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ORIGINAL ARTICLE

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Next steps in the footprint project: A feasibility study of installing solar panels on Bath Abbey

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Abstract

Reduction of the carbon footprint of historic buildings is urgent, given their exceptionally large energy demand. In this study, the performance and cost of a roof mounted photovoltaic system has been simulated for Bath Abbey, a grade I listed building, to test the financial viability of installing such a system. The electrical output of the panels was generated by the software package PVsyst with inputs such as the known dimensions of the Abbey, historical weather data, the orientation of the Abbey's roof, module azimuthal and tilt angles and shading by the spire and roof features. An important result is that even though the roof is not shadowed by other buildings, shading causes a 19% loss of peak power. This model was used to determine a recommended configuration comprising 164 solar panels, separated into two subsystems located on two parts of the roof, each with an inverter. Its predicted electrical output, 45 ± 2 MWh generated in the first year of operation, formed the basis of a cost–benefit analysis. This system will become profitable after 13.3 ± 0.6 years and provide a profit of £139,000 ± £12,000 over its 25-year lifetime. Financial stress tests were performed for key assumptions to ensure that this result was true in all likely scenarios. This result shows that it is likely to make financial sense to install a photovoltaic system on a historic grade I listed building.

KEYWORDS

Bath Abbey, historic building, photovoltaics, renewable energy, solar power

1 | INTRODUCTION

As part of the ongoing decarbonization of society's energy sources, it is important to shift from traditional energy sources to renewable energy sources such as wind and solar. An area that is a particular challenge is reduction of the carbon footprint of historic buildings.[1] These buildings typically have poor energy efficiencies and a disproportionate energy demand and thus a larger carbon footprint compared with more modern buildings. If society is to reach net carbon zero, reducing the carbon footprint of historic buildings is essential given their importance to their communities. The Church of England, as an owner of many historic buildings, has recognized the importance of reducing its carbon footprint by launching campaigns such as 'Shrinking the Footprint' and the 'Big Church Switch'.[2,3] These campaigns have had considerable success, leading to over 5500 churches having electrical energy generated from 100% renewable sources,[4] recently acknowledged in a study of mounting solar panels on the Cathedral of St. Michael the Archangel in Belgrade.[5] In most cases, the churches switched their electrical energy supplier to a supplier that only generates electrical energy through renewable energy sources. However, some churches went further by installing solar photovoltaic (PV) systems on their roofs, generating electrical energy from sunlight. Examples include St John's Church (Manchester), St Peter's Church (Petersfield, Portsmouth) and St Michael's Church (Baddesley).[6,7] A 150 panel PV system was installed on the roof of Gloucester Cathedral in 2016 (Figure 1). In the first year after installation, the system generated 31 MWh of electrical energy, reducing their electrical energy bill by £4000 in 2017.[8] However, few scientific papers have appeared on English churches, an exception being Khatri et al. who discussed the benefits and concerns associated with the application of rooftop solar PV and compared the performance of technologically viable options.[9]

FIGURE 1 A view of Gloucester Cathedral roof upon completion. Image provided by Mypower Solar[15]

Bath Abbey is a grade I listed building in the centre of the city of Bath and is a major tourist site in the city and a place of architectural, cultural and spiritual significance.[10] Here, the grade 1 listing refers to appearing on the National Heritage List for England covering buildings of special architectural or historic interest considered to be of national importance and therefore worth protecting. The objective of this paper, inspired by the success of the Gloucester Cathedral installation, was to investigate whether it would be financially viable for a grade I listed building such as Bath Abbey to install a PV system on its roof and so demonstrate the affordability of solar for historic buildings. To reduce its emissions, the Bath Abbey Footprint programme,[11] a £19.3 million series of actions aimed at improving the building's accessibility and sustainability, was initiated and to which this study contributes. To reduce its footprint, the geothermal hot springs of the local area provide underfloor heating and LED light bulbs installed to illuminate the interior. This work was aided by the Footprint programme. Installing rooftop solar panels is another way the Abbey could reduce its footprint further.

The strengths and weaknesses of mounting solar on the rooftops of historical buildings have attracted much debate. In a model of the installation of a PV system on the Cathedral of St. Michael the Archangel in Belgrade, the software suite PVsyst combined with data on the annual solar radiation in Serbia identified the number of PV modules required to power its lighting.[5] Nina-Cristina et al. described the practicalities of installing solar on a church in Romania, comparing PVsyst with a mathematical model developed at the Technical University of Cluj-Napoca, TUCN. They used local solar irradiation and ambient temperature data provided by TUCN.[12] In a study on the architectural integration of PV systems in the historic city centre of Santiago de Compostela, Lucchi et al. employ solar insolation data and assumed a PV efficiency of 15% and losses of 25% in electricity production to show that PV production could cover 68% of electricity needs of the district.[13] The emphasis here is on integrating PV elements into the building envelope, allowing for distribution of roof typologies and of roofs where the installation of PV modules is allowed. Other studies on the implementation of PV on historical buildings addressed the importance of matching the style of the building with the panels chosen, and minimizing the disruption to the buildings aesthetic to ensure the cultural heritage of the building is preserved,[1] and barriers to installing PV on historic buildings including the visual aspect and the preservation of the historical architecture.[14]

We employed the commercial software package PVsyst (version 6.79)[16] and meteorological data to predict generated daily electricity from the 164 panels that can be fitted on unshaded regions of the Abbey roof. The PVsyst generated model of the Abbey based on scale drawings of the Abbey provided by the Footprint Project is viewed alongside an image of the Abbey in Figure 2. The novelty of this paper is firstly by considering shading effects in detail as they are shown to be important by Fairbrother et al.[17] for built in PV. These effects impact electrical output dependence on panel tilt angles and variations in incident solar power. Secondly, we provide a cost–benefit analysis where we compare the electrical energy (in kWh) bought by the Abbey, with that generated by the PV system. Financial stress tests were performed for key assumptions to allow for likely scenarios. We have allowed for balance of system costs through including the cost of inverters, yearly efficiency degradation and the cost of installation for small-scale PV and estimates taken from the additional costs of the Gloucester Cathedral solar installation. Our financial estimates take account of Smart Export Guarantees (SEGs) introduced by the UK Government at the end of 2019.

2 | METHODOLOGY

Figure 3 shows how the elements of our model are combined to achieve our objective of establishing whether a roof mounted PV system financially viable for Bath Abbey.

2.1 | PV system modelled

We used PVsyst to model the PV system shown in Figure 4. Inverters convert the electrical energy to be compatible with the National Grid. The inverters are chosen to match the power requirement of the arrays. The first sub-array was Huawei Technologies SUN2000-30KTL-A that has a maximum AC output power 33 kWac. The second sub-array was the Sun Power SP 25000 that has a maximum AC output power 22 kWac. The modules were LG 365 Q1C-A5 giving an output of 365 W, module efficiency of 21.1%, power tolerance of ~3% and maximum power at nominal operating cell temperature at 275 W. They were selected as they are a popular model in the UK. Optimizers are included to minimize the impact of the shading on the PV system performance by ensuring that if any individual solar panel is shaded, the maximum current can still flow through that one panel. Other equipment choices could be considered to optimize further the cost and efficiency of the devices to maximize profits.

Bath Abbey architectural information was taken from[10] and from architectural drawings provided by the Footprint project. The wall heights and roof area used in the model come from these sources. While the crenellations have the correct heights, they are approximated by cuboids. The model also lacks other features such as turrets, buttresses, arches and gargoyles as these features contribute little to the shading. All features below roof level are ignored as they do not contribute to the shading.

2.2 | Model of power generated by roof mounted PV modules

To generate the electrical power vs time from the PV system, required inputs are the system components shown in Section 2.1 ,module plane orientation, measured irradiance in the horizontal plane at the ambient temperature and module shading.

For the irradiance levels on Bath Abbey, data are collected from the open source Meteonorm database file 'Bath_MN72_SY.MET' in the PVsyst database. Here, the weather data were interpolated from the three nearest stations, and all stations are within 16 km of the Abbey giving an indication of the spatial resolution.[18] The values were recorded hourly over a ten-year period in the Bath area from 2003 to 2013, the most up-to-date statistics for the area.

Panel orientation was determined by a tool on PVsyst that uses the inputted Meteo file to generate the optimal orientation by using the hourly data over one year to evaluate the transposition factor on 475 tilt angles and azimuth angles. The transposition factor, the ratio of sunlight

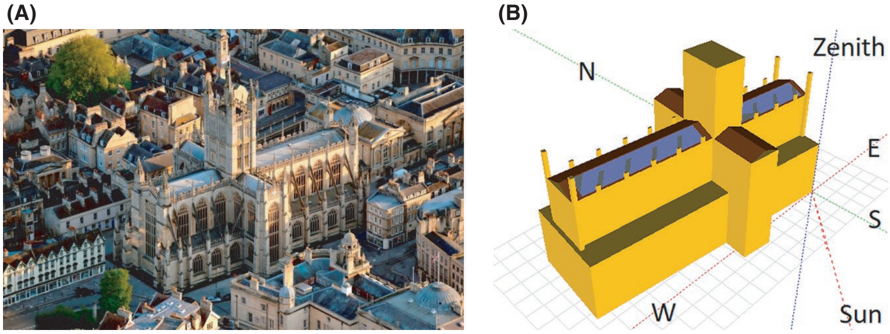

FIGURE 2 (A) A view of Bath Abbey. (B) Model of the Abbey used to evaluate the predicted electrical generation of our system for this study

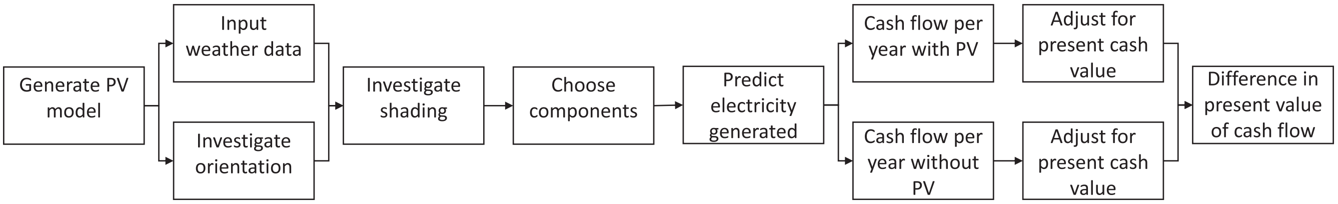

FIGURE 3 A flow chart indicating how the model was used to find the net present value and show whether the decision to install would make financial sense

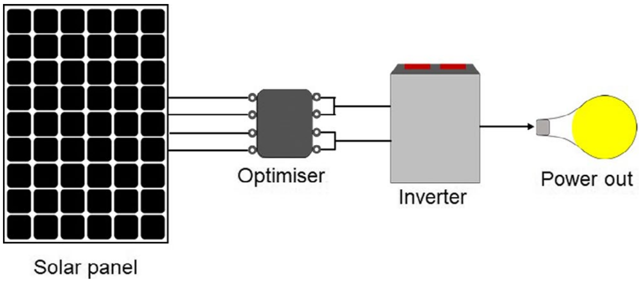

FIGURE 4 Components of the PV system considered in this paper. Two separate systems were used and combined on the south-facing roof of the Abbey

striking the plane to the horizontal sunshine, allows us to evaluate the gains and losses obtained tilting the plane of the solar panel array. The model used to evaluate the transposition factor is based on the work by Hay and Davies.[19] From the Hay and Davies, the incident irradiation on the panels as a function of the angle of tilt and the azimuth angle is obtained for 475 different angle tilts and azimuth angles which then allows for the calculation of the transposition factor for all 475 combinations.

Shading was investigated using three shading factors defined for the three irradiance components from the input meteorological data: the beam, diffuse and albedo components. The simulation determines the time of the crossing of the horizon line by the sun within the simulation hour and applies this fraction of hour as a loss to the beam component. Albedo is a measure of the diffuse reflection of solar radiation. We have analysed the impact of the shading at peak power (12.45 PM on 21 December), when there is high shading and poor irradiance. At this time, global irradiance amounts to a beam component of 363 W and a combined diffuse plus albedo component of 99 W. For the beam component, a shading factor is defined which is simply the shaded fraction of the PV module area for a given sun position.

The shading factor for the diffuse component assumes diffuse light is isotropic and is calculated as an integral of the shading factor performed over all sky directions. It is independent of the sun's position. Contributions to this factor are near-shading obstacles and incidence angle modifier effects (IAM). IAM corresponds with the decrease in the actual irradiance upon the modules' surface, with respect to irradiance under normal incidence. This loss is mainly due to reflections on the glass cover, increasing with the incidence angle. The shading factor of the albedo component depends upon the proximity of close obstacles which block the ground reflection of far terrain. This is generally assumed in an urban environment to be between 0.14 and 0.22 and in this model calculated to have a value of 0.195. This is calculated as an integral according to nearby features.

When the shading calculations are applied in our simulations, two losses are computed: linear shading losses representing the irradiation deficit and electrical shading losses resulting from the electrical mismatches between shaded and non-shaded interconnected PV modules in an array. The electrical shading losses are calculated after accounting for near-shading losses from the irradiance deficit, albedo and diffuse attenuation. The electrical shading loss is expressed in the shading factor as the power loss relative to the array nominal power at standard test conditions (57.28 MWh).

Relative losses are defined as the shading factor loss relative to the contribution of its corresponding beam component. For example, the relative albedo loss is between 0% and 0.1%. As the horizon line rises above 20°, the albedo component tends towards zero. The proportion of light reflected from far terrain is very low. At peak power (when the sun is high in the sky at 12.45 PM and there is a low irradiance deficit), the amount of far terrain (neighbouring buildings, hills) reflection is increased due to increased irradiation, and hence, shading losses from near obstacles increases from 0% (morning, evening) to 0.1% (midday). At 12.45 PM, the albedo component of diffuse irradiance maximizes at approximately 2.4 W.

2.3 | Cost–benefit analysis methodology

The electrical power generated was costed in a cost–benefit analysis of the PV system to decide whether it was a financially sensible to implement the system in the Abbey. The decision about economic viability is based upon the present value of installing PV, defined as the difference in the cash flow the Abbey would experience with and without installing a PV system. We have accounted for inflation based upon the present value of money, as is standard practice when assessing the viability of any investment and for SEG payments. The feed-in-tariff (FIT) payments consist of a tariff for every unit of electrical energy generated and a payment for any electrical energy exported to the National Grid.[20] These payments made most rooftop PV systems very profitable over their twenty-five year lifetime. As of the 31 March 2019, the scheme stopped accepting new customers because it was unsustainable for the National Grid to continue with this pricing model. Any rooftop PV system that was installed after this date would feed unused electrical energy back into the grid at zero tariff,[21] making it more challenging for newly-installed PV systems to appear profitable. A new scheme was implemented on 31 December 2019: the SEG. SEG requires any large utility company to pay for any excess electrical energy their customers generate, which ensures that it is once again easy to profit from the installation of a rooftop PV system.[22]

To calculate the cash flow of the Abbey with a PV system installed, the estimated electrical energy bought E_b by the Abbey from the grid to supplement the PV system to reach their demand is calculated from

$$E_b = E_d - E_g \tag{1}$$

where E_d and E_g respectively represent the amount of electrical energy (in kWh) demanded by the Abbey and generated by the PV system. The electricity demanded is averaged every month between 2015 and 2018, based upon monthly electricity bills, and then divided by the number of days to get a daily electricity demand. It has been assumed this demand will remain consistent into the future. The electricity generated is an output from the PVsyst simulation.

The efficiency of any module will degrade with time. We have assumed an efficiency degradation of 0.4% per year based on specifications provided by the manufacturer.[23] Therefore, the electrical energy generated must be updated each year and consequently the electrical energy bought from the grid.

Next, for a given year, the net cash flow for the Abbey with the PV system will be given by:

$$CF = I - C_{EB} - C_{OM} - C_C \tag{2}$$

where CF represents the cash flow for the abbey in a given year, I represents the income from selling electrical power back to the grid, C_{EB} represents the cost of the bought electrical energy, C_{OM} represents the cost of operating and maintaining the PV system and C_C represents the capital cost of the PV system. By finding the difference between the electricity generated and the electricity demanded on any individual day, and summing this over the year, and multiplying by a SEG rate available on the market (5.5 p/kWh rising at 2% per year), the income can be calculated. It has been assumed that the cost of electrical energy in the first year would be £0.14/kWh (the UK's average) with an electrical energy price inflation of 5%, using averaged electricity price inflation from January 2011 to September 2019 from the UK Office for National Statistics.[24,25] The only significant operating and maintenance cost will be cleaning the panels. This cost has been assumed to be £200 per year rising each year by 2% due to inflation, as it would require professional services due to the significance of the building. The final cost, the capital cost, would be spent entirely in the first year when the system is installed.

TABLE 1 Summary of the capital costs assumed in installing the PV system

Cost item	Cost (£)
Installation	71,000
Roof preservation	30,000
Module, inverters and other components	32,000
Shipping	1000
Total	134,000

The contributions to the capital costs are summarized in Table 1. Installation costs of £1139 per kW installed in 2018/19 are taken from UK government data released annually for small-scale PV.[26] The costs include the cost of safety and access equipment such as a crane with edge protection for the building. On top of this standard installation cost, there are unique difficulties involved in installing a PV system on a building such as Bath Abbey, as mentioned previously. The extra difficulties in calculating this are reflected in the roof preservation cost based on the additional costs of the Gloucester Cathedral installation. The rest of the expenditure for the capital cost is related to the price of the individual parts of the system shown in Figure 4. The cost of modules, inverters and other components varies according to the distributor, but £200 is a fair estimate for the price of these panels, which are currently a few years behind the state of the art and therefore somewhat cheaper on the market. LG's current top of class monocrystalline silicon module, the NeON R 375 sells at approximately £250. The shipping costs for the 2.52 tonnes of modules are included separately to this item.

The above summary allows for the calculation of the net cash flow for any year using Equation (2), noting that the capital cost would be zero for all years except the first. The next step to calculating the present value is to adjust for inflation. This adjustment allows for the investment to be considered in terms of the current value of money. A discount rate d_r of 2% has been used, which can then be used to find the discount factor for a given year with the following equation:

$$DF = \frac{1}{(1+d_r)^N} \tag{3}$$

where DF is the discount factor and N is the number of years since the solar panels were installed. The discount factor is then multiplied by the net cash flow for a given year to give the present value net cash flow for a given year. After this point, the last step for calculating the present value net cash flow for the Abbey is to sum all the net cash flows for a year, adjusted to present value, for all the years up to the year of interest. For example, the cumulative net cash flow for the third year would be the sum of the net cash flows from the first three years.

The cash flow of the Abbey without the PV system must also be calculated; that is, the amount of cash the Abbey will spend on electrical energy without the PV system (adjusted for inflation). Therefore, present value net cash flows for both the scenario of installing a PV system and to continue buying electrical energy from the grid would be known. The difference between the two of these values each year is the present value of installing the PV system, the economic metric used to evaluate the economic viability of installing a PV system on the roof of Bath Abbey. The uncertainty of the result is calculated by considering the two extremities of the predicted power output of the system.

3 | RESULTS AND DISCUSSION

3.1 | Predictions of power generated by roof mounted PV modules

The most important parameter determining the output of silicon PV modules is the angle of tilt (angle between the panels and horizontal) and the azimuth angle (angles between the panels and south) which are the two key angles when finding the optimal orientation. The optimal orientation will depend on the latitude and longitude of the roof. The ideal orientation, generated from PVsyst for our case study, is 0° and 40° for the tilt and azimuth angle, respectively. The Abbey's roof has a 20° tilt and the south-facing roof has a 6° azimuth angle, within 95% of the maximum possible irradiation energy incident on the panels throughout the year (see Figure 5A).

These results show that fitting a tilt adjustment mechanism would improve performance. However, there are already difficulties associated with preserving the integrity of the Abbey's roof. Gloucester Cathedral faced similar concerns and so is a useful example of the logistics to solve this, and the potential costs that may occur when doing so. After a survey, they created a rail fitting to go onto the roof without piercing the covering. The rail was secured to the central ridge of the roof and rested on soft pads in the eaves. To ensure updrafts did not disturb the structure, concrete ballasts were secured under the solar panels. This structure can be viewed in

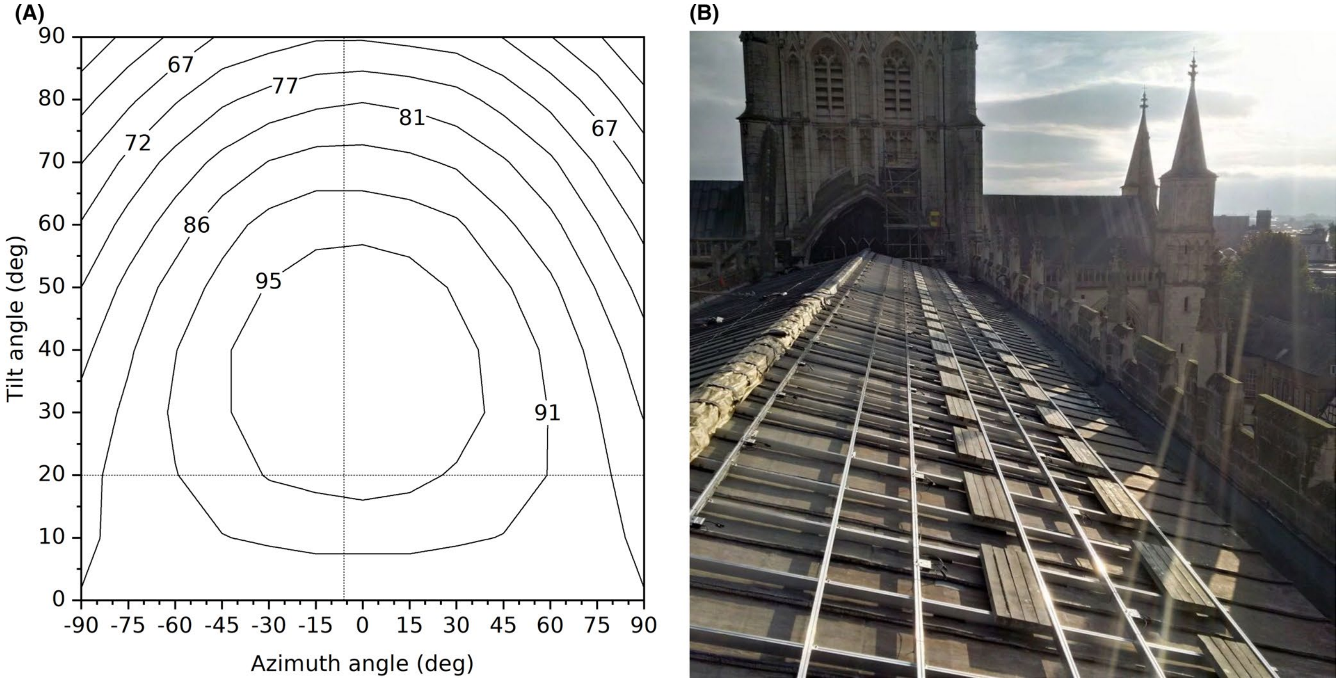

FIGURE 5 (A) The percentage of the maximum performance for different azimuth angles and tilt angles are shown in this contour plot. The Abbey roof has a 20° tilt and an azimuth angle of 6° shown by the dotted lines. (B) Gloucester cathedral's solution to the difficulty of installing a PV system on the roof of a building like the Abbey. Image provided by Mypower Solar[15]

Figure 5B. However, it is worth noting that Gloucester Cathedral has a roof constructed of steel and timber, while the Abbey's roof is predominantly timber, which may give rise to further complications. As a result of these considerations, it was decided for the model that the system should cover the south-facing roof, on both the east and west side of the spire, without any adjustments to account for the ideal tilt or azimuth angle.

From the module dimensions compared to the roof dimensions, we deduced that two subsystems, one either side of the central spire, would be the most effective way of utilizing the region of the Abbey's roof that is not shaded because this region covered the entire south-facing roof. The first sub-array consists of 100 panels (20 panels in series with five of these rows in parallel with one another), and the second sub-array consists of 64 panels (16 panels in series with four of these rows in parallel with one another).

Following the work of Fairbrother et al,[17] we looked at the influence of shading on power output. Shading does not come from other buildings or trees due to the height of the roof (Figure 2A). Instead, the shading comes from the spire, the four larger columns at either end of the roof and the crenellations along the roof. Figure 6 shows that shading a small section of a module can lead to a disproportionately larger reduction in output power depending on the location of that section. Reducing the output of one cell reduces the output of the module due to the series electrical connection. This study is important since shading can damage the modules because different areas of the panel produce different amount of electrical energy for shaded and unshaded regions leading to overheating.

A series-connected set of solar cells or modules is called a string. In our model system, the strings lie parallel to the longest length of the south-facing roof as shown in Figure 7. The effects of the shading on power generation at the peak generation hour on a day in mid-December at 12.45 PM for strings in each sub-array are depicted in Figure 6. Comparison between 6(A) and 6(B) shows that electrical losses dominate in strings 1 and 2 in sub-array 1 due to shading from the crenellations, reducing effective voltage at PV efficiency at maximum power point (P_{MPP}). These losses for strings 6–9 for sub-array 2 (SP 25000) are shown in Figure S1.

Globally, Table 2 shows the PV system experiences a loss of 19.2% over the hour ending at 12.45 PM on 21 December. This loss is dominated by electrical mismatch losses as a result of shading of modules interconnected in the same string. Over the course of a year, the effect on power output is the loss of 34 MWh of irradiance losses from near shadings and 7 MWh from electrical losses.

Our model is a PV system mounted on the Abbey roof can produce a power of 59.9 kW from 164 solar panels with 365 W of power each. Using the PVsyst software, this model predicts that in the first year of installation, the PV system would generate (45 ± 2) MWh of electrical energy. This 5% error has been assumed based upon previous work comparing a model PV System to the measured output of that system.[27] This result means that (35.7 ± 1.5)% of the Abbey's electrical energy would be produced by the system during its first year, decreasing to (32.4 ± 1.5)% of the Abbey's electrical energy by the twenty-fifth year of its lifetime (due to the panels degrading over time). Furthermore, on 46 days of the year, the Abbey is predicted to produce excess electricity (see Figure 8A) so that 4.6% of this electricity can be sold back to the grid to provide income for the Abbey. Figure 8A demonstrates the importance of accurate estimates of the generated power variation with time as the generated power is similar to the average power required, to the extent that the generated power does exceed the required power during the summer months.

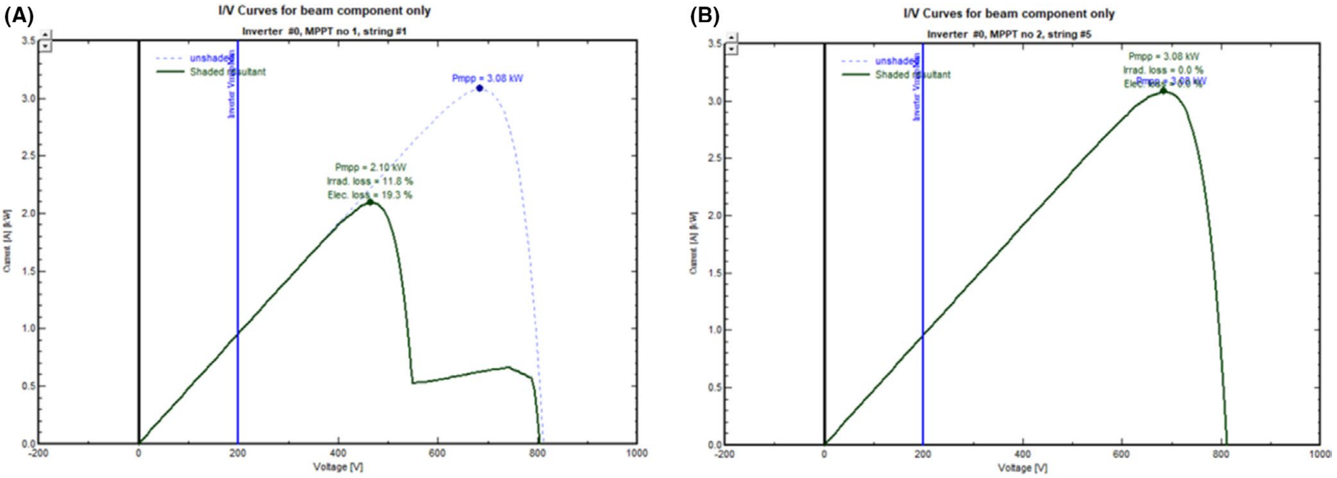

FIGURE 6 Impact of the shading calculation on the power curve at 12.45 PM. (A) Sub-array 1 string 1 in which is the string that has the highest degree of shading. (B) Sub-array 1 strings 5 (both Huawei inverter)

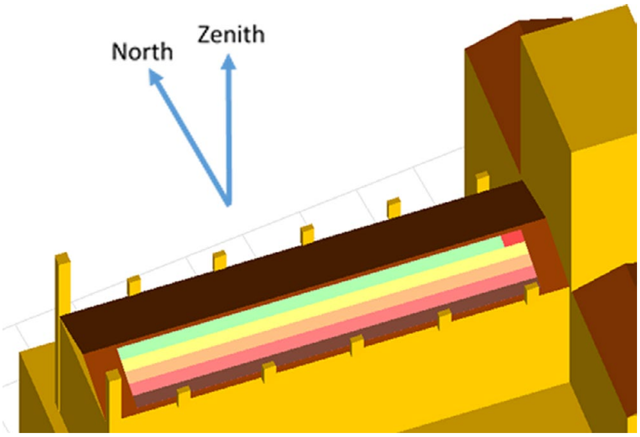

FIGURE 7 Module strings layout showing the exposure of strings 1–2 to shading from the crenellations

TABLE 2 Summary of the shading factors contributing to the performance losses at 12.45 PM on 21 December

Shading factor	Loss (%)	Relative loss (%)
Beam (electrical)	14.8	11.6
Beam (linear)	6.4	5.0
Diffuse	11.9	2.5
Albedo	19.5	0.1
Total		19.2

Note: The loss column shows the calculated shading factor expressed as a percentage loss of the irradiance component. The relative loss column shows the percentage loss relative to the shading factors' beam components' contribution.

3.2 | Cost–benefit analysis

Figure 8B shows that the net present value of installing the PV system becomes positive after (13.3 ± 0.6) years and is predicted to generate a profit of £(139,000 ± 12,000) (based upon the present value of money) compared with not installing any PV system. Given how much of this profit comes from not having to buy electricity, the model was stress tested for different changes to the price of electricity to the 5% increase assumed here. It was found that even with a sustained 3% decrease in the price of electricity, the system would still be profitable as shown in Figure 9A. A similar stress test was performed to see whether the system would still be profitable even if the capital cost was to increase far beyond what we predicted, shown in Figure 9B. The cost could double and the system would still be profitable, albeit less so.

We have assumed that all the electricity generated would be used except on days with excess generation compared with demand. This assumption is backed by information from staff at the Abbey that most of the demand is between 8 AM and 6 PM. Sometimes, during peak sunshine, the electricity generated would be greater than the electricity demanded by the Abbey and so that excess would have to be sold back to the grid. To confirm, our conclusion that the PV system is financially viable would still be true even if the Abbey had to sell some electricity back to the grid, case studies were tested for different proportions of the electricity generated being sold back to

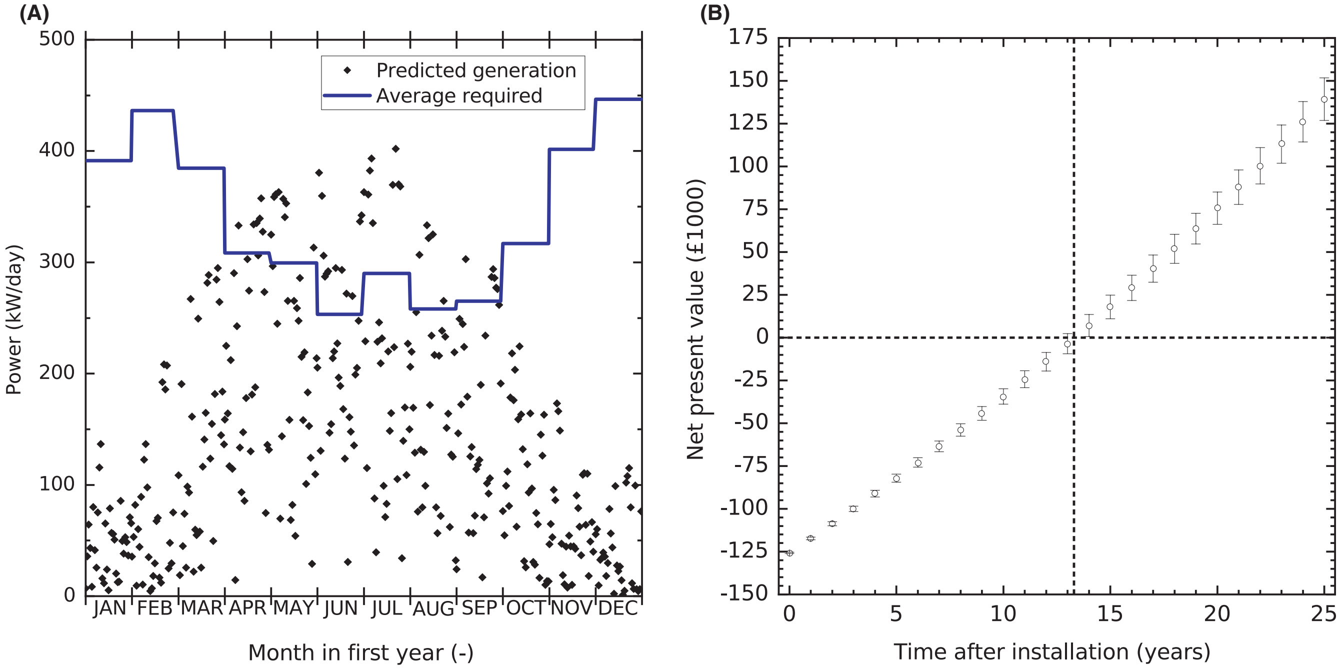

FIGURE 8 (A) Average daily demand for the Abbey based upon monthly data (blue line) compared with the predicted generated daily electricity from the PV system (black dots). (B) The net present value of installing the modelled PV system on the roof of Bath Abbey during the duration of a standard PV system lifetime. The point where the system becomes profitable is shown with the dotted line

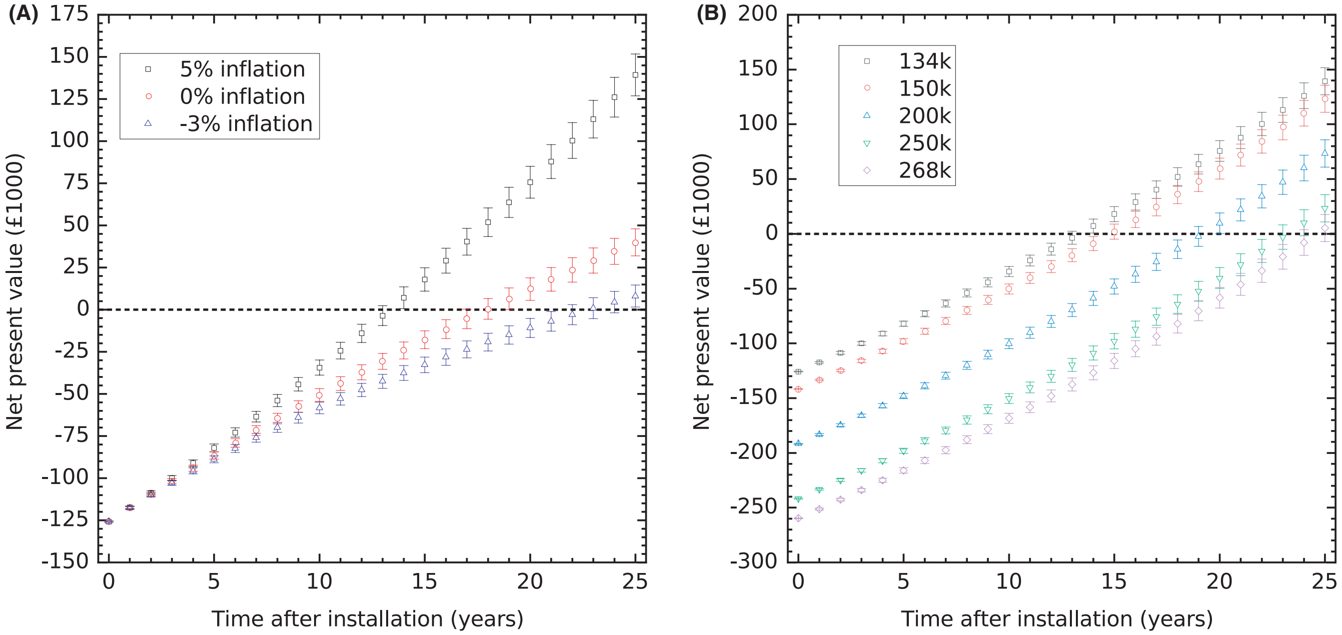

FIGURE 9 Impact of varying (A) change in price of electricity and (B) capital cost on the net present value of the installed system. The dotted line is used to show when the system will become profitable

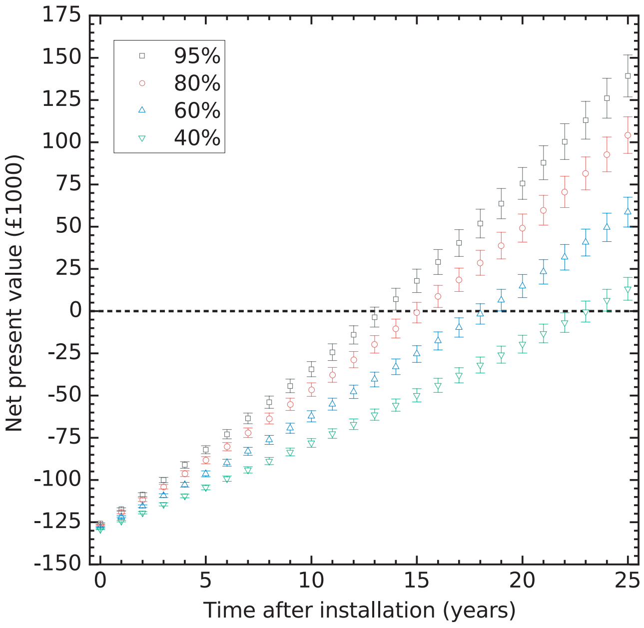

FIGURE 10 Impact of the net present value if the percentage of generated electricity sold to the grid were to increase. The dotted line is used to show when the scenario becomes profitable

the grid and all as low as 40% (a quantity so low that it would be unlikely to ever occur) the system is still profitable (Figure 10).

In the longer term, the break-even point of installing a PV system, here the time after installation before the PV system generates a net profit, can be brought forward by more efficient PV cells if these cells cost the same or less than cells based on crystalline Si. An exciting new PV technology is the perovskite cells so-called as they include a perovskite-structured compound, most commonly a hybrid organic–inorganic lead or tin halide-based material, as the light-harvesting active layer. A tandem Si-perovskite cell consists a stack of two solar cells in which the top cell has a higher bandgap and so absorbs high energy photons in the visible spectrum and transmits the remaining low energy photons to the bottom cell made of a low bandgap material, producing a higher efficiency than a single junction cell. In Si-perovskite tandems, the bottom cell is crystalline silicon, c-Si, and the top cell is a perovskite cell. Two-terminal tandem structures are generally favoured as they avoid the requirement for external cell interconnection, but there must be a low resistance direct connection between the two cells, and good current matching between the cells. For these cells, a medium-term cost estimate assuming an improved perovskite deposition process has a projected likely cost of $1.50/cell, which if combined with 25% efficiency would give a favourable levelized cost of electricity (LCOE) compared with industry standard c-Si cells.[28] If the Abbey delays installation of the PV system until these modules become commercially available, then employing Si-perovskite tandem cells should be considered when designing the system. Volume production of these cells will start in 2022.[29]

Another consideration for the Abbey is the inclusion of a battery. This is considered beyond the scope of this report. The inclusion of a battery would mean that during the 46 days with excess electricity, the leftover is stored in the battery instead of selling it to the grid. The electricity can then be used at another time rather than buying the electricity. To test whether it makes financial sense to include a battery the Abbey would need to provide half-hourly data to know exactly when in the day the Abbey uses its electricity to see how much would be required when the sun goes down. However, this only has the potential to increase the profitability of the system and so the financial conclusion that the PV system would be financially viable is unaffected.

4 | CONCLUSIONS

The decarbonization of historic buildings such as Bath Abbey is essential in the move to net carbon zero. In this study, a PV system has been designed to cover the south-facing roof of Bath Abbey. This system has been designed by considering historical weather data, the orientation of the Abbey's roof, and any shading the system may occur. It was found that the PV system will have a payback time of (13.3 ± 0.6) years following an initial investment of £134,000 and would yield a profit £(139,000 ± 12,000) over the system's 25-year lifetime. This financial saving is a result of reduced electrical energy bills over the lifetime of the system as well as selling some excess electricity. Additionally, financial stress tests have been performed to confirm that the system would be profitable in all likely scenarios. Therefore, this case study provides the important insight that is relevant to other historical buildings, namely despite the additional costs associated with the installation of a PV system on the roof, it can still be a financially sensible decision to do so for the owners of such buildings. Furthermore, it has been argued that the installation would have significant environmental and social benefits.

Beyond the financial aspects, there are other considerations such as the positive impact the PV installation would have on the environment. The installation is predicted to generate (45 ± 2) MWh of electrical energy in its first year which is (9600 ± 400) kg CO_2 equivalent emissions compared with using electricity generated by the National Grid based on data from the UK government, similar to the emissions of an average car driving (57,000 ± 2000) km.[30] There is therefore a significant carbon emission saving for a small-scale installation, noting its meaningful impact in its first year of installation alone.

A second consideration would be the social significance of a key landmark, such as Bath Abbey, installing a PV system. The publicity could encourage others to consider installing solar panels and support some of the Church of England's carbon footprint programmes listed in the introduction. Both these factors would be huge benefits in the long-term process of tackling issues related to climate change.

Some may argue that there would be a public backlash to installing the PV systems as it would spoil the aesthetic of the Abbey, a problem tackled by many of the churches that have installed their own PV systems. An important next step (if this project were to proceed) would be to consult residents of the area, the local authority and conservation officer on the issue. Similar concerns were raised at the beginning of the Gloucester Cathedral project, but the public supported the idea. Solar panels were chosen to match the colour of the roof of the cathedral—a similar approach could be adopted by the Abbey. The system would not be visible from the street and could only be seen from the surrounding hills and so would have minimum visual impact.

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SUPPORTING INFORMATION

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