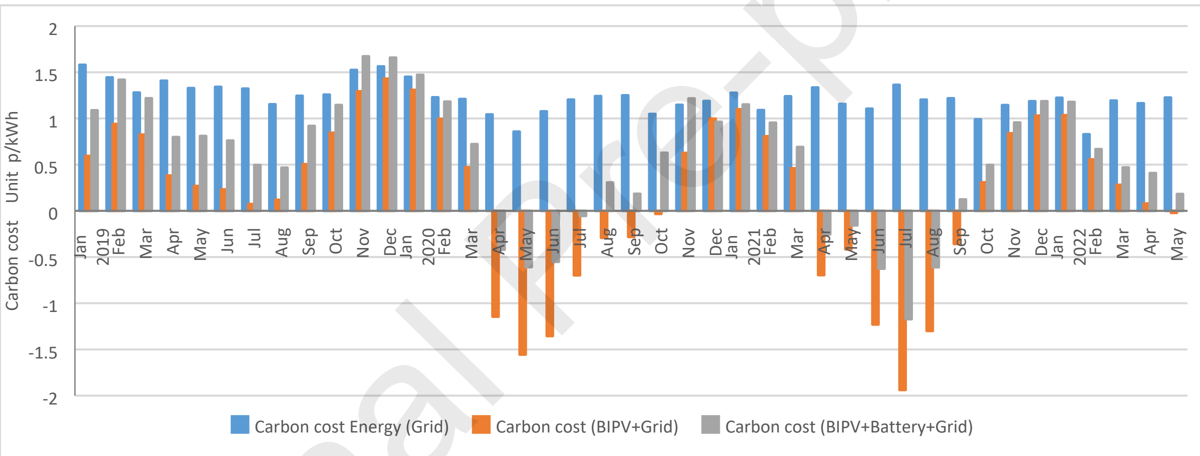


Figure 12. Monthly average unit pricing of Active Building System considering carbon cost unit: p/kWh

5 Conclusion

This paper analyses the operational costs of an Active Building containing BIPV and energy storage over 4 years. The building operation was controlled by the demands of the people utilising it, such that there were some unplanned demand changes, such as increased EV charging in 2019 as well as a reduction in demand during and after the COVID 2019 pandemic. The energy market has also changed significantly over the period analysed, with industry prices rising 25% in one year after a period of stability and domestic prices rising even further. Such prices have made even high cost experimental BIPV cost-effective with a payback period as low as 7 years without subsidy.

Whilst energy storage can improve the self-consumption of a BIPV system and reduce energy costs in the summer period, this reduction is still not enough to compensate for its capital cost in the current energy market. Operating with a strategy beyond 'self-consumption', i.e. buying and selling to the grid can cause an additional cost to the user if the RTE is not compensated by the difference in buying and selling price. There can also be a reduction in self-consumption should the battery be full when there is excess BIPV generation. Parasitic loads and the causes of low RTE need further investigation to optimise battery performance.

It is demonstrated that even in the current electricity market battery storage could help to facilitate deployment of a shared PV system where operators would otherwise face curtailment or low exporting rate. Although the load and generation data and electricity tariffs used for this study are collected from the UK, the findings have some suggestions for other energy markets with similar regulations or decision makers regulating energy markets.

Supplementary Information

Supplementary data file no1 – Electricity tariff.

Supplementary data file no 2– Carbon intensity of electricity from Southern Wales electricity grid

Supplementary– Construction of the Active Office
https://www.youtube.com/watch?v=Zb1wDRA1MLc&list=PLNgm_nsb9e0-yDmzAiwvs4EzD6NB_LTAU&index=13

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Abbreviation

Building-integrated photovoltaics (BIPV)
Direct current DC
Electric vehicle EV
Energy storage systems BESS
Feed-in tariffs FIT
Greenhouse gas GHG
Life cycle assessment LCA
Lithium-ion Li-ion
Lithium-ion phosphate LFP
Photovoltaics PV
Photovoltaic thermal collector PVT
Red Amber and Green RAG
Round-trip efficiency RTE
Smart Export Guarantees SEG
South Wales SW
State of charge SOC
Time-of-use TOU
Uninterruptible power supply UPS

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Credit Author Statement

Guangling Zhao: Writing- draft preparation and editing, Methodology, Data analysis, **Joanna Clarke:** Reviewing and Editing, **Justin Searle**: Data monitoring and data review, review and Editing. **Richard Levis**: Battery operation manage, data monitor, **Jenny Baker**: Methodology, Reviewing and Editing.