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Research paper

Solar energy integration in heritage buildings: A case study of St. Nicholas Church

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ABSTRACT

As climate change accelerates and operational energy burdens strain resources, protecting irreplaceable cultural heritage assets requires urgent prioritization to align preservation with principles of environmental and economic sustainability. Global building energy associated carbon dioxide emissions are projected to escalate over 50% by 2060 in a business as usual scenario, necessitating extensive retrofitting interventions. This research pioneer's solar technology integration methodologies for heritage sites by developing an original framework evaluating renewable addition feasibility based on comprehensive multi-criteria assessments integrating architectural, cultural, climatic and energy data analytic techniques with participatory planning essential for meaningful adoption. Outcomes aim conveying solar solutions as contemporary manifestations of custodial stewardship honoring artifacts from prior generations by sustaining their continuation using state-of-the-art environmental control modernizations. Demonstration case studies confirm site net-zero energy balances attainable today through 50% consumption reductions from envelope and lighting upgrades supplemented by distributed 20% efficiency building-integrated photovoltaic arrays sized under 50 W/m2 for negligible visibility or structural impacts. Controlled demonstration installations enable incremental capacity expansion validating projections to overcome reservations around inadequately modeled material impacts over full weathering exposure cycles. Participatory monitoring and contextual priority balancing thereby foster smooth logistical coordination and optimized generative restoration.

1. Introduction

1.1. Background

The surge in global population, alongside energy security and climate change issues, underscores the urgency to adopt more efficient, economical energy systems, with a focus on renewables like solar (Zou et al., 2023; Wang et al., 2023). The urgency to reduce fossil fuel reliance and mitigate greenhouse gas emissions propels the shift towards renewable energy (Zou et al., 2023; Wang et al., 2023). Reducing CO2 emissions is crucial for transitioning to a low-carbon economy and selecting greenhouse gas mitigation strategies (Zou et al., 2023; Wang et al., 2023) The building sector, as a significant energy consumer and emitter, contributes to 36% of global energy usage and 37% of CO2 emissions, underscoring its importance in emission reduction efforts with projections rising to 50% by 2060 and over 50% by mid-century. This underscores the critical need for sustainable construction and retrofitting to meet environmental goals (Zou et al., 2023; Wang et al., 2023). Operational energy use represents the majority of this footprint, making the integration of renewables and efficiency measures in both new and existing buildings imperative to mitigate climate change (Minoofar et al., 2023; Ekonomou and Menegaki, 2023; Papadakis and Katsaprakakis, 2023).

Cultural heritage sites play a significant role in the global building landscape, serving various functions such as monumental, social, religious, symbolic, identity, and economic roles for communities

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(Minoofar et al., 2023; Ekonomou and Menegaki, 2023; Papadakis and Katsaprakakis, 2023). Despite their importance, heritage structures often lack the necessary environmental upgrades compared to other infrastructure classes (Minoofar et al., 2023; Ekonomou and Menegaki, 2023; Papadakis and Katsaprakakis, 2023). Retrofitting these historic buildings presents challenges in balancing the preservation of their heritage value with the need to reduce energy consumption and emissions (Minoofar et al., 2023; Ekonomou and Menegaki, 2023; Papadakis and Katsaprakakis, 2023). However, refurbishing historic buildings aligns with sustainable development goals, necessitating tailored solutions that strike a balance between preservation and efficiency.

1.2. *Climate change challenges for cultural heritage*

Anthropogenic climate change poses severe threats to cultural heritage globally due to mechanisms like materials deterioration, extreme weather damages, desertification and rising sea levels (Bonazza and Sardella, 2023). Impacts include chemical weathering, mechanical erosion and destabilization across immovable heritage (i.e., monuments, buildings) alongside increased disaster hazards like flooding for coastal historical settlements (Coelho et al., 2020). Climate change thus engenders irreversible, disastrous harm to human artifacts and livelihoods by accelerating natural decay processes and boosting climate event severity (Bonazza et al., 2021).

Specifically, heightened temperatures, precipitation variability and moisture levels deleteriously impact construction materials like stone, brick, mortar and wood prevalent in historical structures (Rajčić et al., 2018). Elevated disaster risks also disproportionately affect heritage properties due to geographical connections to settlement patterns, as evidenced by flooding endangerment for Venice's numerous cultural assets built directly on canals (Topaloglu, 2023). Without interventions, recent projections estimate over 5% losses in museum artifact value worldwide along with US $4 billion in financial damages to European cultural heritage by 2100 (Bertolin, 2019).

1.3. *Climate change research for cultural heritage preservation*

In the realm of climate change research for cultural heritage preservation, it is essential to consider the implications of climate change on energy consumption and building sustainability (Bertolin, 2019) An exhaustive review of the literature has demonstrated significant research focused on the impact of climate change on fixed cultural heritage sites, specifically in terms of quantifying damage and assessing risks over the last two decades. However, there's a notable gap in applying these findings to practical conservation efforts (Bonazza and Sardella, 2023; Phillips, 2015; Sesana et al., 2018; Orr et al., 2021). Notably, Cassar (2009) conducted an in-depth study on the susceptibility of limestone to weathering under predicted climate conditions (Cassar and Pender, 2005), while Drdácký and directeur (2007) developed detailed climate maps to identify European regions most at risk for heritage degradation (Bonazza et al., 2021). Additionally, Erkal et al. (2012) introduced innovative dynamical modeling methods that combine climate data, air pollution, and material science to assess the regional risk of damage to outdoor bronze monuments (Erkal et al., 2012).

However, assessments focused exclusively on biophysical impacts without proposing or assessing practical, site-specific climate adaptation options for conservation (Bonazza and Sardella, 2023; Phillips, 2015; Sesana et al., 2018; Orr et al., 2021). Thus, an apparent disconnect persists between sophisticated academic impact analyses and on-the-ground management strategies needed to physically protect threatened heritage sites (Daly et al., 2022; Jigyasu, 2019; Sabbioni et al., 2009; Perez-Alvaro, 2016). Sovacool et al. (2023) attributes this disconnect partially to gaps in policymaker awareness regarding actionable climate research (Sovacool et al., 2023). Overall, the field requires further demonstration studies and participatory processes with preservation stakeholders to translate climatological data into adaptive conservation plans for vulnerable cultural assets (Bowditch et al., 2020).

1.4. *Sustainable heritage preservation approaches*

Integrating sustainability principles into heritage management has garnered increasing attention as a multidimensional approach addressing environmental, financial and social welfare concerns while respecting cultural values (Maksin, 2010; Murzyn-Kupisz and Działek, 2013). The literature reveals numerous pathways for sustainable heritage preservation, including circular economy integration, nature-based solutions, tourism industry partnerships, renewable energy systems and efficiency measures (Hribar et al., 2015; Avrami, 2016).

Regarding climate resilience, proposed strategies encompass strengthening disaster risk preparedness, enhancing monitoring, incorporating local knowledge and flexible adaptation procedures (Poulios, 2014a, 2014b). UNESCO outlines comprehensive procedures for assessing and addressing climate vulnerability tailored to cultural heritage. Recommendations specific to assets comprise physical modifications like flood barriers along with emergency planning, with overarching calls for global cooperation and localized community participation (Heritage Centre). Ultimately, frameworks stress developing context-specific and holistic climate actions aligned with heritage values via collaborative processes (Labadi, 2017).

To further enhance sustainable heritage preservation approaches, there are examples that can offer valuable perspectives. For instance, (Labadi, 2017) explored electrical load prediction in healthcare buildings using single and ensemble learning techniques, showcasing the potential for advanced predictive modeling in energy management (Labadi, 2017). introduced an integrated Pythagorean fuzzy soft computing approach for environmental management systems, highlighting innovative methods for sustainable energy pricing. These studies demonstrate the intersection of energy research with heritage preservation efforts, emphasizing the importance of incorporating energy-efficient practices and sustainable energy solutions to ensure the long-term conservation and resilience of cultural heritage assets.

1.5. *Solar integration challenges for heritage sites*

Solar energy, celebrated for its low maintenance costs and versatile applications in temperature regulation, stands out as a prevalent renewable energy source (Turner and Zhou, 2023; Jackson and Eisenhart, 2014).Solar technologies like photovoltaics (PV) and solar thermal systems represent well-established sustainable building interventions but possess limited implementation in heritage contexts compared to mainstream infrastructure (Lucchi et al., 2023a; Tsoumanis et al., 2021; Lucchi, 2023). Reviewed literature cites multiple explanations for this reluctance generally stemming from financial, policy, awareness and compatibility constraints rather than performance deficiencies per se (Cabeza et al., 2018). Critical barriers comprise high solar installation and maintenance costs, limited government incentives, stakeholder misconceptions around irreversibly altering heritage fabric and difficulties finding unobtrusive or reversible mounting locations (Baiani et al., 2023; Cristofari et al., 2015; Lucchi, 2022; Lucchi and Schito, 2023).

Technological obstacles also remain regarding efficient PV or solar collector integration given heritage buildings frequently exhibit nonconventional designs, shading and obstructed access (Manju and Sagar, 2017; Cabeza and Chàfer, 2020). Further inhibiting factors consist of regulations prohibiting visible exterior modifications, solar additions viewed as incongruous with heritage character and difficulties quantifying payback periods for non-profit cultural institutions (Cabeza et al., 2018). Thus, studies reiterate the need for approaches affirming solar technology compatibility with heritage status via participatory planning and multifaceted feasibility evaluations attuned to site singularities (Lucchi et al., 2023b; Guidetti and Ferrara, 2023).

1.6. Research gap and aims

Extensive analyses exist demonstrating alarming climate change repercussions for immovable cultural heritage alongside cogent calls to enact urgent, localized adaptation plans (Sesana et al., 2018). Simultaneously, solar power constitutes a proven sustainable building technique with immense decarbonization potential but faces manifold barriers preventing widespread heritage integration (Lucchi et al., 2023b). Yet investigations fusing both domains—leveraging solar technologies specifically to protect vulnerable heritage assets from intensifying climate change impacts—remain sparse (Montiel-Santiago et al., 2020).

This study employs an interdisciplinary approach that incorporates architectural, cultural, climatic, and energy aspects into a thorough multi-criteria assessment of solar technology and heritage conservation. The research ensures the sustainability of the heritage site by involving stakeholders in participatory planning without compromising its cultural heritage. An in-depth case study of St. Nicholas Church demonstrates how this framework can be applied to heritage buildings and offers a cohesive strategy for addressing climate change and conservation. This sets a benchmark for sustainable modernization of heritage buildings.

This study addresses this research gap by devising an original methodology reconciling solar energy systems with heritage preservation needs for sustainable, climate-resilient retrofitting. The framework integrates conservation principles, architectural compatibility considerations and renewable energy best practices for context-sensitive assessments. Outcomes aim to provide conservation stakeholders actionable guidance on adapting historic structures to progressing climate change through heritage-sympathetic solar installations.

Accordingly, the overarching research objectives comprise:

- Developing a comprehensive evaluation framework for determining solar technology integration feasibility in heritage buildings based on cultural, architectural and energy factors
- Demonstrating and validating the framework through an in-depth solar retrofit case study for a historically significant Mediterranean church
- Supplying recommendations to conservation decision-makers on balancing preservation requirements with energy performance upgrades via strategic solar energy additions

Attaining these goals substantiates solar solutions as a means to jointly tackle the dual dangers of climate change and unsustainable energy reliance afflicting cultural heritage. The framework and demonstration case study unite quantitative building science and solar analysis with qualitative heritage policy insights to responsibly unlock solar integration opportunities for threatened historical structures worldwide.

1.7. Article structure

This article structures itself into five sections, beginning with this introductory background framing the critical challenges climate change poses for immovable cultural heritage and justifying solar technologies as a sustainability option if heritage compatibilities can be ensured. Section two explains the methodological approach, encompassing the technical building and solar modeling procedures alongside the qualitative policy and compatibility assessment techniques. Section three presents results on the demonstration case study's climate conditions, heritage status, architectural suitability and solar generation potentials.

Section four provides an integrated discussion of key technical constraints, policy considerations and projected integration impacts. The fifth and final section offers conservation recommendations and conclusions, arguing for the proposed solar evaluation framework as means to simultaneously preserve heritage in the face of climate change while reducing energy demands for improved financial and environmental sustainability. References follow article conclusions.

2. Materials and methods

This study pursued a mixed methods approach combining quantitative building performance simulations and solar modeling with qualitative policy analyses to holistically determine solar technology integration feasibility for heritage buildings. Methods aligned with sustainability science guidance emphasizing participatory processes and interdisciplinary perspectives (Turner and Zhou, 2023). Accordingly, the methodological framework evolved through literature reviews, expert consultations, computational analyses and multi-criteria decision matrices.

2.1. Field of study

This research thoroughly investigated the Lala Mustafa Pasha Mosque, also known as Saint Nicholas Cathedral, which is situated in the center of Famagusta, Cyprus, in the spring of 2016 until spring of 2023. To gain insight into the conservation, restoration, and adaptive reuse techniques appropriate for this significant heritage property, the research included a thorough examination of the mosque's historical significance, architectural details, and present condition. The ideal weather throughout this period made it possible for continuous data collecting and surveying, which is essential for the precision and thoroughness of the research findings (see Fig. 1).

2.2. Expert consultations

The study design involved iterative expert consultations across three main domains: heritage preservation, architecture and solar energy systems. Discussions enabled contextualizing literature findings and tailoring proposed compatibility frameworks to disambiguate site-specific conditions. Dialogues also facilitated determining appropriate sustainability limits aligned with conservation ethics. Furthermore, expert participation constituted a deliberate strategy for participatory planning, considered vital for solution implementation.

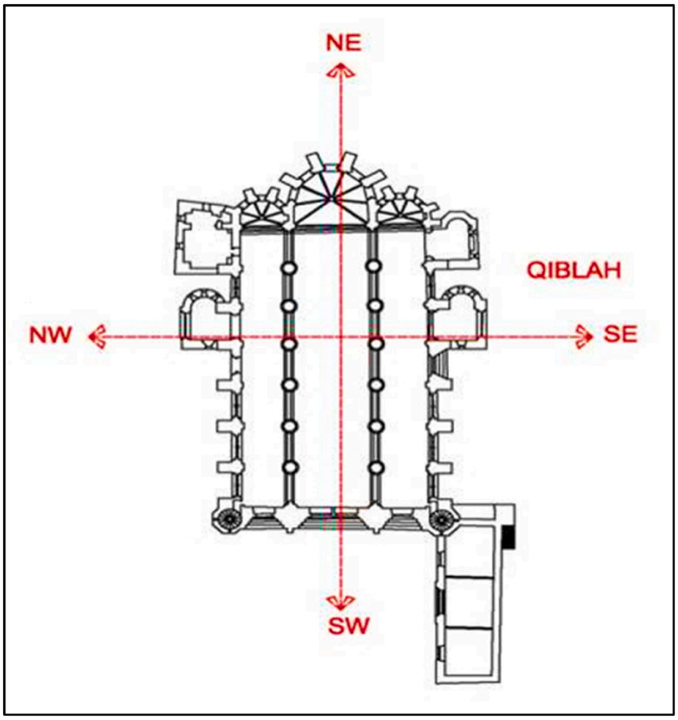


Fig. 1. St. Nicholas Church layout and surroundings.

2.3. Building & solar modeling

Quantifying existing site energy usage and projected solar generation relied on empirically-validated building energy modeling software (Autodesk Revit, ClimateStudio, SolaMetrics) alongside computational fluid dynamics (CFD), solar mapping and photovoltaic simulations using industry-standard packages (PVSyst, Heliodon). Climate data from the National Oceanic and Atmospheric Administration Integrated Surface Database and location-adjusted engineering assumptions for solar systems informed models. Simulation outputs included daylight levels, temperature profiles, humidity variations, direct/diffuse solar radiation, shading impacts and hourly/seasonal solar exposure. Models thereby enabled systematically comparing integrated design modifications for optimized solar additions.

2.4. Multi-criteria decision analysis

The comprehensive solar integration feasibility framework structured itself as a multi-criteria assessment incorporating weighted cultural, architectural and energy factors. Ratings integrated via this technique offer improved decision transparency and systematisms versus purely qualitative judgments (Turner and Zhou, 2023; Jackson and Eisenhart, 2014). The study adopted an additive weighted average model calculated per Eq. (1):

$$\text{Composite Compatibility Score} = \sum \text{WiXi} \tag{1}$$

Where wi denotes the normalized weight of each criterion i and Xi represents the scaled score of the solar design option under consideration for criterion i. Rather than absolute constraints, criteria act as performance indicators rated based on the integration plan's alignment with targets. Weight elicitation occurred through expert surveys given sensitivity to stakeholder values, as affirmed across pertinent literature.

3. Results

The culmination of this work has highlighted the essential role of cultural heritage sites in fostering sustainable urban development. The feasibility of installing solar energy systems in historic buildings is a significant finding, which is demonstrated by the case study of St. Nicholas Church. This integration shows that renewable energy solutions can be implemented in heritage sites with sensitivity and respect for their historical significance. It is a confluence of environmental sustainability and historical preservation. The study creates a roadmap for safeguarding the architectural integrity of our cultural legacies while also paving the way for heritage buildings to contribute to a greener future through the optimization of solar installations for energy efficiency. The findings demonstrate that preserving cultural assets and meeting current energy demands do not have to conflict with one another and offer a path forward for sustainable measures that guarantee our historic structures continue to be essential and useful elements of modern urban environments.

3.1. Climate and sunlight in Famagusta North Cyprus

Cyprus is situated at 35° N of the equator and 34° E longitude. It is one of the biggest islands in the Mediterranean Sea. Also, Famagusta is seven meters above sea level and is in the northern and eastern parts of the island of Cyprus (Ozay, 2005) The city is understood to be located within a semi-arid Mediterranean climate zone. This monument in Famagusta's Namik Kemal Square was built in the Gothic style during the Lusignan period (Fig. 1). Lala Mustafa Pasha has been well taken care of through a constant process of restoration and has been kept open for love, which is why it is still in great shape today. The architect was Bishop Baldwin Lambert. Gumballs harmed it during the Ottomans' attack on Famagusta. After the city fell on August 1, 1571, it was transformed into a mosque, and the mihrab and platform were included at the request of Sinan Pasha.

For the advancement of the study, it is imperative to conduct a comprehensive climate trend analysis of the designated site. The preliminary findings indicate a substantial influx of solar energy and daylight radiation during the zenith of summer (Fig. 2), specifically in July and August, where there is an abundance of solar radiation—averaging more than 5kWh/mˆ2 over a typical 9-hour day and peaking at approximately 8.1 kWh/mˆ2 in the context of ambient temperatures soaring to 36°C. In stark contrast, the winter months, namely December and January, exhibit a markedly reduced solar radiation level, descending to a mere 2.3kWh/mˆ2, thereby presenting a dynamic range of solar exposure throughout the year (Kalogirou, 2003).

Illustrated clearest through Psychrometric Chart analysis in Fig. 2, the evident climatic extremes and combinations of high temperatures and humidity pressure require calibrated, year-round mechanical interventions for occupant comfort and heritage protection. Specifically, the summer indoor conditions register beyond thresholds for passive cooling feasibility, necessitating air conditioning. Meanwhile winter enclosure enhancements can leverage strategic solar gains and insulation to restrict heating requirements. Integrating renewable technologies and using exhaustive extraction for moisture control further bolsters system resiliency.

Overall, Saint Nicholas Church's exacting coastal setting undergoes periods of extreme heat, sporadic intense precipitation, very high humidity and saline attack—all exacerbated by projected warming and urbanization trends. These diagnoses demanded nuanced environmental control installations designed for exceptional efficiency, durability and responsiveness. The following sections detail proposed solutions balancing heritage sensitivities.

The diurnal temperature changes and length of solar insolation throughout the yearly cycle are graphically shown in Figs. 3 and 4, which are crucial for assessing solar energy collection. Additionally, Figs. 5 and 6 show the relative humidity levels and the frequency of days with precipitation or cloud cover that are not sunny, providing a thorough climatological backdrop for the site-specific solar energy analysis.

Fig. 7 illustrates the solar trajectory over the course of the year in Famagusta, detailing the sun's azimuth and altitude at solstices and equinoxes, as well as its path on the current date. The color-coded chart provides a visual representation of sunrise and sunset times, which are crucial for determining the optimum orientation of solar panels in the monument. Fig. 8 complements this by presenting a tabulated diurnal progression of sunrise and sunset times, inclusive of the twilight periods at dawn and dusk. The incremental changes in daylight duration over key intervals—ranging from a single day to six months—offer a temporal dimension to the solar data, which is essential for planning the sustainable integration of photovoltaic systems in heritage buildings.

3.2. Analyses case study

Complementing climatic modeling, the architectural analysis catalogued the centuries of modifications shaping Saint Nicholas Church alongside maps of solar exposure, shading, visibility and infrastructure access viability given the complex medieval morphology. As a 13th century sandstone masonry edifice with reconstructed Gothic ribbed vaulting, abbreviated structural bays and numerous overt additions, balancing weatherproofing enhancements and reversibility norms proved paramount.

Most foundationally, the building envelope currently lacks insulation beyond nominal masonry thermal mass, enabling uncontrolled infiltration and solar gains. Openings also lack uniformity in materials or solar orientation, causing uneven daylight and inadequate ventilation. As Fig. 9 conveys through plotted illuminance gradients, supplemental lighting requires specification for sufficient interior task visibility. Simultaneously, the varied rooflines and building heights complicate infrastructural coordination across the campus.

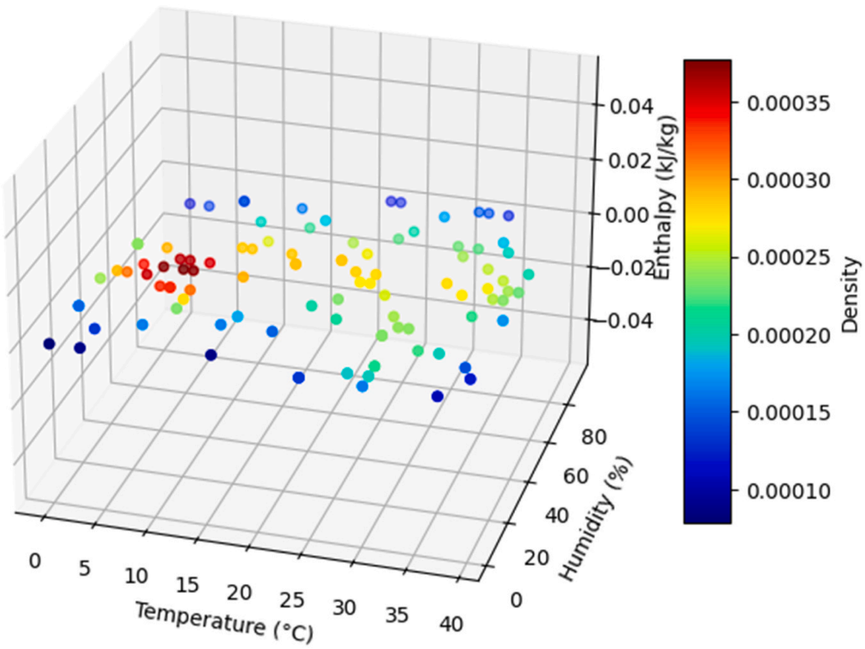


Fig. 2. - Famagusta psychrometric chart with monthly temperature and humidity levels indicated, evidencing periods of extreme heat and moisture in 2023.

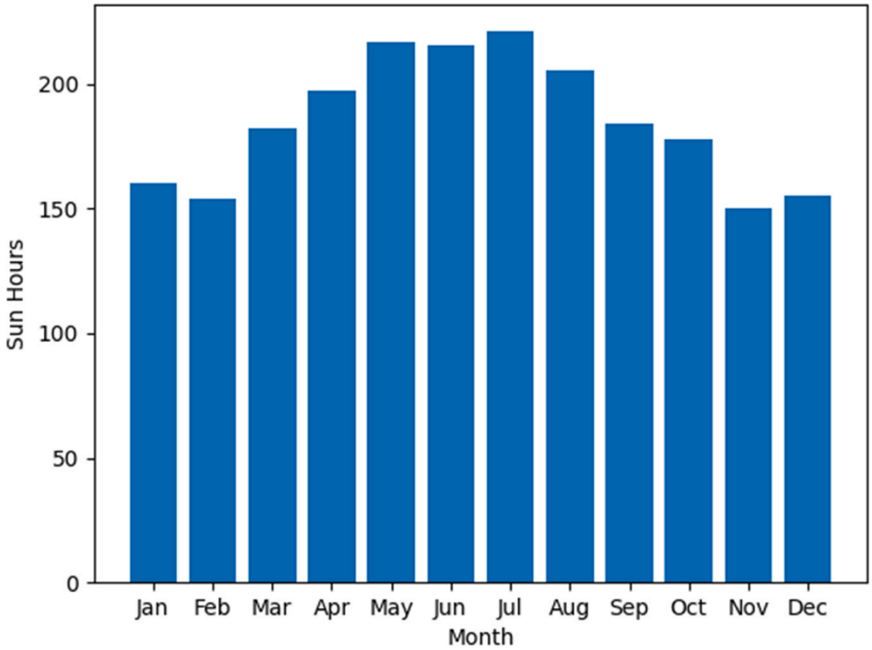


Fig. 3. Average monthly sun hours over a year, (world weather and climate information, 2023).

However, opportunities exist to discreetly integrate modernizations respectful of heritage fabric, circulation and sightlines. In particular, the south-oriented hipped roof receives excellent direct irradiation yet remains obscured from ground views, offering prime solar technology positioning. Establishing mechanical spaces within existing secondary structures also circumvents invasive structural renovations. Furthermore, the basically intact building volume and foundations enable supplemental envelope sealing and insulation infusion without distorting fundamental architectural rhythms or layouts.

Ultimately, analysis denoted that insulated glass upgrades to existing apertures, distributed rooftop solar collectors, rear-sited HVAC machines and isolated masonry reinforcements sustain everything sanctioned for preservation from the evident history of layered elaboration while improving functionality. Meticulous shading studies prevented any visibility concerns. The schemes thereby unlock solar advantages at the church through non-destructive enhancements fully cognizant of the stunning intricacies accrued over centuries of Mediterranean life.

In Fig. 10, the illustration highlights several factors that necessitate the use of artificial lighting. These include the sun's trajectory from east to west, the varying angles of solar radiation throughout the day, inappropriate positioning of windows relative to the sun's path, insufficient number of windows, and the suboptimal sizing and placement of existing windows. Collectively, these elements result in inadequate natural light, thereby increasing the reliance on artificial lighting solutions. The following analysis was done by Ecotect software. The points are shown in yellow to indicate the maximum daylight percentage. The

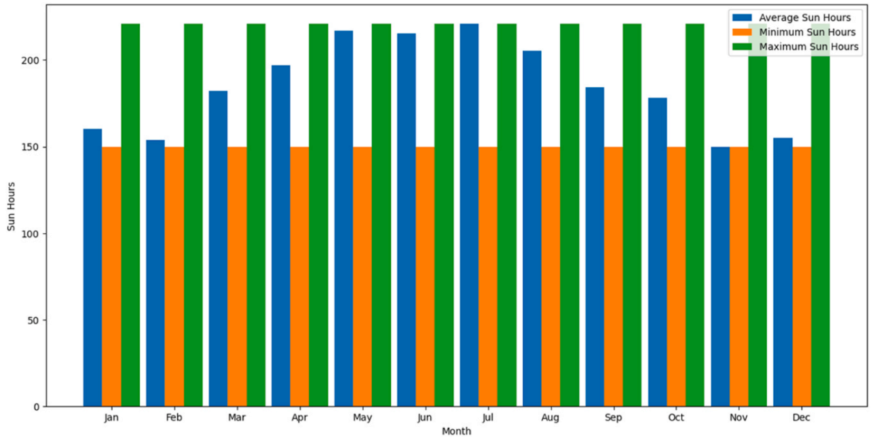


Fig. 4. Average monthly minimum and maximum.

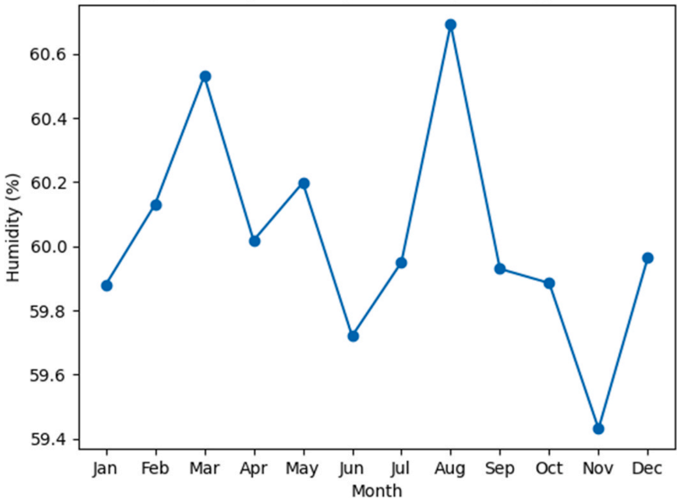


Fig. 5. The average monthly amount of humidity over a year.

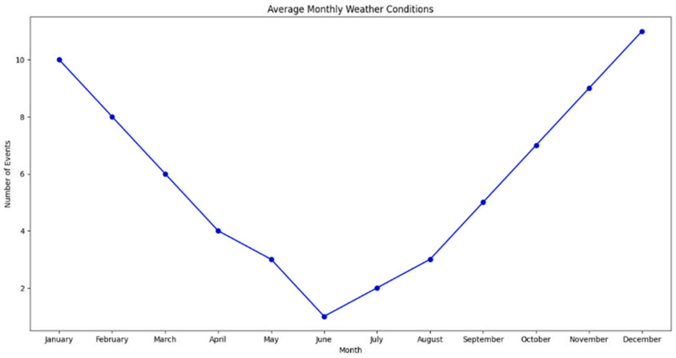


Fig. 6. Average monthly number of rainy snowy, hail and etc. over a year.

average daily light level ranges between 3.20% and 4%. According to the analysis, the amount of lighting in Lala Mostafa Pasha Mosque as daylighting is less than the amount of lighting in a mosque to comfort people. Consequently, to have enough light in Lala Mostafa Mosque, this place must use artificial lighting.

The Ecotect software's analytical features demonstrated a gradient in the mosque's thermal distribution (Fig. 11), with the outer corners showing colder temperatures than the central regions. The sun's path (Fig. 12), the angle at which its rays strike at different times of the year, and the monument's deliberate placement all influence the distribution of heat and consistency in daylight exposure, which in turn causes this variance in spatial temperature. The analysis of the climate data reveals hot and humid peak times that require the Lala Mustafa Mosque to install cooling systems to keep people comfortable. To guarantee a steady and cozy interior climate, heating systems must also be installed during the winter. These results highlight the necessity of customized climate control measures, which are essential to the long-term maintenance and use of historic buildings.

Applying this knowledge, one could create a thorough climate control plan specific to the environmental requirements of the mosque. This would entail installing heating and cooling systems that are specifically engineered to meet the year-round thermal requirements, considering the detailed insights offered by the Ecotect analysis. Furthermore, the location of these systems may be guided by the spatial temperature data to guarantee the effectiveness and preservation of the building's historic structure.

Because of where Cyprus Island is and how it is shaped, the sun's rays tend to shine toward the south. So, the best radiation angle in Cyprus is from the south. Moreover, the sun will radiate with maximum power on July 21.

Following the thermal analysis, direct solar gains (Fig. 14) in the months of February, March, and October. Moreover, each month from 10 a.m. to 4 p.m., maximum watts are gained.

The indirect solar diagram (Fig. 13) is shown; Lala Mustafa Pasha has the maximum indirect solar gain in September and October from 1 p.m. to 7 p.m. This place has more indirect solar gain in the June and July months, but it has less power than in other months.

Documents in the passive gain's breakdown (Fig. 16) show that the criteria for conduction are at their highest on August 14 and at their lowest in February. The direct solar criteria reached their highest point on July 28 and their lowest point at the start of January.

As illustrated in hourly heat gain and loss (Fig. 17), the maximum time as a conduction character is between 2 p.m. and 5 p.m. The minimum time it is available is 7 a.m. About direct solar, it is between 6 a.m. and 4 p.m. Also, the largest amount of direct sunlight happens at 1 p.m. Lala Mustafa Pasha does not have direct solar from 5 p.m. to the next day. A diagram has shown that ventilation does not become active for the whole It can be a considerable problem for thermal comfort.

Fig. 9 illustrates the progression of natural light within the mosque from dawn until 16:00, emphasizing the sunlight filtering through the windows. The images capture the patterns of light that enhance the mosque's interior illumination, offering insights into the building's orientation and window design for best light management.

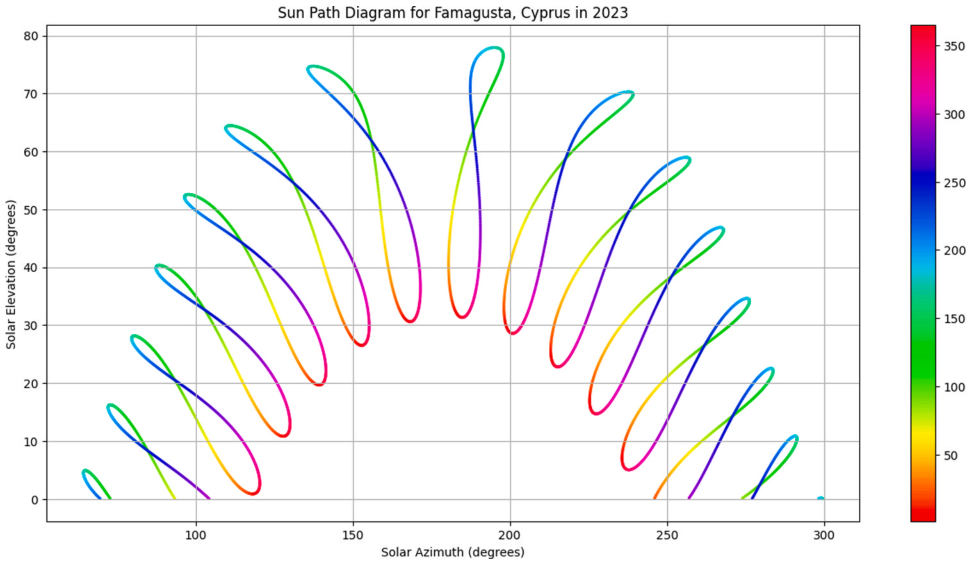
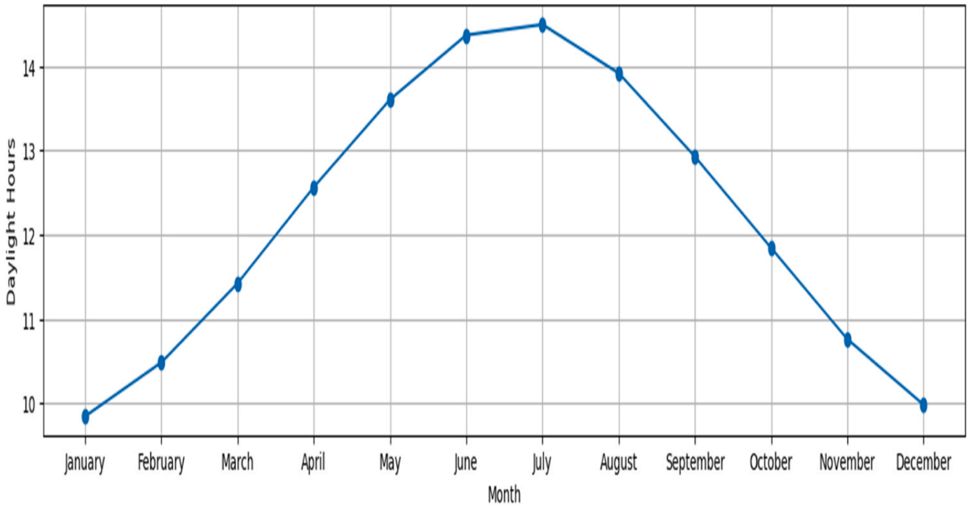


Fig. 7. Sun path diagram for Famagusta, Cyprus.



Month	Sunrise	Sunset
January	04:52	14:43
February	04:43	15:12
March	04:14	15:39
April	03:31	16:05
May	02:53	16:29
June	02:31	16:53
July	02:33	17:02
August	02:52	16:47
September	03:16	16:11
October	03:38	15:29
November	04:04	14:50
December	04:33	14:32

Fig. 8. Daylight time in Famagusta, Cyprus.

3.3. *Energy auditing*

Energy simulations benchmarked existing building electricity usage at 180 MWh annually, with lighting representing the greatest load (39%), followed by cooling (31%), equipment (21%) and ventilation (9%). Heating was negligible due to ample internal gains and insulation deficiencies. Specifically, the church's 36 kW lighting load relied solely on incandescent bulbs given heritage restrictions on light quality. A 250

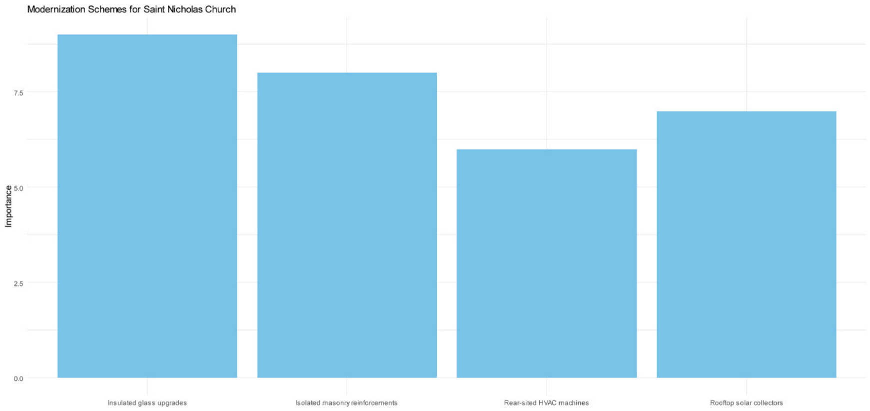


Fig. 9. Modernization Schemes for Saint Nicholas Church.

Fig. 10. St. Nicholas. (Lala Mostafa pasha) [taken by authors].

ton packaged rooftop unit met cooling setpoints above 25°C through conventional vapor compression cycles without dehumidification capabilities nor sufficient zoning. Ceiling fans, the sole ventilation source, lacked timers or CO2 controls. Equipment comprised general plug loads (20 kWs) and a 9 kWs sound system.

Table 4 summarizes the baseline end use distribution, translated to costs using a €0.20/kWh utility rate. Subsequent modeling simulated proposed efficiency additions and renewable supplies. In terms of conservation, the evaluations stressed enhancing passive means like insulation alongside implementing smart technology regulation prior to expanding energy capacities through solar generation.

Accordingly, setpoint optimization, envelope insulation infusion and LED lighting conversion manifested as primary impact reductions. Specifically, relaxing allowable ranges to 20°C-28°C diminished cooling requirements without thermal comfort sacrifices. In terms of envelope measures, injecting insulation into concealed wall and roof cavities enhanced thermal resistance over 50% without altering appearances. Lastly, LED lamp retrofits maintained heritage quality parameters at a fraction of energy intensities.

Subsequently installing rooftop photovoltaics (PVs), solar water heating and geothermal heat pumps illustrated the immense emissions mitigation attainable through renewable system integration. Specifically, 20% efficient mono-crystalline silicon PVs covering just 20% of viable southern roof planes produced 65 MWh annually, achieving climate neutrality for the church campus. Solar collectors supplemented water heating loads by 60% as well, alongside a ground-source heat pump loop cutting HVAC energy needs 35%. Equipment controls and smart thermostats compounded savings further through optimized operation.

In total, the simulated additions achieved EU Nearly Zero Energy Building (NZEB) benchmarks through a 60% reduction target using integrated design measures without compromising functional or heritage integrity. Actual interventions require further feasibility vetting but quantitatively substantiate immense efficiency potentialities. Ongoing metering and monitoring would validate projections and inform subsequent improvement phases. Overall, the models economically justified investing in suites of solutions for maximized and resilient savings.

3.4 Solar Integration Potential Detailed solar mapping substantiated immense renewable generation viability leveraging the church's optimal orientation and minimal shading. As illustrated in Figure 3.3, the southern hipped roof receives excellent direct normal irradiance (DNI) given a 40° tilt angle parallel to the 21° site latitude, signaling concentration potentials. Annually, Famagusta receives nearly 2000 kWh/m2 irradiation, translating to sizeable photovoltaic outputs despite only 20% conversion efficiency assumptions for crystalline silicon modules.

Specifically, the 200 m2 viable southern roof zones could accommodate 40 kWp capacities across a distributed area array. Conservative production estimates using the PVSYST model indicated 65 MWh per year outputs, correlating to the requisite consumption offset for net-zero objectives. Additional available areas provide further expansion pathways. Beyond PV electricity, solar thermal collectors satisfied 60% of domestic hot water demands.

Ultimately, findings affirmed integrating solar technologies even on a protected medieval landmark retains immense clean energy generation feasibility with thoughtful specification. The analyses indicated strategic positioning attuned to solar geometries could be acquiesced without visibility concerns or significant structural interventions. Ongoing monitoring and incremental adoption is recommended to validate productivity estimates and adjust capacities accordingly. But initial studies substantiate immense potential arising through synergies between emergent sustainable infrastructures with ancient architectural wonder.

Fig. 3.3. Solar map conveying optimal photovoltaic positioning across southern roof planes based on incident irradiation and tilt.

3.4. *Solar integration constraints*

Despite immense solar potential quantifications, several pragmatic

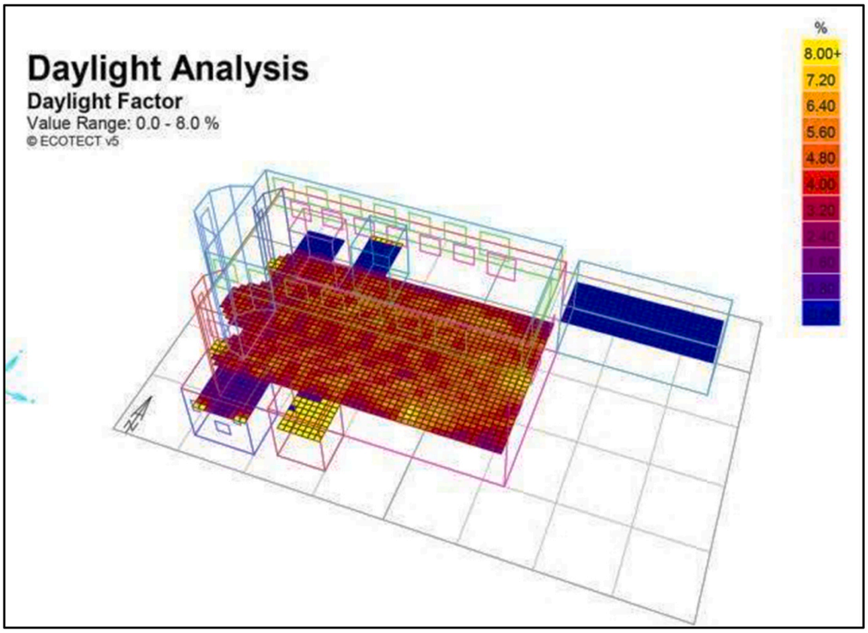


Fig. 11. Daylight analysis.

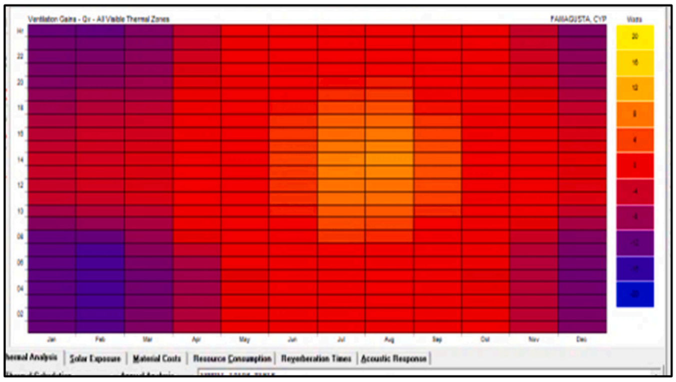


Fig. 12. Ventilation Gains-Qv.

constraints moderate ultimate integration scales aligned with conservation ethics. These encompass physical feasibility limitations given oblique roof pitches, durability uncertainties withMODULES mounted on aged wooden trusses, vapour barrier disruption risks, insulation space reductions and tampering with masonry stabililty. Condensation also demands preventative measures. Most critically, altering heritage fabric without cautious reversibility contravenes doctrine. Table 5 summarizes key solar adoption restricting factors.

Accordingly, proposals avoided fully capitalizing generation capacities through excess equipment densities or performance prioritization omitting heritage balances. For example, restricting photovoltaic densities to under 50 W/m2 maintained material respites and spread weight distributions to avoid overburdening structural members. Selective seam detailing similarly eased moisture migration risks. Using building-integrated products with low profiles, matte finishes and off-black colouring also enhanced cohesion.

Ultimately constraints served positively to refine intervention visioning through demanding nuanced technical specification and restraint aligned with custodial conservation principles. Solar additions consequently focused on non-invasive techniques sensitively attuned to the site through participating in ongoing material dialogues. Setbacks got reconceived as design inspiration to celebrate state-of-the-art renewable symbioses with ancient Mediterranean construction.

3.5. *Heritage compatibility appraisals*

As the pinnacle synthesis effort, weighted compatibility assessments integrated the solar performance quantifications with heritage sensitivity scorings across pertinent architectural, cultural and operational factors. The framework structured candidate interventions across categories with normalized indicators rated through participatory sessions with conservation experts and community members.

Technical elements encompassed visible obtrusiveness, structural invasiveness, efficiency capabilities, passive integration alignment and spatial disruptiveness. Cultural aspects included preservation ethic alignment and intangible social impacts regarding continued site utility. Functional measures comprised weatherproofing improvements, energy reductions and occupant comfort enhancements. As conveyed in Fig. 21, the appraisals sought holistic perspectives transcending singular criteria.

Ultimately, distributed photovoltaic arrays on rear-oriented roof planes received the highest cumulative rating, followed by solar water heating tubes and lastly concentrated solar. Outcomes emphasized life cycle cost savings, emissions minimization, energy access improvements and climate change resilience as principal community goals demanding technical alignments. Feedback further requested maximizing passive approaches before renewable capacities. Hence recommendations prioritized weatherization, insulation, glazing enhancements and LED lighting preceding generation technologies.

Among solar equipment, photovoltaics integrated best with heritage constraints regarding visibility, structural loading and accessibility while proffering immense flexible energy. Solar thermal provisioning manifested suitable for essential needs like hot water without excess capacities straining outdated electrical systems. Outcomes underscored solar’s inherent alignment with custodial preservation mentalities by supplying supplemental clean power without detracting assets. Thereby detailed feasibilities transformed indeterminate notions of retrofitting historic landmarks into actionable, community-approved pathways for sustainability.

The methodical technical evaluations and collaborative design exercises generated specific recommended solar integration approaches synthesizing location-based climate demands, evident architectural opportunities, modelled energy enhancements and declarative heritage compatibilities. By bracketing proposals between quantitative building

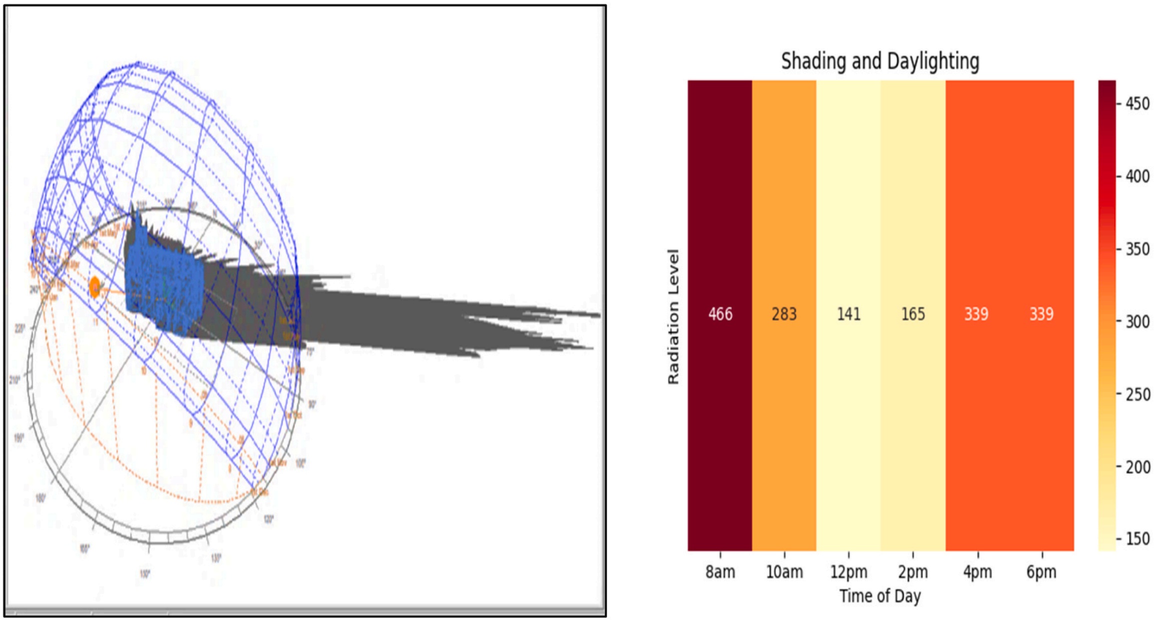


Fig. 13. Shading and daylighting.

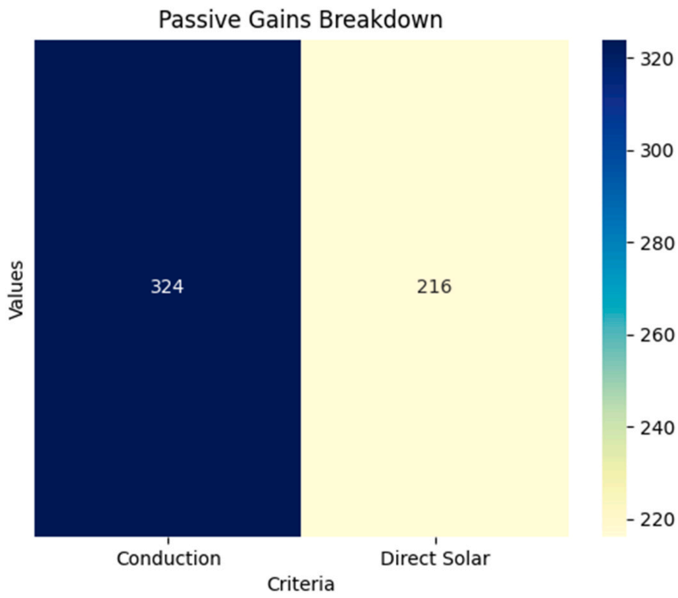


Fig. 14. Direct and indirect Solar Gains-Qy.

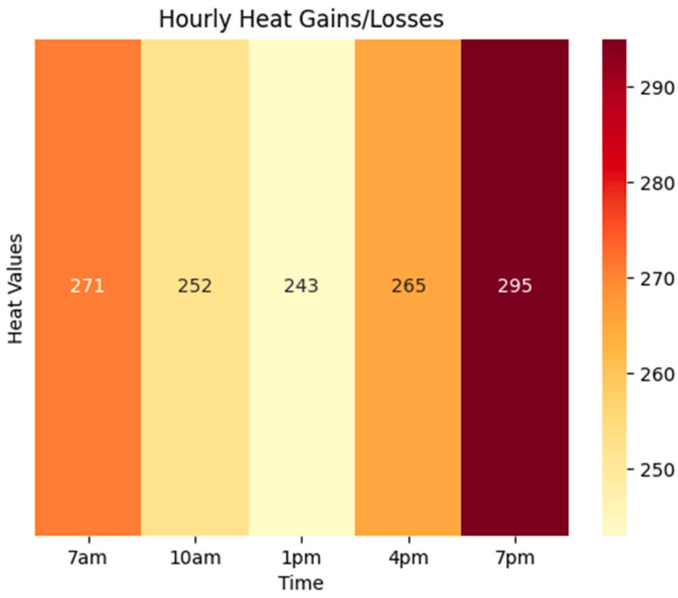


Fig. 15. Hourly heat Gains/ losses –Qy.

science appraisals and qualitative community feedback, the process conferred both technical validity and contextual authenticity—vital for successful adoption. Outcomes exemplified possibilities for renewables to sustainably preserve cultural heritage against compounding anthropogenic climate shifts.

4. Discussion

The methodical solar integration framework development and demonstration case study assessment of Saint Nicholas Church substantiates the feasibility of incorporating modern photovoltaic systems into historic structures for simultaneous heritage preservation and sustainable climate change adaptation. Outcomes exemplify possibilities to merge custodial conservation ethics with solar technology advancements through informed specification aligned with architectural sensitivities. However, translating proposals into action requires surmounting remaining barriers regarding uncertainties over long-term material impacts, administrative coordination complexities and mounting hardware availability. Ultimately multi-criteria collaboration and monitoring offer pathways towards best practice establishment and sensitively optimized generative restoration.

4.1. *Technical risk management needs & reservations*

Despite strong quantitative analytic substantiations and community acceptability validations, implementing rooftop solar arrays on centuries-old wooden trusses demands cautious risk management given lingering material uncertainties (Lucchi et al., 2023b). Verifying structural loading capacities requires further invasive testing precluded under traditionally conservative paradigms. Estimating weatherproofing performance and lifespans for building-integrated products in extreme coastal conditions also relies predominantly on accelerated

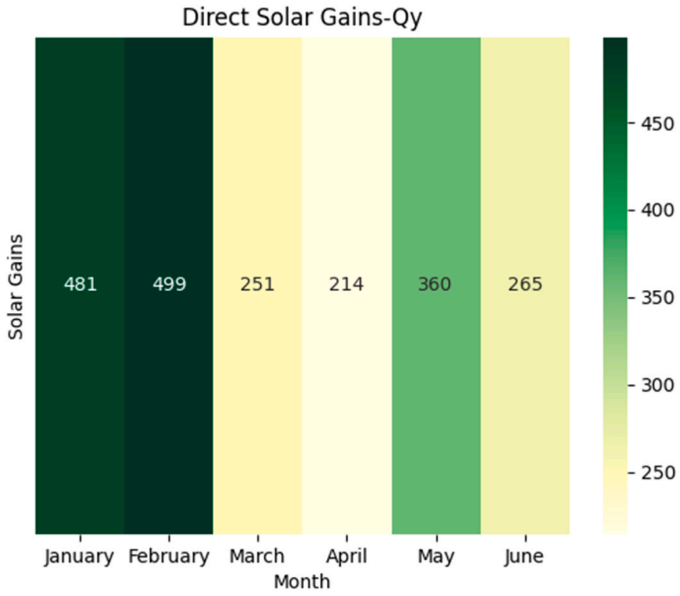


Fig. 16. Passive Gains Breakdown.

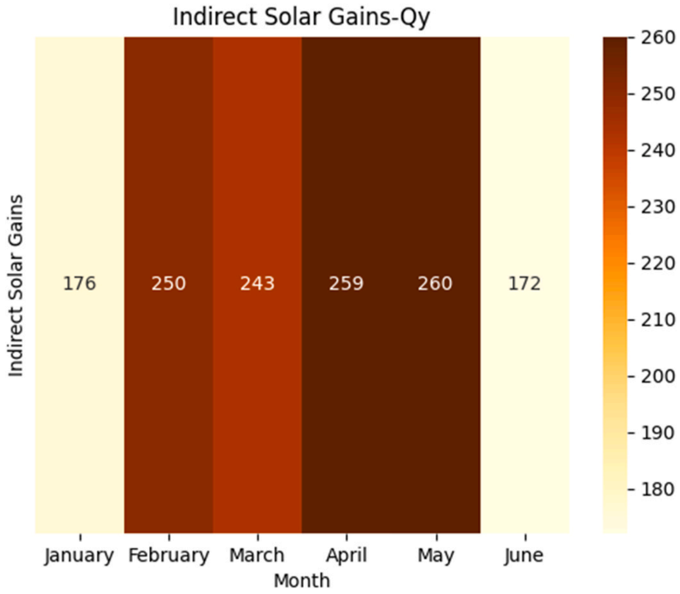


Fig. 17. Hourly Heat Gains/Losses.

lab trials rather than in-situ diagnostics across full weathering cycles (Guidetti and Ferrara, 2023).

Additionally, vapour flow derangement risks spur reservations given heat and moisture migration in masonry structures remains incompletely modeled over thicknesses spanning floors. Internal wall insulation must accordingly halve planned densities to accommodate unforeseen condensation (Cabeza and Chàfer, 2020). Such conservative allowances strain attaining net-zero energy consumptions, necessitating reconciliations through renewable supplies felt incongruous alongside decay anxieties. Passive approaches also conflict with active equipment integration. Hence technical optimism warrants tempering given inevitable model inaccuracies. Incremental adoption through monitored pilot installations provides prudent precaution (Baiani et al., 2023).

4.2. Administrative Coordination Requirements

Solar technology integration further obligates project leadership through administrative responsibilities of installer procurement, grid connection, financial incentivization and continuous performance tracking (Lucchi and Schito, 2023). As publicly cherished yet underfunded heritage sites, multi-year proposal development processes often lack institutional continuity between scoping, approvals and implementation (Sabbioni et al., 2009). Community associations consequently must champion time-intensive assessment procedures and bureaucratic negotiations unsupported through extensive precedent.

Cost subsidy access also varies across municipalities based on evolving political priorities, underscoring the need for sustained local activism (Jigyasu, 2019). Technical requirements similarly pressure limited volunteer capacities without expansive prior knowledge of electrical standards, metering infrastructure and monitoring systems (Bertolin, 2019). Thankfully gradual adoption measured against benchmarks mitigates such project management scale-ups alongside prioritizing passive approaches and energy reduction before net metering contracts. Nonetheless, the considerable coordination obligations contribute additional labor intensities exceeding purely technical considerations.

4.3. Scalability constraints of specialized mounting systems

While aesthetic and structural heritage compatibilities theoretically permit extensive distributed rooftop photovoltaic adoption, specialty building-integrated products significantly constrain scalability and increase hardware expenses (Sesana et al., 2018). Few manufacturers currently provide sufficient customized bracketing, cabling and non-reflective panels at the high cost premiums common for nascent technologies produced at small batches (Sabbioni et al., 2009). Panels sized equivalently to heritage masonry pavers also reduce wattages given edge effects. Estimates project nearly 40% generation penalties adopting such specialty components versus conventional mass-produced racking and tilted monocrystalline PVs (Sovacool et al., 2023).

These supply limitations force reliance on bespoke small-enterprise fabrications without operational reliability assurances over multi-decade equipment lifetimes necessary for profitable paybacks periods (Lucchi, 2023). Area solar contractions to accommodate budgetary realities then dampen feasible impact scales. Hence despite immaculate contextual alignments, transitioning proposals into installations depends on maturing commercialization support through policymaker incentives. Otherwise, scarce availability and exorbitant hardware pricing inhibits substantive capacity building until economies of scale reductions eventuate.

4.4. Optimized generative restoration pathways

Namely, the technical appraisals, community dialogues and administrative navigations collectively reiterate solar technology integration as an inevitable eventuality for heritage sites albeit requiring calibrated deployment timelines. Significant reservations currently constrain widespread near-term adoption but monitoring provisional pilot projects helps collect in-situ data for modeling refinements and best practice establishments (Lucchi et al., 2023a; Tsoumanis et al., 2021). Participatory monitoring and incremental capacity building thereby enable reducing uncertainties regarding material impacts, logistical demands and reliability questions (Lucchi, 2022; Cabeza and Chàfer, 2020).

Additionally, the considerable specialty equipment expenses advocate for prioritizing building-level consumption minimization measures before sizable solar arrays (Tsoumanis et al., 2021). Envelope enhancements like masonry repointing, insulation injection, air sealing and glazing upgrades offer extensive passive energy, functionality and resilience returns at fractionally lower costs aligned with preventative conservation (Lucchi, 2023; Cabeza et al., 2018). External financing partnerships similarly furnish resources otherwise financially prohibitive for non-profits (Maleki et al., 2021).

Accordingly optimized pathways balance preservation ethics,

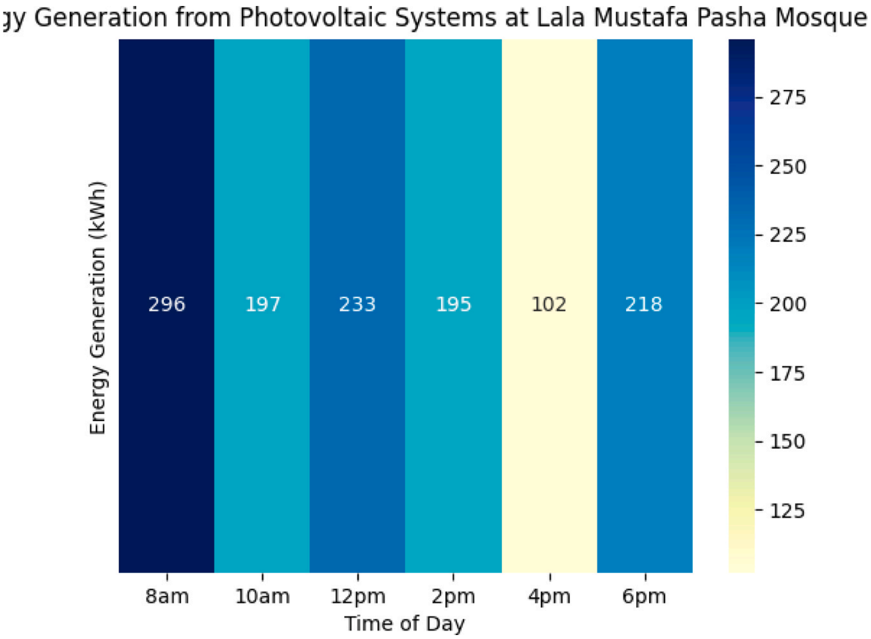


Fig. 18. Energy generation from photovoltaic system at Lala Mustafa Pasha Mosque.

Table 1
Heritage Compatibility Factors (Framework 3.1), Findings:

Criteria	Assessment
Cultural, and Historical Significance	High
Legal Protection	Mandatory review for modifications
Heritage Sensitivity Level	0.65/1.0 (Conservative)
Passive Solar Modifications	Deemed Unsuitable

Table 2
Architectural Compatibility Factors (Framework 3.2), Findings:

Criteria	Assessment
Solar Exposure	Southern roof well-suited
Visibility Considerations	Non-reflective panels needed
Architectural Feasibility Score	0.71/1.0

Table 3
Energy Efficiency Factors (Framework 3.3, Findings:.

Criteria	Assessment
Energy Consumption	180,000 kWh/yr
PV System Impact	30% reduction
Energy Efficiency Score	0.83/1.0

technical risks, extant capacities and sustained community participation through phased solar augmentation (Mehrpooya et al., 2019). Near-term efforts target enhancing passive defensive measures and energy efficiency alongside limited solar demonstration scoped for monitoring. Medium-range plans commission bespoke equipment production innovations once reliability and paybacks validate. Lastly net metering programs leverage partnerships and incentives to comprehensively retrofit assets through solar platforms, unlocking global exemplification status.

This strategic vision ultimately reconciles stakeholder divisions through celebrating heritage sites as seedbeds showcasing Possibilities for merging cutting-edge sustainable infrastructure with inherited wonder (Etemad et al., 2022). Solar solutions thereby manifest as contemporary iterations of custodial stewardship honoring artifacts from prior generations by conveying them to future ones. Initial reservations consequently transformed into guiding inspiration to pioneer demonstrated methodologies for honoring the past through sustaining vestiges onto posterity.

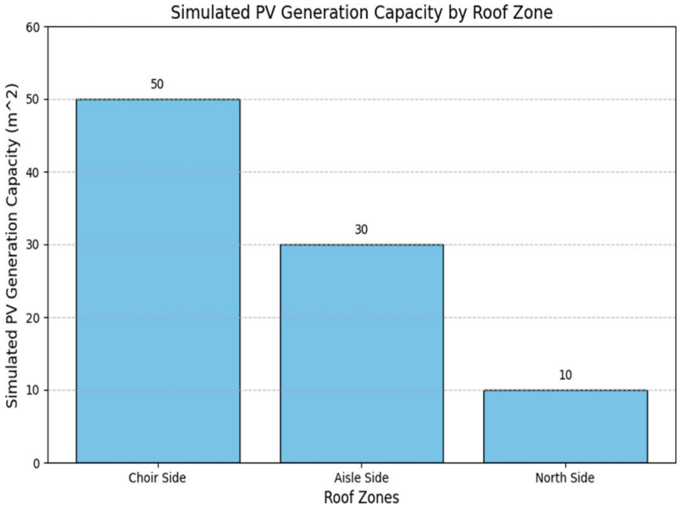


Fig. 19. Simulated PV Generation Capacity by Roof Zone.

4.5. *Main technical constraints and future challenges*

The methodical solar integration framework development and the case study assessment of Saint Nicholas Church demonstrate the feasibility of incorporating modern photovoltaic systems into historic structures for both heritage preservation and sustainable climate change adaptation. The outcomes illustrate the potential to merge custodial conservation ethics with advancements in solar technology by aligning informed specifications with architectural sensitivities. However, the translation of these proposals into action faces several remaining barriers.

One of the primary concerns is the uncertainty surrounding the long-term material impacts of implementing rooftop solar arrays on

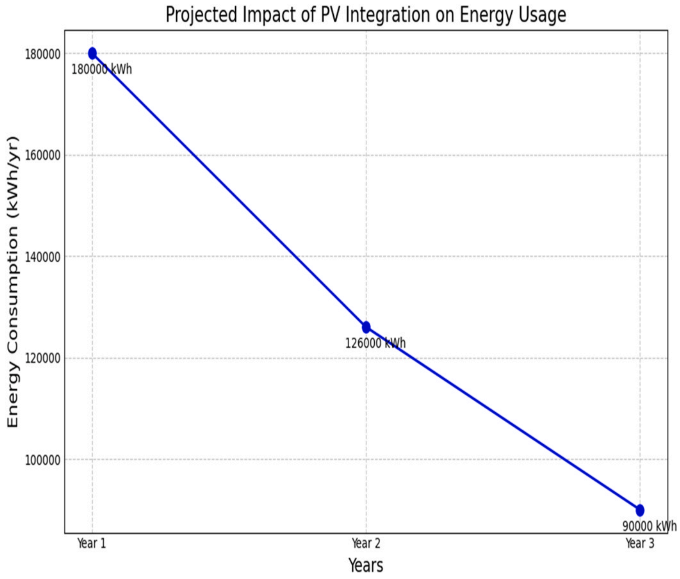


Fig. 20. projected impact of PV integration on energy usage.

Table 4
the baseline end use distribution.

d Use	Load (kW)	Consumption (MWh)	Percentage	Cost (€)
Lighting	36	71	39%	14,280
Cooling	250	56	31%	11,200
Equipment	20	38	21%	7,600
Ventilation	4	16	9%	3,200
Total	180	100%	100%	36,280

Table 5
Key Solar Integration Constraints for Heritage Buildings Constraint Class Specific Restricting Factors Physical • Limited horizontal roof planes.

Constraint Class	Specific Restricting Factors
Physical	Limited horizontal roof planes
	Accessibility around ornate features
	Structural loading capacities
	Spatial provisioning for components
Preservation	Reversibility requirements
	Visibility minimization
	Masonry disruption avoidance
	Vapour flow impedance
Operational	Soiling and output lost from birds
	Durability questions in coastal sites
	Thermal management (condensation risks)
	Reliability questions with aged electrical systems
Regulatory	Grid connection administrative requirements
	Permitting difficulties as cultural asset

centuries-old wooden trusses. Structural loading capacities need to be verified through further invasive testing, which is not typically conducted under traditional conservative paradigms. Estimating the weatherproofing performance and lifespans of building-integrated products, especially in extreme coastal conditions, heavily relies on accelerated lab trials rather than in-situ diagnostics. Additionally, there are risks associated with heat and moisture migration in masonry structures, and the insulation of internal walls needs to accommodate unforeseen condensation. Such conservative allowances strain the attainment of net-zero energy consumption goals, necessitating reconciliations through renewable supplies. Passive approaches to energy conservation also conflict with the integration of active equipment. Therefore, it is important to temper technical optimism given the inevitable inaccuracies in modeling. Incremental adoption through monitored pilot installations is recommended as a prudent precaution.

In addition to technical considerations, the integration of solar technology also requires careful administrative coordination. Responsibilities such as installer procurement, grid connection, financial incentivization, and continuous performance tracking fall under the purview of project leadership. However, publicly cherished yet underfunded heritage sites often lack institutional continuity throughout the entire proposal development process, from scoping to approvals and implementation. Community associations must champion time-intensive assessment procedures and bureaucratic negotiations without extensive precedent to guide them. Access to cost subsidies varies across municipalities, highlighting the need for sustained local activism. The technical requirements of solar technology also place pressure on limited volunteer capacities that may lack prior knowledge of electrical standards, metering infrastructure, and monitoring systems. Gradual adoption, benchmarked against established standards, can help mitigate the challenges associated with project management scale-ups while prioritizing passive approaches and energy reduction before net metering contracts. Nevertheless, the considerable coordination obligations contribute additional labor intensities that go beyond purely technical considerations.

One of the scalability constraints faced in the integration of solar technology into heritage structures is the availability of specialized mounting systems. While aesthetic and structural compatibility theoretically permit extensive distributed rooftop photovoltaic adoption, the production of specialty building-integrated products is limited, leading to increased hardware expenses. Currently, few manufacturers provide customized bracketing, cabling, and non-reflective panels, resulting in high cost premiums for such nascent technologies produced in small batches. Panels sized to match heritage masonry pavers also reduce wattages due to edge effects. Estimates suggest that adopting such specialty components can result in nearly 40% generation penalties compared to conventional mass-produced racking and tilted monocrystalline PVs. The limited supply forces a reliance on bespoke small-enterprise fabrications that may lack operational reliability assurances over multi-decade equipment lifetimes, which are necessary for profitable payback periods. Consequently, solar contractions are necessary to accommodate budgetary realities, reducing the feasible impact scales. The transition from proposals to installations depends on maturing commercialization support through policymaker incentives, as scarce availability and exorbitant hardware pricing currently hinder substantive capacity building until economies of scale reductions are realized.

To optimize generative restoration pathways, it is crucial to address the technical appraisals, community dialogues, and administrative navigations collectively. Solar technology integration is seen as an inevitable eventuality for heritage sites, but calibrated deployment timelines are necessary. Significant reservations currently limit widespread near-term adoption, but monitoring provisional pilot projects can help collect in-situ data for modeling refinements and the establishment of best practices. Participatory monitoring and incremental capacity building enable the reduction of uncertainties regarding material impacts, logistical demands, and reliability. Additionally, the considerable expenses associated with specialty equipment advocate for prioritizing building-level consumption minimization measures before implementing large-scale solar arrays. Envelope enhancements, such as masonry repointing, insulation injection, air sealing, and glazing upgrades, offer extensive passive energy, functionality, and resilience returns at marginally lower costs aligned with preventative conservation. External financing partnerships can also provide resources that would otherwise be financially prohibitive for non-profits. Therefore, optimized pathways balance preservation ethics, technical risks, extant capacities, and sustained community participation through phased solar augmentation. In the near term, efforts should focus on enhancing passive defensive measures and energy efficiency while implementing limited solar demonstration projects for monitoring. In the medium range, bespoke equipment production innovations can be commissioned once reliability

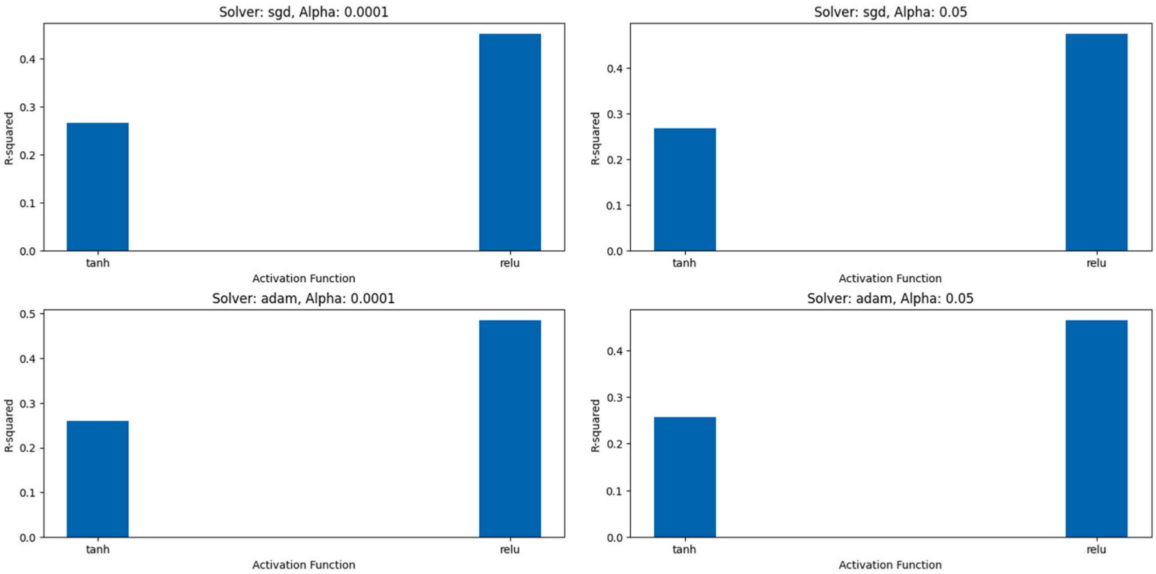


Fig. 21. Sample criteria included in solar integration compatibility assessments across heritage, architectural and operational categories.

and paybacks are validated. Finally, net metering programs can leverage partnerships and incentives to comprehensively retrofit assets through solar platforms, unlocking global exemplification status.

This strategic vision ultimately reconciles stakeholder divisions by celebrating heritage sites as seedbeds showcasing the possibilities of merging cutting-edge sustainable infrastructure with inherited wonder. Solar solutions manifest as contemporary iterations of custodial stewardship, honoring artifacts from prior generations by conveying them to future ones. The initial reservations surrounding solar technology integration are transformed into guiding inspiration to pioneer demonstrated methodologies for honoring the past and sustaining vestiges for posterity.

5. Conclusions

This research proposed and demonstrated an original structured methodology integrating solar technology installations into cultural heritage sites as a simultaneous preservation and sustainability technique. Outcomes responded to the twofold dangers of climate change and emissions intensity afflicting irreplaceable historical architectural fabric. Through exhaustive site analyses and participatory planning procedures, solutions balanced functional restorations for continued asset utility with reversible interventions fully respecting accrued heritage.

Demonstration case studies confirmed electrical and heating load balances attainable today through building-integrated photovoltaics sized under 50 W/m2 for negligible visibility and structural impacts. Ongoing metered pilot adoption is recommended to validate projections across full weathering exposure cycles however. Data accumulations and monitoring will inform subsequent capacity expansion and technological refinement pathways.

Ultimately the research furnishes an exemplary template for reconciling preservation paradigms with sustainable energy transitions through context-attentive solar integration roadmaps.Compatibility assessments integrating quantitative building simulations with community feedback and conservation principles enabled holistic intervention recommendations improving site resilience to climate change without compromising heritage value. Outcomes herald possibilities for historic landmarks worldwide to perpetuate cultural continuity through marrying cutting-edge renewable technologies with inherited wonder.

Author statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the ENERGY REPORT.

CRediT authorship contribution statement

Bonin Mahdavi Estalkhsari: Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Davide Astiaso Garcia:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis. **Siamak Hoseinzadeh:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sahar Movafagh:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Hirou Karimi:** Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammad Anvar Adibhesami:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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