Future Cities
and Environment

Brennan, DA, et al. 2019. Performance Characterisation and Optimisation of a Building Integrated Photovoltaic (BIPV) System in a Maritime Climate. *Future Cities and Environment,* 5(1): 8, 1–9. DOI: https://doi.org/10.5334/fce.62

TECHNICAL ARTICLE

Performance Characterisation and Optimisation of a Building Integrated Photovoltaic (BIPV) System in a Maritime Climate

Desmond A. Brennan, Craig White, Michael Barclay, Tom Griffiths and Richard P. Lewis

A seasonal analysis of a long-term dataset produced by an off-grid classroom facility showcasing several solar orientated renewable technologies is presented. The performance of the building's BIPV and battery storage system is characterised and optimisation strategies are discussed.

The building experiences a typical oceanic climate defined by a relatively narrow annual temperature range and a high level of annual precipitation, resulting in significant fluctuation in PV performance throughout the year. On clear days, the battery system reaches capacity quickly and PV power output drops to the base load of the building. This curtailment of solar generation highlights the importance of developing control strategies to optimise system performance.

Maximising the performance of the building requires accurate methodologies for predicting PV generation and detailed knowledge of building demand profiles. Significant correlation is observed between the solar irradiance, battery state of charge and PV power output, demonstrating the importance of these variables in any solar forecasting model. Demand profiles are deterministic and follow classroom routine. A baseline accounts for persistent systems such as the building management system that are active throughout the day, with demand peaking during occupancy. This information could be incorporated into scheduling algorithms to optimise performance. Consumption is more aligned with the solar generation profile than typical residential buildings that peak in the evening as levels of solar generation fall. The synergistic effect of buildings with different demand profiles could be a mitigation method to minimise the temporal mismatch between solar generation and consumption.

Keywords: Solar Energy; BIPV; Photovoltaic System; Battery Storage; Smart Control

Introduction

Globally, buildings account for nearly 40% of energy usage and 36% of CO_2 emissions, with figures higher if the embodied energy in construction is considered (Magoules et al., 2012). The wide spread adoption of renewable energy generating technologies in the built environment is critical to offset this high-energy usage and reduce environmental impact. Amongst such technologies, building integrated photovoltaic (PV) power and battery storage systems are gaining acceptance because of their economic feasibility and ability to meet electrical and thermal load requirements (Biyik et al., 2017).

PV technologies have experienced rapid growth over the last decade, with cumulative installations exceeding 230 GW globally (Das et al., 2018). In the U.K alone, a reduction in cost combined with government policies such as the Feed in Tariffs, which allow consumers to profit by exporting energy generated locally from renewable sources back to the grid network, has led to the increased adoption of small scale commercial and residential photovoltaic systems. **Figure 1** shows the increase in cumulative power output from installations registered with the U.K Feed in Tariff over the last several years. Cumulative installations are in the region of 5 GW, with almost one million registered users nationwide (UK Government, 2018). Self-generation and storage can help reduce the reliance on centralised and often distant generators, reduce losses associated with transmission and distribution across large networks, and principles such as block-chain trading can be employed to pass excess generation on to the local area (Burmester, 2017).

Barriers preventing the wider dissemination of solar technologies include the intermittency of energy generation and misalignment with temporal demand profiles. Renewable sources such as solar vary considerably in terms of energy density and load factors when compared to traditional energy sources such as fossil fuels, and performance of PV installations is highly dependent on unpredictable seasonal environmental factors. Increasing the level of PV systems in the energy network could increase the level of

Swansea University, Swansea, SA1 CCC, UK

Corresponding author: Desmond A. Brennan (desmond.brennan@swansea.ac.uk)

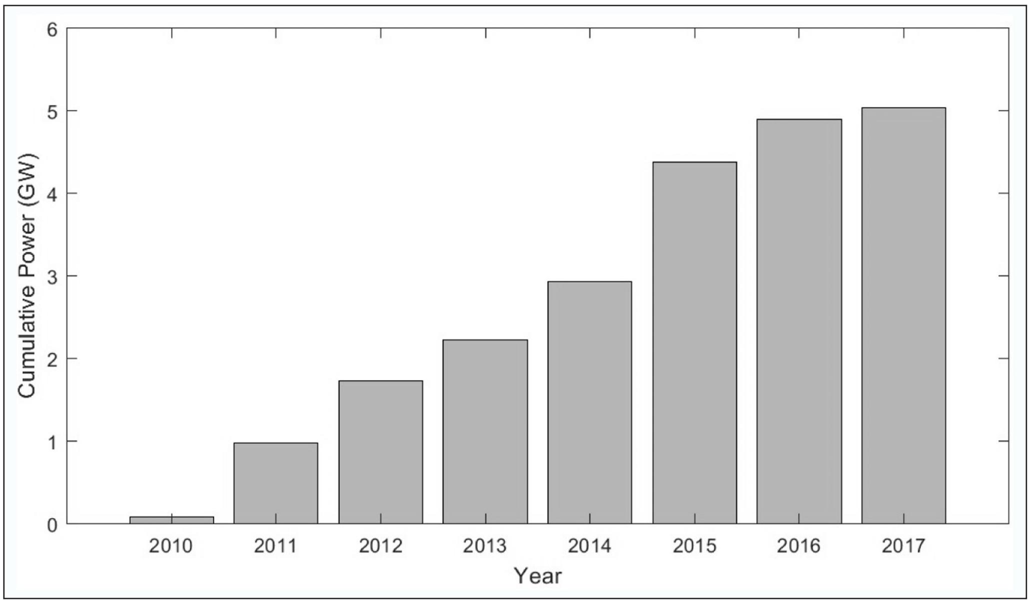

Figure 1: Cumulative power output of PV installations registered with U.K Feed in Tariff (UK Government, 2018).

stress on the power system, endangering reliability and quality of supply, and energy companies have expressed publicly the dangers of increasing solar capacity (Palmer et al., 2017). Demonstration of technologies at building scale is critical to understanding such issues.

In this paper, a long-term analysis of a PV and battery system performance dataset produced by an off-grid educational facility is presented. The seasonal performance and feasibility of building-integrated PV with battery storage in the UK climate is investigated. Similar analyses reported in literature are currently limited to purpose built experimental rigs and arrays, and data on active installations in buildings is not widely available and often limited to months with low granularity. The study here benefits from the building being in frequent use as a lecture theatre, allowing characterisation of user impact on system performance based on a building being used as its primary design function. Maximising the performance of the building system requires planning, accurate methodologies for predicting PV generation, and detailed knowledge of building demand profiles. The paper will demonstrate how this knowledge can be extracted from the dataset.

Active Classroom Demonstrator Building

The Active Classroom is the UK's first off-grid classroom facility based at the Swansea University Bay Campus, and was purpose-built to showcase several solar based technologies in the built environment that can generate and store energy in situ. The classroom is a single storey building with a floor space of 180 m^2 and consists of six rooms: a lobby, a classroom/lecture theatre, a laboratory, breakout and washroom facilities, a storeroom, and a plant room to house the battery storage system. **Figure 2a**) shows how these spaces are arranged within the building envelope.

The classroom was built from abundant materials and using sustainable manufacturing practices. The structural frame uses a unique modular assembly and off-site construction method. Electrical energy is generated by the building integrated photovoltaic modules and stored in the battery system; this provides all electrical power and supplements solar thermal space heating and hot water requirements. The classroom is in regular use on the university campus as a lecture theatre, meeting venue, and to hold laboratory classes. Images of the completed structure, building integrated photovoltaics and battery system are provided in **Figure 2b–d**).

Building energy behaviour is influenced by numerous factors including day of year, weather, structural design and the thermal properties of materials. Demand side management is crucial to lessen building energy use and their environmental impact. The building is fitted with a full data-collection suite, allowing real-time monitoring of performance metrics, and is used to test and validate smart control algorithms.

System Overview

Technologies incorporated in the structure demonstrate how conventional building materials and the building envelope itself, such the roof and façade, can be functionalised to generate energy. The Active Classroom is fitted with a solar array that consists of building-integrated copper-indium-gallium-selenide (CIGS) thin-film photovoltaic modules manufactured by Bi-PV Co, a spin out company from Swansea University research into printed solar cells. The system has a 17 kWp power output under standard test conditions. Solar panel efficiencies are approximately 14%. The solar modules are lightweight compared to conventional silicone solar modules and can be mounted on the building roof without the need for additional load bearing. Such panels are of interest to the construction industry as the photovoltaic cells and junction boxes are incorporated in the steel roofing panel allowing the roof and solar array to be installed simultaneously. The panel modules are coated with a self-cleaning hydrophobic coating, reducing the need for regular maintenance; cleaning is aided by the regular rainfall in the geographical area.

Figure 2: Active Classroom demonstrator building: **a)** architectural diagrams **b)** completed classroom **c)** CIGS building integrated photovoltaic modules **d)** plant room housing battery storage.

The solar modules feed into inverters for DC-AC voltage conversion and maximum power point tracking, and supply two 30 kWh aqueous hybrid ion battery storage systems manufactured by Aquion Energy, giving a total storage capacity of 60 kWh. Such battery systems are promoted as an environmentally friendly alternative to conventional battery technologies such as lithium. The batteries use sodium based aqueous electrolytes in combination with thick electrodes. This architecture reduces energy density but enables a simple design similar to lead-acid batteries making them a realistic low-cost alternative, non-toxic, and requiring little maintenance (Peters et al., 2017).

A HVAC system provides the heating and ventilation for the building, with an additional printed electrical underfloor heating system in the main classroom space. The south façade of the building is fitted with a transpired solar collector (TSC) which consists of perforated steel cladding coated with a highly absorbing IR industrial prepaint system. As the coating warms in direct sunlight, a thin layer of air at the boundary layer is also warmed via conduction. This warm air is drawn in as part of the HVAC system, giving a temperature uplift to the supplied fresh air and the input to an air source heat pump.

Data Aquisition

The Active Classroom is equipped with a full data collection suite monitoring performance metrics such as solar irradiance, photovoltaic power output, consumption and generation metering, and temperature, humidity and air quality metrics. Data is polled and transmitted to an external database server. Polling frequency depends on the type of sensor. Data has been collected continuously since completion of the structure in October 2016, and will be acquired throughout the lifetime of the building. Storing collected data into a relational database system such as MySQL is advantageous as it allows rapid statistical analysis of performance data.

Active Classroom Demonstrator Building

Seasonal Performance

The performance of a PV and battery system can vary widely depending on geographical location, seasonal environmental factors, and the type of technology used. It is important to consider this behaviour when planning building control strategies. Simplistic definitions based on the calendar month are frequently used, that do not account for the characteristics of the building or user behaviour (Zarkadis et al., 2014). PV performance can be counter intuitive, for example, a study of the seasonal variation of PV in the climate of Qatar, a country that receives a high level of sunlight, suggests higher levels of PV performance during winter months, not the warmer summer months, allowing to greater efficiencies due to lower ambient temperatures, skies clearer of dust, and regular rainfall to clean the panels (Touati et al., 2017). Initially, the dataset was analysed to categorise this seasonal variation in the UK climate.

Swansea is located on the western coast of the United Kingdom and experiences a typical oceanic climate (maritime climate) characterised by a relatively narrow annual temperature range and a high level of precipitation.

Meteorological seasons are defined as spring (March–May), summer (June–August), autumn (September–November) and winter (December–February). **Table 1** provides climate data for the region during 2017. Typically, temperatures are cooler in the winter months with average highs of 11°C, and warmer in the summer months with average highs of 19°C observed during 2017. Cloud cover and precipitation is high throughout the year, which suggests a sub-optimal environment for solar energy systems.

Solar generation only occurs during hours of sunlight, the number of which can vary throughout the year depending on location. In the U.K, the number of daylight hours increases from a minimum of eight hours during the winter solstice of the northern hemisphere in December, to a maximum of 16 hours during the summer solstice in June. An average annual solar insolation of 900 $kWm^{-2}y^{-1}$ is typical for the Swansea area, peaking in the summer months during longer hours of daylight, and a favourable tilt of the earth's axis.

Solar irradiance was measured in 10 second intervals using a Kipp & Zonen SMP3 pyranometer positioned in plane with the roof of the classroom at a pitch of 15°. Solar irradiance curves for an arbitrary day in April, August and December are provided in **Figure 3**. Values peak at solar noon when the sun is at its highest point in the sky. Highs of 1,400 W/m^2 and lows of below 100 W/m^2 were observed over the year. Although solar irradiance is generally higher in the summer months, values can vary considerably, not only throughout the year, but also throughout the day due to variations in overlaying cloud. Considerable overlap is observed between the seasons, particularly during spring, summer and autumn.

Figure 4 shows a calendar heat map of PV generation for the year 2017 in kWh. Low levels of solar generation

Table 1: Climate data for the Swansea region during 2017.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. Daylight Hours	8.00	9.82	11.39	13.33	15.39	16.00	15.97	14.26	12.40	10.29	8.80	7.65
Avg. High °C	8.00	9.00	11.00	13.00	17.00	18.00	19.00	18.00	17.00	15.00	11.00	9.00
Avg. Low °C	3.00	4.00	5.00	5.00	10.00	12.00	12.00	12.00	11.00	10.00	4.00	4.00
Precipitation mm/month	55.80	50.40	49.60	6.00	24.80	39.00	58.90	40.30	75.00	24.80	3.30	34.10
Insolation kWh/m²/month	22.90	37.80	69.10	106.20	141.10	141.90	148.10	124.00	82.80	49.30	27.60	18.30
Cloud Cover %	68.70	75.10	72.20	69.90	70.80	74.80	70.70	68.30	68.30	76.90	67.20	65.20
Average PV generation (kWh)	8.79	10.94	22.72	21.02	20.16	25.02	20.28	22.32	21.22	16.51	13.03	10.06

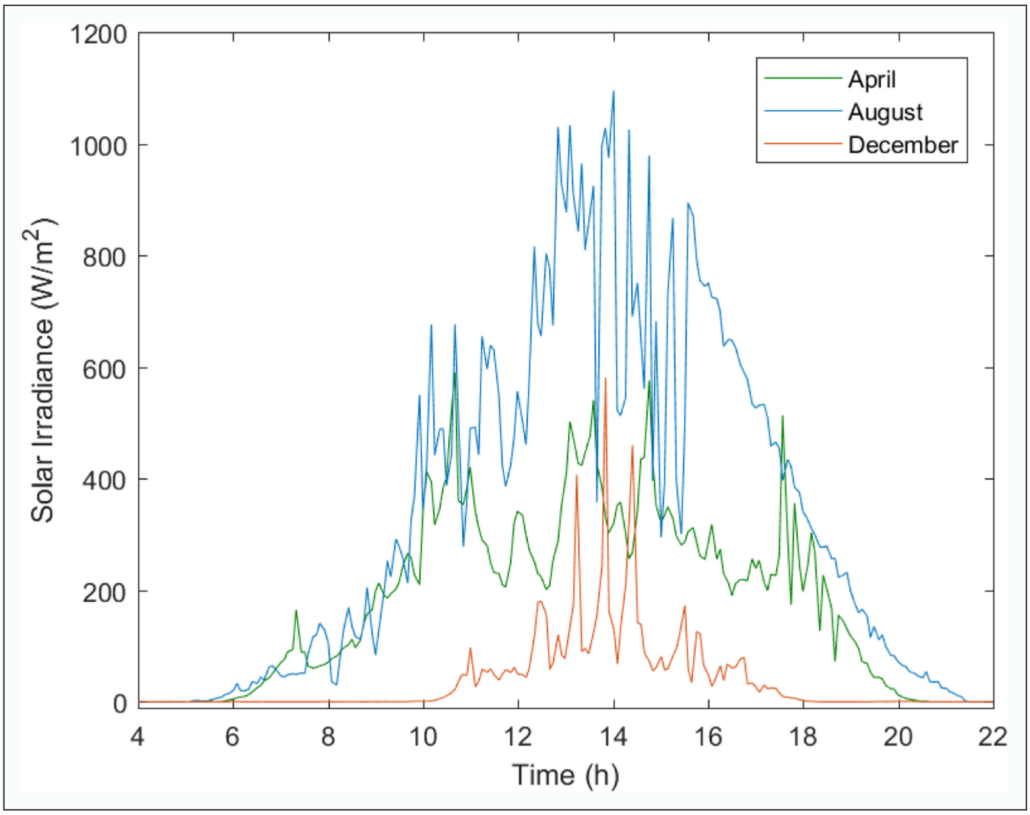

Figure 3: Solar irradiance (W/m^2) against time of day for arbitrary days in April, August and December 2017.

are represented by red coloured cells, and high levels are represented by green coloured cells. Average monthly generation values are also provided in **Table 1**. Generally, higher levels of solar energy generation are observed in the summer months, correlating well with the number of daylight hours and average temperature. June displayed the highest average daily generation, whilst January displayed the lowest average daily generation. Total generation in the winter months was 57% less than generation in the summer months. Peak daily generation values occurred during a local heat wave in mid-June where temperatures touched 30°C. No correlation between precipitation and solar generation was observed – a similar study in (Touati et al., 2017) suggests solar module performance can reduce over time as they gather dust and debris, and that heavy rains can act to clean PV panels, though in a much drier climate than the U.K. It is believed that the self-cleaning coating used on the panels in this study could aid in this cleaning effect, particularly during long periods of rain.

System performance varies considerably when large amounts of overlaying cloud is present. **Figure 5** provides the PV power output (kW), battery state of charge (%) and indicative solar irradiance for a) a clear day, and b) a day with considerable overlaying cloud. During periods of clear skies, irradiance values are greater and the battery system charges at a faster rate. As the battery system approaches full charge, generation tails off, dropping to the building baseload when at a state of charge of 100%. Contrastingly, on a cloudy day, solar irradiance and PV power output can decrease dramatically and the battery system struggles to charge. In an off-grid system, electron flow and PV generation to the battery system stops once the battery system is full. This means energy generated by the solar panels is lost when the batteries reach full capacity, highlighting the importance of a system being connected to a wider distribution network to maximise system performance.

Total generation over the year was almost 6,500 kWh. This value is in the region of 1.5 times the annual electrical energy consumption of a typical U.K family home, demonstrating that PV technology utilising battery storage methods can meet the electrical domestic requirement in the U.K, despite a sub-optimal climate (OFGEM, 2017). It is important to highlight that the classroom facility was off-grid. If the system was connected to the wider distribution network, more PV power could be drawn without the constraint of battery capacity, and larger levels of energy generation would be expected. Excess energy generation could be exported to the grid at a profit to offset energy costs.

Despite the basic behaviour described in this section, solar generation can vary wildly from day-to-day, even

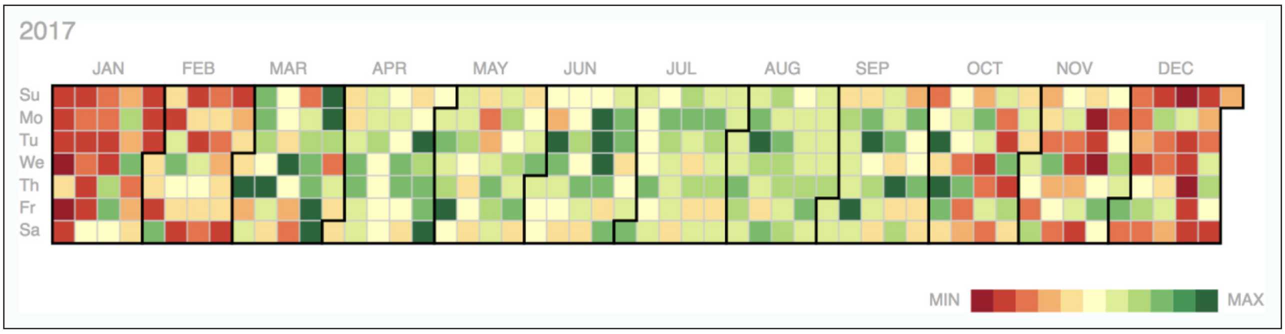

Figure 4: Calendar heat map of daily PV generation 2017 (kWh).

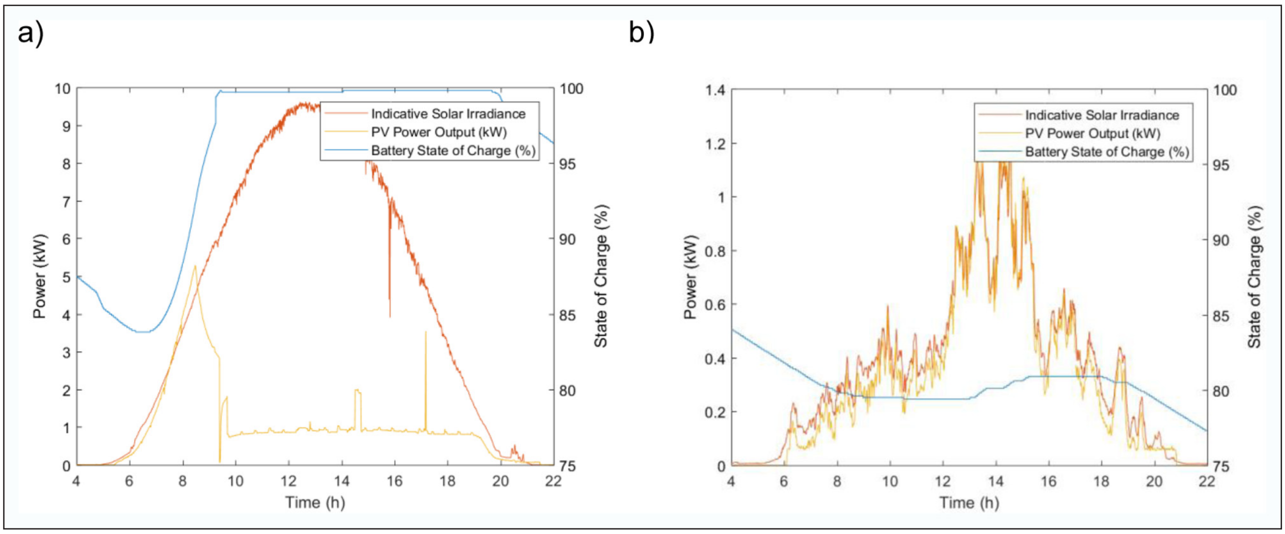

Figure 5: PV power output (kW), battery state of charge (%), and indicative solar irradiance during **a)** a clear day, **b)** a day with a large amount of cloud cover.

during similar months and times of year, highlighting the importance of planning and control systems to optimise solar energy systems.

Forecasting

One of the largest barriers to the wide spread adoption of solar is the intermittency of energy generation, demonstrated in the previous section. Generation is governed by seasonal environmental parameters that can vary considerably with geographical location, making the planning, control and optimisation of such systems difficult. An accurate method to forecast PV power generation could help to reduce this uncertainty and increase the reliability of solar installations (Zarkadis et al., 2014). A detailed account of different techniques for forecasting solar generation are summarised in (Das et al., 2018).

A long-term dataset such as that presented here can be used to aid the development of accurate forecasting models, particularly with relation to the building in question as it includes information regarding local parameters such as shading, angle of incidence, reflections etc. Photovoltaic performance is a function of many different environmental variables; the relationships between such parameters and the power output of the solar modules can be identified and extracted from the dataset. In this section, the relationship between different environmental variables and the performance of the classroom PV and battery system is characterised.

Firstly, the correlation between solar irradiance and PV power output was investigated – this is the most important parameter when discussing solar energy generation because it is this energy that is converted to electrical energy. Referring again to **Figure 5**, strong correlation is observed between solar irradiance and PV power output during periods when the battery is charging. This is demonstrated by the overlaying curves representing irradiance and PV power output during periods of charging. When the batteries are approaching full charge, the PV power output becomes constrained by the building consumption, and this correlation also falls to zero.

Correlation between solar irradiance and PV power output is heavily dependent on the state of charge of the battery system. **Figure 6a** shows the PV power output plotted against solar irradiance for a battery state of charge

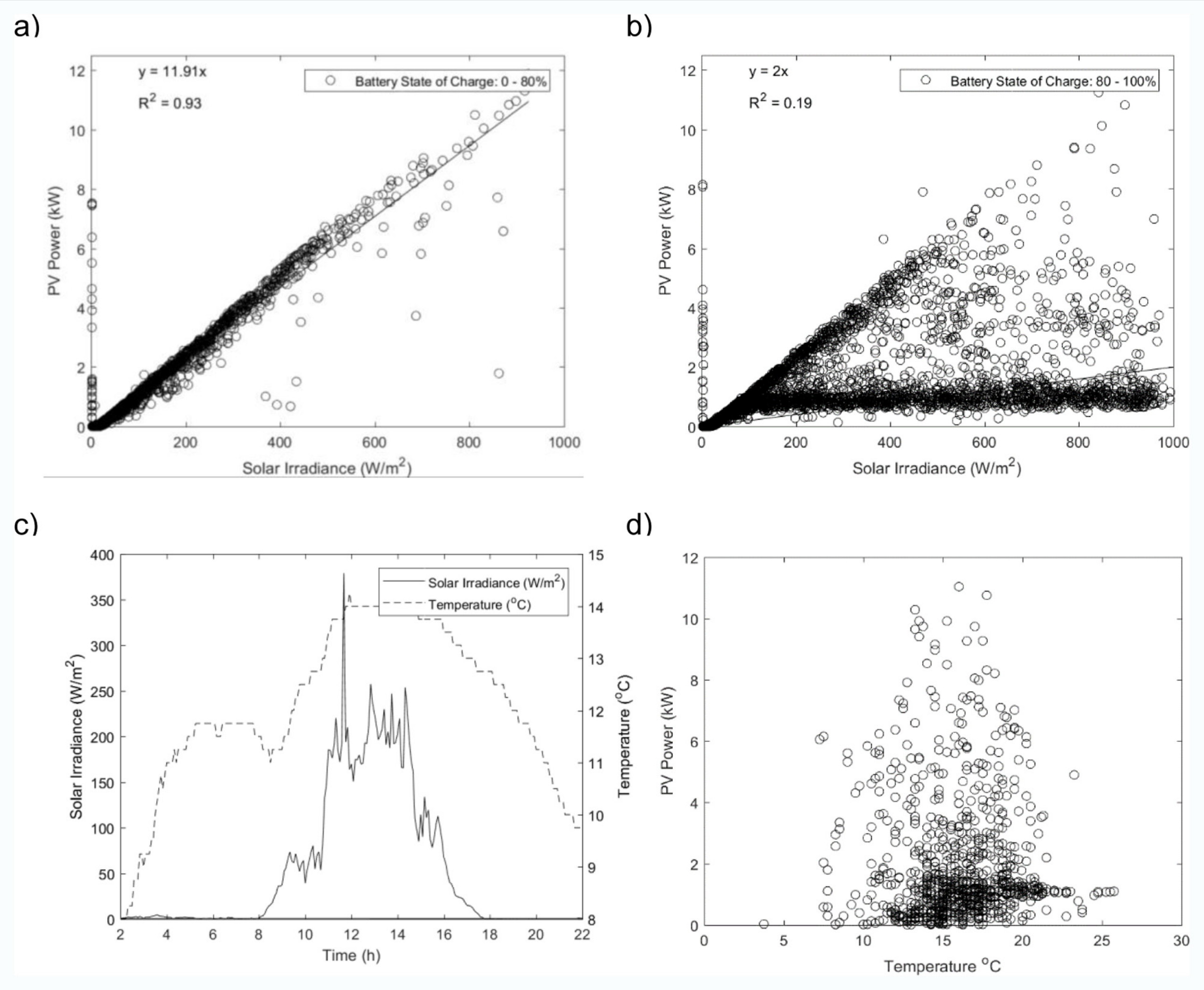

Figure 6: solar irradiance (W/m^2) v PV power output (kW) with battery state of charge between **a)** 0–80% and **b)** 80–100%; **c)** ambient temperature (°C) and solar irradiance (W/m^2) for an arbitrary day; **d)** ambient temperature (°C) v PV power output (kW).

between 0–80%, and **Figure 6b** shows the same plot for battery state of charge between 80–100%, averaged over 15 minute intervals for periods of daylight during 2017. The relationship between solar irradiance and PV power output is linear at a battery charge below 80%, showing high accuracy with an R^2 value of 93%. Performing linear regression yields an expression directly relating the PV performance to solar irradiance measurements that could be useful in any forecasting model or as part of a building management system. Above a battery state of charge of 80%, this relationship is significantly weaker. A large portion of the data points are distributed parallel to the x-axis with an almost zero gradient. The difference in correlation between solar irradiance and the PV power output at different battery charges is the result of the PV output dropping to the base load of the building at maximum state of charge. This is more common at high irradiance values because the battery system reaches full charge more quickly. The behaviour observed here is unique to an off-grid PV battery system, the ability to distribute energy to a wider grid network when the batteries reach capacity could remove the dependency on PV performance to battery state of charge.

Other environmental variables recorded included the ambient outside temperature. **Figure 6c** shows the solar irradiance and ambient temperature during an arbitrary day. The ambient temperature rises and cools from dusk to dawn – the dip early morning is a result of shading. Solar irradiance increases from zero at dawn, to a maximum at midday, and falls back to zero at dusk, loosely tracking ambient temperature. Both peak at midday. **Figure 6d** shows PV power output plotted against ambient temperature. Large variation is observed at similar temperatures – though the spread is much smaller at minimum and maximum temperatures. The efficiency of solar technology decreases at high ambient temperatures, which could suggest the reduction in spread of PV power output at greater temperatures. An optimum temperature for PV performance of around 15°C is suggested by the data. Unlike with solar irradiance, the relationship with PV power output is not as strong, demonstrating how variables can be weakly correlated to PV performance.

Generation and Demamd

In addition to the problems associated with the intermittency of solar energy generation is the misalignment of generation with temporal demand profiles. Solar electrical generation peaks around mid-day when the sun is at its highest point in the sky and drops to zero between sunset and sunrise. In the U.K, demand is at its highest during late afternoon due to increased occupancy of residential buildings when, depending on the time of year, levels of solar generation are low. A seasonal misalignment also exists – demand is greater in winter months because of increased requirement for space heating, whilst solar generation is reduced during this period allowing for shorter days and lower levels of solar irradiance. In any system, it is important that energy is delivered at the right time. Storage techniques work to accumulate this energy for use later, but to maximise their efficiency, awareness of the demand profiles of the system are required. A long-term dataset such as that presented here can be used to identify deterministic trends in energy demand that can be used in the development of control schemes.

Figure 7 shows an hourly breakdown of the total energy generated and total energy consumed during the year 2017 in kWh. As to be expected of a solar source, energy is only generated during daylight hours peaking at around

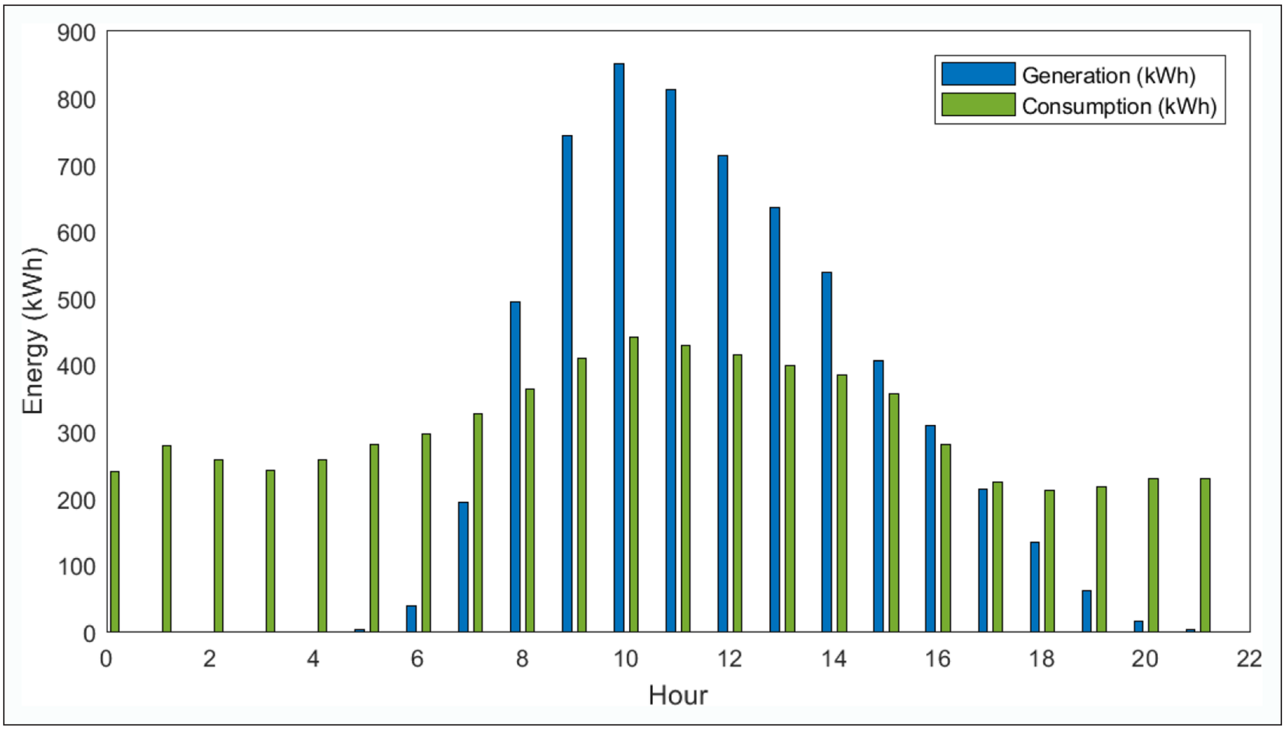

Figure 7: Hourly breakdown of consumption and generation over the year 2017.

mid-day – for the classroom, peak generation occurs slightly earlier due to the inclination of the solar modules. Electrical demand is observed at all hours, highlighting the need for storage techniques. Demand profiles show a continuous baseline throughout the day, even during zero occupancy, which matches the energy requirements of persistent systems such as the building management system (BMS) and HVAC. Demand increases from early morning due to heating requirements, and peaks during the operating hours of the classroom. Interestingly, peaks in solar energy generation are more aligned with peaks in classroom demand than with peaks in national domestic demand, suggesting solar technology generation profiles are better aligned with commercial demand profiles than residential demand profiles. The co-location of buildings with different demand profiles – such as commercial and domestic – could be a mitigation method to minimise the temporal mismatch between generation and consumption often observed when only a single building topography is considered.

Contracts between small scale generators and distribution networks for the export of energy often stipulate time frames for energy export, and impose penalties for violating such agreements. To ensure contractual commitments can be met, it is important to be aware of system demand. Control algorithms such as that described in (Beaudin et al., 2015) that optimise the processes of battery charge, load supply, and grid export – if a connection to a wider distribution network is available – to maximise profit, also require advanced knowledge of energy generation and demand profiles. Awareness of the baseline electrical consumption of the system, and advanced knowledge of classroom occupancy that could be used to estimate demand, provide critical information for such scheduling algorithms.

Conclusions and Future Work

In this paper, a seasonal analysis of a long-term dataset produced by an energy positive classroom facility on the Swansea Bay Campus in the United Kingdom is presented. The building is the UK's first off-grid classroom facility, showcasing several solar orientated renewable energy technologies including building integrated CIGS photovoltaics and battery storage. A bespoke data-collection system is installed, allowing real-time monitoring of performance metrics such as solar irradiance, PV and battery metering, temperature, humidity and air quality. The building can be used to validate and develop smart control algorithms to optimise the PV – battery system. The study benefits from the length and high granularity of the dataset, and the building being in frequent use as a lecture theatre on the university campus, allowing characterisation of user impact on the system. Data on such technologies in the working environment is not widely available and limited to low granularity. Here, the dataset is used to characterise the seasonal performance of a PV – battery system in the U.K climate – a climate considered sub-optimal for solar orientated technologies, and to highlight important considerations in building control strategies.

Located on the western coast of the United Kingdom, the classroom experiences a typical maritime/oceanic climate characterised by a relatively narrow annual temperature range and a high level of precipitation throughout the year. Generally, solar energy generation is at a minimum in the winter months and a maximum in the summer months when temperatures are higher and hours of daylight are longer. Generation in the winter months was 57% less than generation in the summer months. On a clear day, solar irradiance and the power output of the PV is high, and the battery system reaches capacity fast. For an off-grid facility, PV power output drops to zero as the battery system reaches full charge. This curtailment of power demonstrates the importance of a system being connected to a wider distribution network to optimise performance. Despite this general behaviour, high variability of solar performance is observed throughout the year, with much overlap between seasons – particularly during spring, summer and autumn. Even though the climate is considered sub-optimal for solar technology, the system generated almost 1.5 times the average electrical demand of a typical U.K family home, highlighting the potential of solar technology.

The reliability of solar installations could be improved with access to accurate methodologies to predicting solar energy generation. The dataset has been used to identify the correlation of different environmental variables to PV power output. In an off-grid scenario such as the classroom, strong correlation is observed between the solar irradiance, battery state of charge, and PV power output, highlighting the importance of accurate methodologies for measuring these variables as part of a short-term solar forecasting model. Linear correlation is observed between the solar irradiance and PV power output, with the form of the equation and strength of correlation depending on the battery state of charge. Finally, the dataset has been used to identify trends in generation and consumption that could be useful as part of a building control algorithm. The classroom has a baseline energy consumption that can be extracted from the dataset. Consumption peaks during the operating hours of the building. Knowledge of the demand profile of the building is critical to optimisation of the solar and battery system, and could be used as part of a scheduling algorithms.

Limitations of the study are the length of the dataset and how it is restricted to a single building, which could reduce the scope and statistical significance of the results. The statistical performance of the system could vary from year to year as environmental parameters fluctuate, and could be unique to the performance of the building in question. The study will improve as the length of the dataset increases, and by benchmarking against new data streams from other buildings.

Further work on the building will include the installation of a grid connection allowing distribution of locally generated energy. The building will be used to develop building control algorithms that schedule buying and selling energy from the grid, maximising profit from government policies such as 'Feed in Tariffs', and minimising stress on grid network. An office that showcases similar technologies is under construction at the campus and the ability to exchange energy between the two battery systems will be investigated, and incorporated into the building management system. This co-location of buildings with different consumption profiles could be a mitigation method to minimise the temporal mismatch between generation and consumption often observed when only a single building topography is considered.

Acknowledgements

This work has been conducted as part of the research project 'Joint UK-India Clean Energy Centre (JUICE)' which is funded by the RCUK's Energy Programme (contract no: EP/P003605/1). The projects funders were not directly involved in the writing of this article.

Competing Interests

The authors have no competing interests to declare.

References

Beaudin, M and **Zareipour, H.** 2015. Home energy management systems: A review of modelling and complexity. *Renewable and Sustainable Energy Reviews*, 45: 318–335. DOI: https://doi.org/10.1016/j.rser.2015.01.046

Biyik, E, Araz, M, Hepbasli, A, Shahrestani, M, Yao, R, Shao, L, Essah, E, Oliveira, A, Cano, T, Rico, E, Lechon, J, Andrade, L, Mendes, A and **Ath, Y.** 2017. A key review of building integrated photovoltaic (BIPV) systems. *Engineering Science and Technology, an International Journal*, 20: 833–858. DOI: https://doi.org/10.1016/j.jestch.2017.01.009

Burmester, D, Rayudu, R, Seah, W and **Akinyele, D.** 2017. A review of nanogrid topologies and technologies. *Renewable and Sustainable Energy Reviews*, 67: 760–775. DOI: https://doi.org/10.1016/j.rser.2016.09.073

Das, U, Tey, K, Seyedmahmoudian, M, Mekhilef, S, Idris, M, Deventer, W, Horan, B and **Stojcevski, A.** 2018. Forecasting of photovoltaic power generation and model optimization: A review. *Renewable and Sustainable Energy Reviews*, 81: 912–928. DOI: https://doi.org/10.1016/j.rser.2017.08.017

Magoules, F and **Zhao, H.** 2012. A review on the prediction of building energy consumption. *Renewable and Sustainable Energy Reviews*, 16: 3586–3592. DOI: https://doi.org/10.1016/j.rser.2012.02.049

OFGEM, UK. 2017. Typical domestic consumption values for gas and electricity. Available at: https://www.ofgem.gov.uk/gas/retail-market/monitoring-data-and-statistics/typical-domestic-consumption-values [Last accessed: 01/10/2018].

Palmer, D, Koublie, E, Cole, I, Betts, T and **Gottchalg, R.** 2017. Comparison of solar radiation and PV generation variability: System dispersion in the UK. *12th Photovoltaic Science Application and Technology Conference*. DOI: https://doi.org/10.1049/iet-rpg.2016.0768

Peters, J and **Weil, M.** 2017. Aqueous hybrid ion batteries – An environmentally friendly alternative for stationary energy storage? *Journal of Power Sources*, 164: 258–265. DOI: https://doi.org/10.1016/j.jpowsour.2017.08.041

Touati, F, Chowdhury, N, Benhmed, K, Gonzales, A, Al-Hitmi, M, Benammar, M, Gastli, A and **Ben-Brahim, L.** 2017. Long-term performance analysis and power prediction of PV technology in the State of Qatar. *Renewable Energy*, 113: 952–965. DOI: https://doi.org/10.1016/j.renene.2017.06.078

UK Government Department of Energy & Climate Change. 2018. Feed in Deployment Statistics. Available at: https://www.gov.uk/government/collections/feed-in-tariff-statistics [Last accessed: 01/10/2018].

Zarkadis, N, Ridi, A and **Morel, N.** 2014. A multi-sensor office-building database for experimental validation and advanced control algorithm development. *Procedia Computer Science*, 32: 1003–1009. DOI: https://doi.org/10.1016/j.procs.2014.05.525

How to cite this article: Brennan, DA, White, C, Barclay, M, Griffiths, T and Lewis, RP. 2019. Performance Characterisation and Optimisation of a Building Integrated Photovoltaic (BIPV) System in a Maritime Climate. *Future Cities and Environment,* 5(1): 8, 1–9. DOI: https://doi.org/10.5334/fce.62

Submitted: 21 October 2018 **Accepted:** 12 December 2018 **Published:** 13 February 2019

]u[*Future Cities and Environment,* is a peer-reviewed open access journal published by Ubiquity Press.