IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: S Khatri *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **290** 012154

Potential and Impact of Incorporating Roof Photovoltaic to Enhance Environmental Sustainability of Historic English Churches in the United Kingdom

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Abstract. The Church of England (CofE) is responding to climate change by taking measures to reduce their CO_2 footprint under its flagship programme -'Shrinking the Footprint', to facilitate the CO_2 emission reduction target of 80 % by 2050. Meeting this target will require both energy efficiency measures and zero carbon energy generation of which solar PV technology is a frontrunner as it has a substantially lower CO_2 footprint than grid's electricity, with no moving parts, low maintenance and a long service life. Conventional church roofs built along the East-West axis offer the ideal pitches and orientation for collecting solar energy. However, within the CofE's vast estate of over 15,000 church buildings, 78 % of these buildings are listed and hence care must be taken to protect the building fabric. With this context in mind, this study identifies the benefits and concerns associated with the application of rooftop solar PV on historic English Churches and evaluates viable technologies currently available. The specific design and procedural requirements have been investigated and the process map of the implementation methodology established and illustrated through a case study of an existing church. Results showed that rooftop solar PV system has the potential to reduce the GHG emissions substantially, ranging between 75 %–84 % for electricity and between 20 %–27 % for gas based on the current demand and the choice of technology option. Findings on the issues, design options and life cycle environmental impacts are analysed with discussion and recommendation of future adaptation at a national level.

1. Background

The Church of England's church buildings form the nation's largest 'estate' of built heritage encompassing 45 % of the grade-I listed buildings in England. Of the 15,779 churches, 78 % are listed [1] The Church of England (CofE) recognizes the significant role it could play in building a more sustainable future and is evaluating environmentally friendly approaches toward every day activities [2].

Online energy audit by CofE collected from 430 CofE buildings across England in 2012/13 indicated the total annual carbon emissions (CO_{2e}) from energy use in the Church estate (including churches and other buildings) was between 608,706 and 1,013,490 tonnes of which nearly 50 % was used by churches, 18 % by offices and 15 % by schools.[3].

The Church of England aims to build on its many policies and projects as part of the global effort to tackle climate change, leading with its flagship programme *Shrinking the Footprint*, which committed CofE to a carbon reduction target of 80 % by 2050, with an interim target of 42 % by 2020 [4].

To radically improve the sustainability of Historic English Churches, a transformation in the way church buildings are maintained and operated is required. The sources of low carbon or renewable energy most likely to be employed by churches are bio-fuels, ground source heat pumps, or electricity generated by solar photovoltaic cells (PV) [5]. Solar PV has the greatest potential with its very low life cycle energy payback time and carbon footprint. In a benefit unforeseen by medieval architects, the traditional east-west church structure, with the altar at the east end of the nave that forms a long pitched south-facing roof is ideal for capturing sunlight. Despite it being accepted that the CO_2 emission reduction goal can be achieved by the application of on-site solar PV systems, with sporadic examples already exist, there is no in-depth study to demonstrate how such a potential resource can be practically and widely utilized. This study therefore seeks to investigate and establish the process of installing roof PV systems in historic churches and the associated economic, environmental and heritage implications with the aim that the methodology developed could be adopted for wider applications.

1.1. Sustainability and the Historic Environment

Historic churches are a trademark of the English town and countryside. These historic buildings are material expressions which have significance to present and future generations, and form part of the tangible cultural heritage [6]. An important factor in the preservation of historic buildings in the present context is sustainability. Schoor, et al [7] appropriately state that preserving historic buildings does not always align with the ambition to promote sustainability in the built environment. The aesthetic considerations and structural integrity of historic buildings have a direct impact of the retrofit and sustainability measures. Scognamiglio, et al. [8] reiterate that photovoltaics offer a huge potential in terms of cost and CO_2 savings, but their application on historic buildings is still a critical issue, since the coordination between photovoltaics and historical buildings is perceived to be striking from the "aesthetical" point of view. Longo et al. [9] argue that the idea of protecting and preserving historic buildings in its entirety is only philosophical, however, not recognizing the value of their preservation is injudicious. Visual impact and conservation issues play an important role in choosing the scenario which provides a well-balanced solution for improving energy efficiency likely to be adopted [10].

Retrofitting a historic church roof with PV for solar energy generation cannot ignore the associated conservation issues. Relatively few attempts have been made on methods for decision making to deal with the problem of balancing energy retrofits and cultural heritage values in historic buildings. However, the EU funded project Energy Efficiency for EU Historic Urban Districts' Sustainability (EFFESUS) is in the process of developing a software tool, with six impact assessment modules to support such location-specific decision-making process for the retrofit of historic buildings and districts. The methodology involves (a) heritage significance evaluation and (b) heritage impact definitions, which are compared using a heritage balancing process.

Designated heritage assets in the UK are protected by a range of planning laws and acts. Various guidelines, such as English Heritage Guidance and local planning guidelines to provide a defined framework for the preservation, rehabilitation, restoration, and reconstruction of historic properties. Listed Building Consent is required for installing solar PV on listed buildings [11]. In addition, the CofE buildings require permission from the Consistory Court of the Diocese, called a Faculty, and is preceded by an application to the Diocesan Advisory Committee (DAC) [12].

It can be claimed that not installing PV will have the least impact on Historic English Churches, but this is not a long-term solution and will reduce the ecological value of the building. More importantly, in the long term, the economic and functional value of the building may reduce which fundamentally impacts its heritage significance. A pragmatic approach is therefore required in retrofit policies for historic buildings, as we are approaching a turning point where marginal aesthetic or traditional reasoning may have to give way to the current environmental obligations.

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1.2. *PV technologies*

The key component of a PV system is the PV panels that convert sunlight into electricity. The associated components include: mounting/racking structures, inverter that converts DC into AC; meters and optional energy storage devices such as a battery unit or hot water store. Technical and physical characteristics of PV modules have major influence on the system acceptance. Their key characteristics are summarised in the following Table 1.

Table 1. Key characteristics of potential PV panels [13]

PV panel type	Key characteristics
Crystalline silicon 	Most widely used PV technology; have the highest efficiency amongst other PV technologies; two types multi-crystalline or monocrystalline silicon – the later has higher efficiency. Generation 128–165 kWh/m^2/Year; Energy Pay Back Time: 2.7–3.8 years; Greenhouse Gas Emissions 40–50 gCO_{2e}/kWh/Year
Thin Film 	Characterized by one or more thin layers of PV material; favourable because of their minimum material usage and rising efficiencies. Some module efficiencies almost rival that of crystalline solar cells; Generation 53–128 kWh/m^2/Year; Energy Pay Back Time: 0.68–1.39 years; Greenhouse Gas Emissions 16–35 gCO_{2e}/kWh/Year
Solar Slate/tile 	Solar tiles, also known as solar shingles or solar slates, are built into the structure of the roof in the same overlapping way as traditional roof slates. The capacity per sq. meter for solar tiles would be significantly lower than traditional PV systems.
Organic PV	Developing technology that uses conductive organic polymers or small organic molecules for light absorption and charge transport. It has the benefits of low cost, high throughput manufacturing, simple in fabrication and installation. Not readily available in the UK

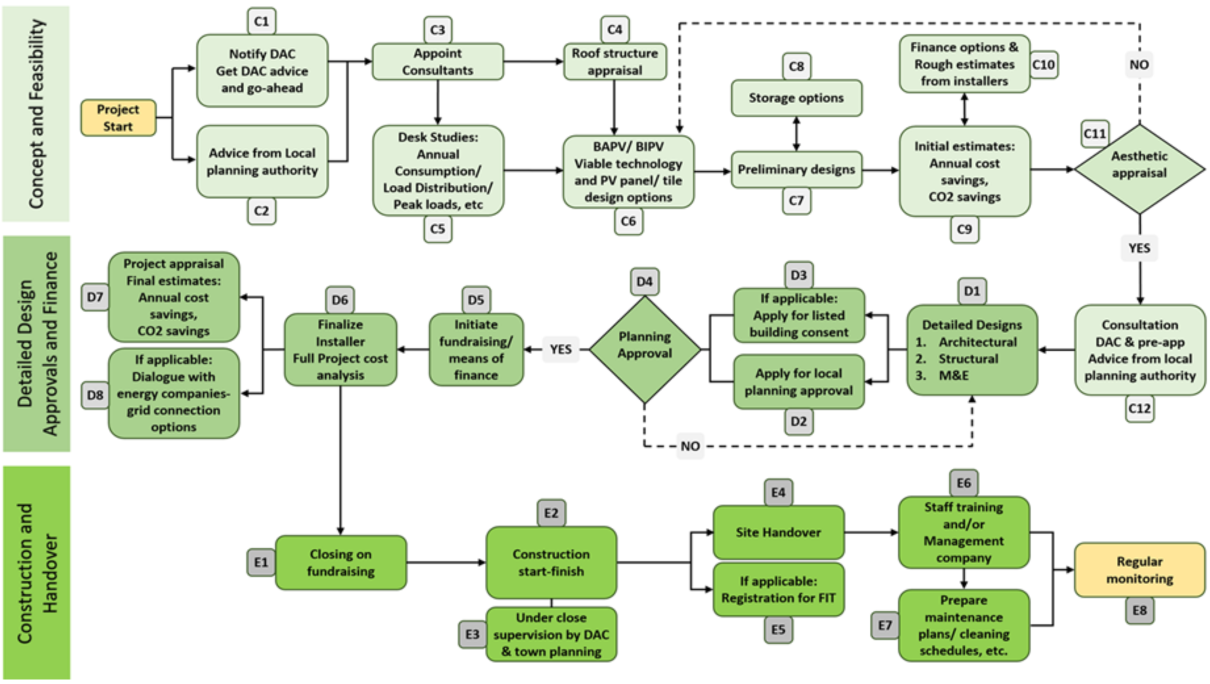

Figure 1. Flow chart of methodology for design and implementation

1.3. Implementation methodology

The implementation of PV system on roofs CofE churches is investigated and the process is divided into three key stages i) Concept and Feasibility, ii) Detailed Design Approvals and Finance and iii) Construction and Handover, as shown in the flow chart in Figure 1. Brief comments with reference to the relevant code in the chart are outlined in **Table 2**.

Table 2. Key tasks of the processes in the methodology flow chart in Figure 2

Code	Process	Key tasks
C1	Notify DAC	Notify Diocese Advisory Committee (DAC) and follow their advice notes before undertaking any major or minor works in church buildings.
C2	Advice from Local Planning Authority (LPA)	CofE may exempt from certain provisions of the planning acts (Historic England, 2018) but the Conservation Officer at the local planning authority (LPA) must be approached to get advice on whether LPA consent will be required on a range of issues.
C3	Appoint Consultants	Appoint consultants having the necessary skills to conduct the techno-commercial feasibility studies
C4	Building & Roof Structure Appraisal	To determine the area available for the installation of the PV panels, confirm the structural integrity and the load bearing capacity and any additional improvements/ alterations that may be required
C5	Analysis of Energy Consumption	Energy consumption in the Church complex is assessed based on the past energy bills. Segregated seasonal consumptions are evaluated to consider any benefits of storage and the optimum storage capacity
C6	Technology Options	Current technology options – crystalline silicon, thin film, building integrated PV and organic PV – are evaluated to determine the most optimum system.
C7	Preliminary Design	Use performance simulation software to evaluate each of design options
C8	Storage Options	The feasibility of battery storage would be analysed based on hourly consumption pattern generated from the analysis. Additional storage options in the form of heat (e.g. hot water) would also be considered.
C9	Initial Estimates	Analysis would be done to compute the annual cost and the CO_2 savings for each techno-commercially viable options.
C10	Finance Options Estimate	The rough estimate of the costs of the various options and the various finance options available for funding the same need to be examined.
C11	Aesthetic Appraisal	This is an important aspect that would be considered by the DAC and the LPA. If the aesthetic appraisal is deemed positive, the project would move to the C12 stage, otherwise it would move back to the C6 stage.
C12	Pre-Application Process	Engagement with the LPA and in consultation with DAC to conduct a pre-application process to determine the preliminary views of the LPA and address the various concerns
D1	Detailed Designs	The detailed designs would include architectural, structural, mechanical and electrical drawings and layouts with the location of the key components,
D2	Planning Approval Application	Need to be submitted to the LPA and should address all the concerns and issues raised by the LPA during the pre-application process.
D3	Listed Building Consent	to be submitted along with and as a part of the planning approval application if a listed building consent is required
D4:	Conditional Planning Approval	Upon finding the proposal consistent with the legal framework after advertising and obtaining the comments from various concerned quarters, the LPA would provide a conditional approval. Move back to the D1 stage if disapproved.
D5	Initiate Fundraising/ Means of Finance	Identify means of finance required to fund the installation
D6	Finalize Installer	Quotes from at least three installers would be invited after ensuring that the scope of work for the installation is identified precisely.

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Code	Process	Key tasks
D7	Project Appraisal	Appraise the cost of the installation, the annual savings in energy costs and the CO_2 savings
D8	Grid Connection	Dialogue with Energy Companies and the Distribution Network Operator if any modifications need to be made with the existing grid connection to accommodate the export capacity and sale conditions
E1	Closing on Fundraising	Prior to start of construction, the availability of funding and the timing of drawdown of such funding would be confirmed.
E2	Construction Start-Finish	The installer would be provided a notice to proceed. The construction schedule, including delivery of key components to the site, would be agreed with the installer and monitored regularly to ensure delivery of the installation as per the agreed scope and timeline.
E3	DAC & Town Planning Supervision	The involvement of the DAC and the LPA would be ensured that the installation is line with their requirements and expectations.
E4	Site Handover	Ensuring that the installation is done that all the observations of the LPA and the DAC are addressed, that the performance of the system is as per the guaranteed parameters in the installation contract.
E5	Registration for FIT	An application for registration to the FIT program would be made to ensure that the revenues from the electricity exported to the grid would accrue to the church.
E6	Staff Training /Management Company	Training for in-house operation and maintenance or establish management contract after system warranty period
E7	Maintenance Plans/Cleaning Schedules	Scheduled maintenance timeline needs to be agreed during which regular maintenance activities,
E8	Regular Monitoring	Appropriate software should be installed on the computer systems of the church to review regular and real-time performance of the installation.

2. Case study

St. Barnabas Church in Hove was selected to demonstrate and test the implementation of the proposed methodology. It consists of a main church building approximately 38 m x 18 m with a floor area of 630 m^2, an attached parish hall and a vicarage building. It is traditional east-west structure, with the altar at the east end of the nave, and a long north and south-facing roofs with a pitch of 50° and at an azimuth of 188°. Three scenarios are studied:

- Scenario 1: This scenario is based on the activities in the Church in 2016 and 2017.
- Scenario 2: This scenario assumes increased activities in the Main Church, with the activities in the Parish Hall and the Vicarage being the same.
- Scenario 3: In addition to the increased activities in the Main Church, it is assumed that the Parish Hall is converted to a café.

Figure 2. Visual evaluation of three design options

2.1. Results & Discussion

Summary of main results of the analysis is shown in **Table 3** with highlights of the key findings explained in the following sections.

Table 3. Summary of Performance of Techno-Commercially Viable Options

	SCENARIO 1		SCENARIO 2		SCENARIO 3	
	Electricity	Gas	Electricity	Gas	Electricity	Gas
Annual Demand in kWh	4,191	97,012	5,170	121,468	11,812	133,697
Annual Demand met from PV system (kWh)						
Mono Crystalliine	3,737	26,608	4,651	26,224	10,845	23,092
Thin Film CdTe	3,737	26,608	4,651	26,224	10,845	23,092
Solar Tile/Slate	3,682	19,319	4,604	18,915	10,389	15,437
Annual Cost Savings in £						
Mono Crystalliine	£1,841	£961	£1,947	£947	£2,611	£834
Thin Film CdTe	£1,841	£961	£1,947	£947	£2,611	£834
Solar Tile/Slate	£1,004	£698	£1,112	£683	£1,756	£558

Note: The GHG Emissions Impact of battery storage has not been considered in the above analysis

Net Lifetime GHG Savings from PV System (kg CO2e)						
Mono Crystalliine	33,128	163,343	42,765	160,986	108,096	141,757
Thin Film CdTe	37,403	163,343	47,040	160,986	112,371	141,757
Solar Tile/Slate	33,806	118,594	43,529	116,120	104,542	94,764

Lifetime GHG Emissions of PV System	Lifetime GHG Emissions kg CO2e	EPBT (Years)
Mono Crystalliine	6,286	3.80
Thin Film CdTe	2,012	0.68
Solar Tile/Slate	5,029	2.70

2.1.1. Consumption Pattern of Electricity and gas. The overall consumption pattern of electricity in the Vicarage is more or less the same in all the four seasons, with a varying degree of peak load ranging from a maximum of 5 kW in winter to a minimum of 3 kW in summer. The consumption pattern in Scenario1 and Scenario 2 is also more or less the same, wherein the consumption is concentrated in two parts of the day, from 09:00–14:00 and then again between 16:00–21:00. The consumption pattern in Scenario 3 is drastically different due of conversion of the Parish Hall into a café that operates the entire day from 7:00, peaks at around 11:00 and then gradually reduces to zero at around 23:00. As expected the consumption of gas is highest during winter (62 %), followed by spring (24 %), and with autumn and summer being more or less the same (around 7% each).

2.1.2. Broad Techno-Commercial Viability. The preliminary design of the four options, revealed that Organic PV resulted in annual generation of around 9 MWh as compared to 60 MWh, 47 MWh and 36 MWh for Mono Crystalline, Thin Film CdTe and BIPV Slate/Tile respectively. Such low generation from Organic PV would render it economically unviable at the current levels of technology and efficiency.

2.1.3. Viability of Storage. An analysis of the hourly consumption pattern of electricity across seasons and across the three scenarios, highlighted that there is a substantial consumption of electricity during evening hours whereas the generation from the PV system would be during the day. Battery storage would be useful in ensuring higher levels of self-consumption inside the church complex. Further, there is significant heating requirement in spring and winter which will enable the usage of electricity for heating purposes. However, to ensure storage through heat, proper insulation must be provided.

2.1.4. Cost, CO_2 Savings & Aesthetic Considerations. The cost and CO_2 savings are the highest from Monocrystalline and the lowest from Solar Slate. However, due to aesthetic and heritage considerations, solar slate may be the preferred solution for the Church complex.

2.2. Conclusions and future work

It can be concluded from this study that the churches in England (15,779 in number) could potentially generate significant amount of clean solar electricity annually, resulting in a substantial reduction in GHG emissions. Out of the 15,779 CofE churches, approximately 12,600 are listed buildings that are protected by public law and require permissions from various authorities for installation of rooftop solar PV systems. Thus, the proposed rooftop PV solutions need to address the visual impact and heritage concerns that listed buildings present.

There are currently three techno-commercially feasible options for rooftop PV systems. If these options are ranked from 1 to 3 based on the three identified criteria comprising economic benefit, GHG emissions and visual impact (Figure 2) & heritage considerations, would lead to the conclusions tabulated in table 3.

It can also be concluded that battery storage coupled with the rooftop PV system would provide significant value to churches by increasing the amount of self-consumption from the electricity generated from the PV system, which can be used both for powering the electric appliances and also for water and space heating.

Table 4. Ranking of the Three Techno-Commercially Feasible Options against Key criteria

Technology	Economic Benefit	Net GHG Emission Savings	Visual Impact & Heritage Considerations
Monocrystalline	1	1	2
Thin Film CdTe	2	2	2
Solar Tile/Slate	3	3	1
(Rank 1 is the most preferred where Rank 3 is the least preferred)			

From the case study conducted at the St. Barnabas Church at Hove, it can be concluded that rooftop solar PV system has the potential to reduce the GHG emissions substantially, ranging between 75 %– 84 % for electricity and between 20 %–27 % for gas based on the current demand, depending on the choice of one of the three technology options.

Based on the consumption profile of St. Barnabas Church at Hove and the generation profiles emanating from the application of the three technologies, it may be concluded that connectivity with the grid is required to ensure flexibility of operation and to meet the demand at all point in time. Going totally off-grid will require an extremely expensive storage option which will not be techno-commercially feasible. Current work builds the foundation for evaluating the potential and practical implementation of PV systems on church roofs to improve the sustainability of such buildings. Ongoing work is underway to establish the potential impact of PV implementation on all viable CofE church roofs and to develop demonstrations to showcase such viability.

Acknowledgments

Authors wish to acknowledge assistance and support from the Diocese of Chichester of Church of England and in particular Fr. Lawrence MacLean – Vicar of St. Barnabas Hove & Diocesan Adviser for Fundraising & Sustainability, and Dr David Greenfield – Delivery Director of Diocese of Chichester Energy Stewardship Programme.

IOP Conf. Series: Earth and Environmental Science **290** (2019) 012154 doi:10.1088/1755-1315/290/1/012154

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