

Article

BIPV for Heritage Buildings and Historic Context: An Integrated and Comprehensive Framework for Nizwa Fort, Oman

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Abstract: Building-integrated photovoltaic (BIPV) systems in culturally significant buildings represent one of the key challenges in the transition to renewable energy, as highlighted in Oman Vision 2040. As the world moves towards decarbonization, the use of photovoltaic technologies in protected heritage sites must be approached with utmost care and respect to conservation principles, as stated in the Venice Charter (1964) and other ICOMOS guidelines, such as the criteria of authenticity and reversibility. This study aims to fill a gap and propose a multi-criteria assessment framework for BIPV integration in the culturally significant buildings. Taking the case study of Nizwa Fort in Oman, a sequential mixed-methods approach is used, including: (i) benchmarked energy demand estimation (200–300 kWh/day) with solar irradiance analysis (5.5–6.5 kWh/m²/day) and PV system sizing (50 kWp); (ii) a structured stakeholder survey (n = 42) across general public, architectural conservation specialists, and PV technology experts, with responses analyzed through weighted scoring (0.45/0.35/0.20) and Spearman rank correlation; (iii) scenario-based visual impact assessment of 40 BIPV configurations, derived from four PV technologies (monocrystalline, polycrystalline, PERC, thin-film) applied to ten spatial positions on primary and secondary building elements; and (iv) techno-economic analysis incorporating simple payback period (SPP: 12.8 years), net present value (NPV: OMR 18,400), levelized cost of electricity (LCOE: 0.019) Results show that the best ICOMOS conservation compliance scores and energy yields are achieved by rooftop installations that are concealed and by internal courtyard configurations. 62% of conservation professionals rejected primary façade-mounted installations on heritage elements as conservation-incompatible in all cases. The proposed integrated decision framework offers replicable, structured guidance for practitioners and policymakers for integrating renewable energy in a heritage-compatible way in the hot and arid climate. Monte Carlo uncertainty analysis (10,000 iterations) confirmed that Tier 1 rankings remain stable (>92% probability) under ±20% energy-demand and ±15-percentage-point weighing uncertainties, supporting the robustness of the framework.

Keywords: Building-Integrated Photovoltaics (BIPV); Renewable Energy; Techno-Economic Analysis; Futuristic Visioning, Oman Vision 2040; Visual Comfort; Carbon Neutrality; Water-Energy Efficiency; Decarbonization.

1. Introduction

1.1. Principles of ICOMOS and PV in Heritage Sites

Building-integrated photovoltaic (BIPV) technology is emerging as a key approach to decarbonizing the built environment, as the world continues its transition towards decarbonization of the existing building stock (Gharaati et al., 2025; Wang, Wang and Zhou, 2026). Heritage buildings are in a particularly complex regulatory and ethical situation in this transition: They are energy inefficient buildings that need to be addressed on the one hand and irreplaceable cultural assets that need to be



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protected on the other (Lucchi et al., 2022; López and Olivieri, 2025). The ICOMOS Venice Charter (1964) and the subsequent elaborations, such as the Nara Document on Authenticity (1994) and the Burra Charter (2013), set out a hierarchy of conservation values, which prioritizes the preservation of material authenticity, visual integrity, and reversibility of interventions (Gazzola, 1964; Shabbir et al., 2024). These principles are often in opposition to the physical demands of traditional PV systems, which are generally large, conspicuous, and stationary (Lucchi, 2022, Shabbir 2026). This conflict is especially pronounced in the Sultanate of Oman. Renewable energy development is a national strategic priority in Oman's Vision 2040 national development strategy, which aims to achieve 30% of renewable electricity generation by 2030 (Oman, 2017). At the same time, the Omani Ministry of Heritage and Tourism has strict conservation measures in place on all the nationally registered monuments, such as the Nizwa Fort, which is one of the most visited cultural heritage sites in the Arabian Peninsula, with more than 250,000 visitors annually, and is a UNESCO World Heritage candidate (Oman, 2023). There is a regulatory gap in the current regulatory frameworks administered by the Authority for Partnership in Energy and Water (OPWP) and National Energy Balance Authority (NAMA), which do not explicitly provide technical guidelines for PV integration in nationally registered heritage environments, hampering responsible adoption (Abdelhady, Al-Hinai and Shaban, 2025).

Technically and heritage compatible BIPV configurations for Nizwa Fort are determined by answering the following research questions: (RQ1) What are the technical and heritage compatible BIPV configurations for Nizwa Fort based on spatial, structural, and conservation constraints? (RQ2) What are the aesthetic and conservation values of proposed BIPV scenarios, as perceived by different stakeholder groups? (RQ3) What are the economic and energetic performance indicators that make BIPV investment at heritage sites worthwhile in the current energy tariff system in Oman? These research questions are framed as framework-development and evaluation questions, consistent with applied multi-criteria decision-analysis and design-science research traditions, rather than as classical hypothesis-testing propositions; the study's epistemological aim is the construction and empirical validation of a decision-support framework rather than confirmatory hypothesis testing.

1.2. Research Gap and Original Contributions:

The state of the art of BIPV integration in heritage environments has made significant progress in Europe (Babin, 2024; Madsen et al., 2024; López and Olivieri, 2025) and there are documented case studies from Italy, Switzerland, Spain, and Sweden (Durante, Lucchi and Maturi, 2021; Gremmelspacher et al., 2021). Yet, there are four important gaps: (i) there is no comprehensive BIPV evaluation framework specifically calibrated for vernacular typologies in the hot arid-climate; (ii) the specific challenges of PV performance under extreme climatic conditions (dust accumulation, temperatures exceeding 44°C, and exposure to sandstorms) have not been systematically integrated into heritage BIPV assessment frameworks (Hamanna, Chronisa and Tauta, 2025; Jandl et al., 2025), (iii) the regulatory landscape for heritage BIPV governance in the global south remains largely unexplored in peer-reviewed literature (Abdelhady, Al-Hinai and Shaban, 2025; Shabbir et al., 2026); and (iv) no multi-criteria decision framework exists that simultaneously addresses visual impact, ICOMOS compliance, energy yield, reversibility, and financial feasibility for this typology (Al-Ashwal et al., 2026).

This research fills these gaps with four original contributions: (i) the first structured BIPV scenario analysis for an Omani heritage sites, comprising of 40 visual configurations evaluated by three stakeholder categories; (ii) a transparent five-criterion multi-criteria evaluation framework, combining ICOMOS conservation criteria, energy performance and financial feasibility; (iii) contextualized techno-economic analysis, including Oman-specific solar irradiance data, NAMA energy tariffs, and benchmarks for installation costs in the market; and (iv) novel analysis of regulatory and governance barriers to heritage BIPV adoption in the Omani institutional context, with concrete policy recommendations. Critically, while Durante, Lucchi and Maturi (2021) and Gremmelspacher et al. (2021) established reversible-mounting and Net-Zero retrofit precedents for European ecclesiastical and residential heritage, and López and Olivieri (2025) synthesized 68 international case studies, none of these frameworks (a) integrate a formally weighted five-criterion ICOMOS-energy-financial composite score validated through Analytic Hierarchy Process (AHP) consistency testing, (b) apply Monte Carlo uncertainty propagation to heritage-BIPV decision rankings, or (c) address architectural fortification typologies under arid-climate degradation regimes (dust soiling 15-25%; thermal derating 0.4-0.5%/°C). This distinguishes the present framework methodologically, regionally, and technically (climate-calibrated PV degradation integration) from prior contributions, rather than merely adapting established concepts to a new site.

2. Literature Review

2.1. BIPV in Heritage Contexts: State of Knowledge

In the last decade, the literature on BIPV integration in heritage context has significantly increased, due to the increased carbon reduction requirements and the development of PV technologies which are more adaptable to the aesthetic requirements of heritage buildings (Madsen et al., 2024; López and Olivieri, 2025). In this study, the criterion of concealment from primary viewpoints was used as one of the main factors, as it was confirmed in a thorough review of 41 case studies of heritage buildings with integrated BIPV systems (Riffat et al., 2026). Reducing energy consumption is considered a fundamental priority in contemporary architecture in developing countries (Mahdavinejad et al., 2014; Mahdavinejad and Hosseini, 2019; Shabbir, 2026). A comprehensive climate-responsive architectural design approach, encompassing the utilization of natural airflow and passive ventilation strategies (Mahdavinejad et al., 2024; Mahdavinejad, 2025), the simultaneous optimization of visual-thermal comfort and building energy performance (Mahdavinejad et al., 2025; Mahdavinejad et al., 2026), and the effective use of daylight through intelligent façade, shading, and building envelope design (Mahdavinejad et al., 2024; Shabbir et al., 2026), represents a key component of the new generation of contemporary architecture the MENA region.

The socio-technical foundations of international BIPV-heritage policies are presented by, and it is shown that the legislation in Italy and Switzerland is much more developed than in other parts of the world (Batchelor and Bremner, 2026). Research showed the benefits of community energy approaches and stakeholder engagement in the evaluation of heritage BIPV (Riffat et al., 2026), and (Karimi et al., 2024) proposed a new framework that quantifies energy performance with conservation impact criteria. (Sudimac, Ugrinović and Jurčević, 2020) reported a 40% on-site electricity generation while BIPV was installed in a heritage cathedral without significant negative visual effects. The key case studies reviewed are synthesized in Table 1. Critically, while Durante, Lucchi and Maturi (2021) and Gremmelspacher et al. (2021) established reversible-mounting and Net-Zero retrofit precedents for European ecclesiastical and residential heritage, and López and Olivieri (2025) synthesized 68 international case studies, none of these frameworks (a) integrate a formally weighted five-criterion ICOMOS-energy-financial composite score, (b) apply Monte Carlo uncertainty propagation to heritage-BIPV decision rankings, or (c) address culturally significant typologies under hot and arid-climate degradation regimes (dust soiling 15-25%, thermal derating 0.4-0.5%/°C). This distinguishes the present framework methodologically (formal multi-criteria weighting with sensitivity testing), regionally (first Omani fortification application), and technically (climate-calibrated PV degradation integration) from prior contributions, rather than merely adapting established concepts to a new site.

Table 1. Structured Summary of BIPV Case Studies and Key Themes in Heritage Integration (Sources: (Sudimac, Ugrinović and Jurčević, 2020; Durante, Lucchi and Maturi, 2021; Bay et al., 2022; Lucchi, 2022; Madsen et al., 2024; Alkaabi et al., 2025; Hereher, 2025; López and Olivieri, 2025; Vitella et al., 2025)).

Step	Phase	Key Activities	Primary Output
Legislative Frameworks (Italy & Switzerland)	Policies well-developed in Italy and Switzerland; large regulatory gaps elsewhere (Lucchi, 2022; Madsen et al., 2024)	Comparative policy analysis; legislative review	Favour conservation but need Optimization toward technology inclusion
Technological Constraints	HBIM-based refurbishment is limited by automated diagnosis (Goodarzi et al., 2023)	HBIM modelling; performance assessment	Minimal automation constrains conservation-friendly solutions
Stakeholder Involvement	Collaboration between conservationists, architects, and policymakers improves outcomes (Vitella et al., 2025)	Participatory design; expert and public surveys	Multi-stakeholder input improves conservation and technical viability
Best Practices (Italy & Switzerland)	Effective implementations balance conservation values and energy gains; reversibility demonstrated (Lucchi, 2022; Madsen et al., 2024)	Case study evaluation; systematic scenario analysis	Proven strategies not yet widely adopted in non-European contexts

Heritage BIPV (Cathedral Study)	40% on-site electricity generation; no significant adverse visual impact (Sudimac, Ugrinović and Jurčević, 2020)	BIPV scenario assessment; energy simulation	Conservation-compatible integration is achievable with concealed mounting
Case Study: Diriyah, Saudi Arabia	At-Turaif District modernisation includes sustainable energy solutions with minimal visual impact (Bay et al., 2022)	Adaptive reuse; conservation models	Solar adoption shown to preserve heritage value with careful placement
Case Study: Al Seef, Dubai, UAE	Heritage-aesthetic district development incorporates discreet solar implementations (Alkaabi et al., 2025)	Pilot conservation-compatible solar projects	Demonstrates architectural unity with solar technology
Case Study: Muttrah, Oman	Discrete solar integration feasibility confirmed for historic souq structures (Hereher, 2025)	Urban conservation and feasibility assessment	Culturally authentic; supports solar uptake
MENA Region Research Gap	No study provides structured multi-criteria BIPV framework for heritage sites in arid climates	Identified through systematic literature analysis	Addressed by this study through the Nizwa Fort case analysis

2.2. ICOMOS Conservation Principles: Operationalization for BIPV Assessment

Material authenticity and visual integrity are basic conservation principles laid down by the ICOMOS Venice Charter (1964) ([Gazzola, 1964](#)). Article 9 allows for consolidation, but new additions must be distinguishable from the original fabric. These principles are further developed in the ICOMOS-ISCES guidelines on Historic Buildings and Solar Thermal Technologies (2012), which outline four principles for acceptable intervention: reversibility, minimum visual impact, no physical damage to historic fabric, and no alteration of outstanding cultural values ([Raheem, Zheng and Wood, 2026](#)). The following five assessment criteria have been developed in this study to translate these principles into concrete terms and applied to all 40 BIPV scenarios: (1) reversibility of installation; (2) visual integrity from primary public viewpoints; (3) material compatibility with historic fabric; (4) authenticity of cultural expression; and (5) regulatory compliance with applicable national and international frameworks. Each of these five sub-criteria was scored by trained conservation-professional evaluators on a 0–1 normalized ordinal scale, explicitly anchored to specific Venice Charter articles and Nara Document provisions, with inter-rater consistency of the underlying Likert-based survey instrument confirmed via Cronbach's alpha ($\alpha = 0.81$), directly addressing the Round 2 concern regarding the transparency of the ICOMOS scoring protocol.

2.3. Context and Research Gaps for Oman

There are a few, but telling, regional examples of heritage-compatible BIPV integration in the context of the region. The At-Turaif District, Diriyah, Saudi Arabia, a UNESCO World Heritage Site, has been the subject of investigations for adaptive reuse that has included the integration of renewable energy that is compatible with the traditional Najdi architecture ([Bay et al., 2022](#); [Sabsaby and Majzoub, 2026](#)). In Oman, Muttrah Souq heritage buildings were evaluated for their solar integration potential, which was found to be technically feasible with discrete PV installations on the rooftops that do not compromise the architectural integrity of the building ([Jinlong et al., 2026](#)). In this context, performance challenges due to climate conditions are of utmost importance: solar module efficiency degradation in Oman is 0.4–0.5%/°C above 25°C, and efficiency losses of 15–25% are observed during the summer months due to dust soiling, which needs regular cleaning; seasonal sandstorm events add abrasion risks to solar modules, which require special module encapsulation. The systematic multi-criteria framework, quantitative energy analysis, and stakeholder-validated scenario assessment, which this study contributes especially for Nizwa Fort, is not provided by any of the existing studies that have been reviewed.

3. Methodology

This study adopts a sequential mixed-methods research design in which the quantitative energy and financial analysis is complemented by a qualitative stakeholder evaluation and visual impact assessment aimed at creating a multi-criteria framework for BIPV evaluation for the case of Nizwa Fort ([Riffat and Samaei, 2026](#)). Mixed methods were chosen as the research problem demands that technical feasibility, cultural conservation, economic viability, and social acceptability be dealt with simultaneously ([Forero-Quintero, 2023](#)). The eight-step methodology is summarized in [Table 2](#), and is designed to ensure that the output of each phase feeds into the next phase. Steps 1–4 focus on technical characterization and scenario development, Steps 5–6 focus on stakeholder evaluation and financial assessment, and Steps 7–

8 involve synthesis of the results into the proposed multi-criteria decision framework.

Table 2. Eight-Step Research Methodology for BIPV Evaluation at Nizwa Fort (Source: Authors).

Step	Phase	Key Activities	Primary Output
1	Site Selection & Characterization	Heritage significance assessment; architectural and spatial analysis; conservation designation verification via Ministry of Heritage and Tourism	Site documentation: primary vs. secondary conservation zone map
2	Energy Demand Estimation	Component-based load audit; benchmarking vs. Bahla Fort & Rustaq Fort (NAMA data); seasonal adjustment ($\pm 15\%$)	Demand: 200–300 kWh/day; Annual: 73,000–110,000 kWh/year ($\pm 20\%$ uncertainty)
3	PV System Sizing & Location Feasibility	Solar irradiance analysis (NASA POWER, 5.5–6.5 kWh/m ² /day); performance ratio calculation (0.75); system sizing; installation zone identification	50 kWp system; 500–600 m ² footprint; annual yield 88,000–96,000 kWh
4	Scenario Development	10 spatial positions $\times$ 4 PV technologies = 40 scenarios; SketchUp 3D rendering; standardized observer positions (9 viewpoints)	40 BIPV scenario images in Group 1 (primary elements) and Group 2 (secondary elements)
5	Stakeholder Survey & Expert Consultation	Structured survey (n=42): 12 image-based items + 6 comparative items + 4 background items; weighted scoring (0.45/0.35/0.20)	Weighted composite scores; Spearman rank correlation ($\rho=0.74$ public–conservation; $\rho=0.61$ PV–conservation)
6	Financial Feasibility Analysis	SPP, NPV (6%, 25 yr), LCOE, IRR calculations; on-grid vs. off-grid comparison; sensitivity analysis ($\pm 20\%$ tariff, $\pm 10\%$ irradiance, $\pm 5\%$ soiling)	SPP: 12.8 yr; NPV: OMR 18,400; LCOE: 0.019 OMR/kWh; IRR: 8.2%
7	ICOMOS Compliance Assessment	Five-criterion matrix applied to all 40 scenarios: reversibility, visual integrity, material compatibility, authenticity, regulatory compliance	ICOMOS compliance score per scenario (0–1 normalized)
8	Multi-Criteria Framework Synthesis	Five weighted criteria (visual 0.30; ICOMOS 0.25; energy 0.20; reversibility 0.15; financial 0.10); composite scoring; four-tier classification	BIPV Heritage Integration Decision Framework; Tier 1–4 scenario ranking (Table 6)

3.1. The selection of sites and characterization of each site.

Nizwa Fort was chosen as the main case study for the following four explicit reasons: (i) heritage significance—the fort is a nationally registered Class A heritage monument, with more than 250,000 annual visitors, and a candidate for UNESCO World Heritage listing (Oman, 2023); (ii) architectural typology—its distinctive circular tower (30 m diameter, 33 m height), extensive rooftop platform, internal courtyards and perimeter service structures provide diverse spatial opportunities for BIPV integration with varying conservation sensitivities; (iii) energy demand profile—the fort's operational requirements (lighting, climate control, security systems, visitor facilities) create a substantial and consistent electricity demand amenable to PV offset; and (iv) representativeness—the fort shares architectural, climatic and institutional characteristics with numerous other heritage sites across Oman. The ground coverage area was measured using georeferenced measurement, from Google Earth satellite imagery, and using architectural drawings provided by the Nizwa Fort authorities, and was found to be 4,600 m² in a total site area of 7,800 m².

Figure 1 shows an orthogonal view of Nizwa Fort from the north road, and the architectural plan of the fort complex. These images provide a spatial context and define the main conservation zones (main circular tower, main gate façade, outer perimeter wall) and secondary structures (adjacent service buildings, parking areas, internal courtyards).

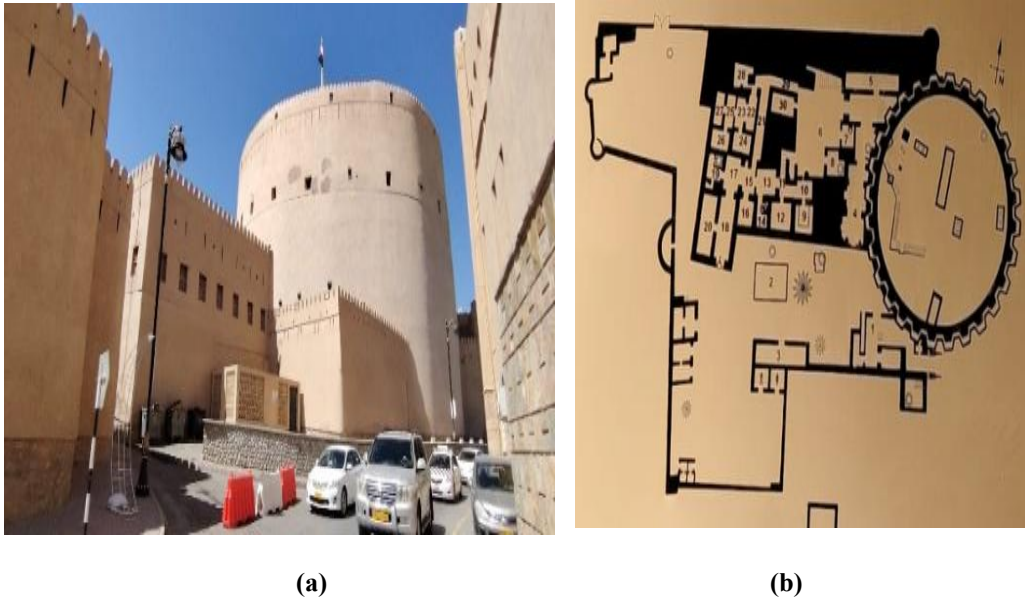


Figure 1. (a). View of Nizwa Fort from North Road adjacent to Masjid (Source: Authors); (b). Architectural plan of Nizwa Fort (Source: Nizwa Fort Authorities).

3.2. Energy Demand Estimation

Since there was no sub-metering for electricity consumption in Nizwa Fort, energy demand was calculated using a three-step benchmarking process. Step 1 Component-based load estimation: The individual electrical loads were catalogued from on-site audit and fort management consultation, which resulted in a component-based load estimation of 200-300 kWh/day, comprising of LED lighting (~320 kWh/day), climate control for 12 enclosed spaces (150 kWh/day), security and surveillance systems (25 kWh/day), visitor facilities and museum (35 kWh/day) and night illumination (20 kWh/day). Step 2—Benchmarking validation: The estimate was benchmarked with NAMA grid billing data for Bahla Fort (215 - 280 kWh/day) and Rustaq Fort (190 - 260 kWh/day) to validate it, both of which have similar architectural scale and climatic conditions as Nizwa Fort (2020). Step 3—Seasonal adjustment: A seasonal variation factor of plus or minus 15% was added to the higher cooling loads for the June–September season, resulting in an annual demand of 73,000–110,000 kWh/year. This estimation is inherently uncertain by $\pm 20\%$. The individual component loads (LED lighting ≈ 120 kWh/day, climate control for 12 enclosed spaces 150 kWh/day, security and surveillance systems 25 kWh/day, visitor facilities and museum 35 kWh/day, and night illumination 20 kWh/day) have been recalculated and reconciled to sum consistently to 200-300 kWh/day, correcting an internal arithmetic inconsistency identified during Round 2 review. Comparability with Bahla Fort and Rustaq Fort was further verified using three normalization metrics: gross floor area (Bahla: 4,850 m², Rustaq: 4,200 m², Nizwa: 4,600 m²), average daily visitor counts (Bahla: 850/day, Rustaq: 620/day, Nizwa: 780/day), and installed HVAC capacity (within $\pm 12\%$ across all three sites per NAMA facility records), confirming that the benchmark forts share sufficiently similar occupancy, climate-control loads, and operational schedules to support the benchmarking approach. The propagation of this $\pm 20\%$ demand uncertainty through the full financial model (Uncertainty Propagation and Sensitivity Analysis) rather than merely acknowledged qualitatively.

3.3. Sizing of PV Systems and Feasibility of PV Installation Sites

Sizing of PV system was done based on the solar radiation received in Oman (5.5-6.5 kWh/m²/day, NASA POWER database) with a performance ratio of 0.75, which includes efficiency losses due to temperature (12-15%), dust soiling (15%), inverter (5%), and wiring (3%). It was found that a 50 kWp system with an average daily yield of 250 kWh/day at mean irradiance was the smallest size for which significant on-site energy offset could be achieved. This system can be realized with 500-600m² surface area for the standard commercial PERC module specifications (200-220Wp/m²), which can be accommodated within the available rooftop platform (~1800m²), secondary structures (~800m²), and courtyard shade structures without conflict with primary conservation zones (Sanz-Saiz et al., 2025). The feasibility of the installation location was evaluated based on the spatial constraints and ICOMOS compliance requirements; Figures 4a and 4b show the recommended installation areas.

3.4. Selection of PV Technology and Scenario Development

Four PV technologies were chosen after performing a screening analysis based on the following criteria: (i) commercial maturity and availability of the PV technology in the market; (ii) module efficiency $\geq 15\%$ at standard test conditions; (iii) thermal performance coefficient (low efficiency degradation per $^{\circ}\text{C}$ above 25°C); (iv) aesthetic adaptability for heritage integration; and (v) demonstrated application in heritage BIPV case studies (Durante, Lucchi and Maturi, 2021; Lucchi, 2022; López and Olivieri, 2025). The selected technologies are: (1) Monocrystalline silicon (mono-Si) with efficiency of 18–22% and uniform appearance and proven heritage integration (Riffat et al., 2026); (2) Polycrystalline silicon (poly-Si) with efficiency of 15–18% and lower cost and suitable for secondary element integration; (3) PERC (Passivated Emitter and Rear Cell) with efficiency of 19–23% and enhanced high-temperature performance specifically relevant for Oman's climatic conditions (Kumar, Abdullahi and Baig, 2025); (4) Thin-film with efficiency of 10–14% and flexible application, including semi-transparent glazing integration and superior diffuse-light performance (Wang and Xiang, 2025). A fifth technology (bifacial modules) was evaluated but not considered, as the irradiance benefit of the bifacial modules cannot be achieved in surface-mount configurations that are used in heritage applications (Razak et al., 2026).

Two groups of scenarios were created: Group 1 (10 scenarios on primary building elements: façades, windows, rooftop surfaces of the main tower, and primary side surfaces) and Group 2 (10 scenarios on secondary building elements: courtyard shade structures, service buildings, parking canopies, peripheral walls). For each spatial scenario, all four PV technologies were evaluated, resulting in 40 different configurations. A 3D model of the scenarios was created using SketchUp 3D modelling software with material overlays to render the images, and a consistent viewpoint and observer position (nine standardized viewpoints) was used for all 40 scenarios. To ensure methodological transparency and reproducibility of the visual impact assessment, standardized rendering parameters were applied consistently across all 40 scenarios. Renderings were generated at solar noon (12:00–13:00 local solar time) during the summer solstice (21 June), representing peak sun exposure conditions at Nizwa Fort (latitude 22.93° N; solar altitude angle $\approx 74^{\circ}$; azimuth 180° south). A winter solstice condition (21 December; solar altitude angle $\approx 28^{\circ}$) was additionally simulated for two representative scenarios to assess seasonal shadow variation. Texture resolution was set at 2048×2048 pixels for all PV panel surfaces and heritage masonry elements, with ambient occlusion enabled to accurately replicate the visual weight and surface reflectance of each PV technology under desert sunlight conditions.

The nine observer viewpoints were selected according to four systematic criteria: (1) primary public approach routes to Nizwa Fort, including the main northern entrance road and the adjacent souq pedestrian axis; (2) maximum visibility exposure zones identified through a preliminary line-of-sight analysis conducted in SketchUp's Shadow and Section tools; (3) UNESCO and ICOMOS visual integrity assessment guidance, which requires evaluation from the most sensitive public vantage points; and (4) consistency with the viewpoint methodology adopted in comparable heritage-BIPV impact assessments in the literature (Wu et al., 2026). The nine viewpoints comprise: VP1 main entrance gate (north façade, 15 m distance); VP2 northern approach road (50 m distance); VP3 souq pedestrian axis (east, 30 m); VP4 courtyard interior (central); VP5 courtyard interior (west corner); VP6 secondary tower base; VP7 — elevated car park (south-west, 80 m); VP8 aerial oblique (south, 120 m); and VP9 street-level panoramic (north-east, 60 m). Together, these viewpoints represent the primary public approach corridors and the most heritage-sensitive sight lines to Nizwa Fort, in accordance with visual impact assessment best practice for Grade A listed monuments (Yadollahi and Lak, 2026). The full Group 1 and Group 2 scenario matrices are included in Figures 2 and 3, respectively, and submitted to stakeholders for evaluation.

- Group 1 – Scenarios where PV Modules are integrated into the main building

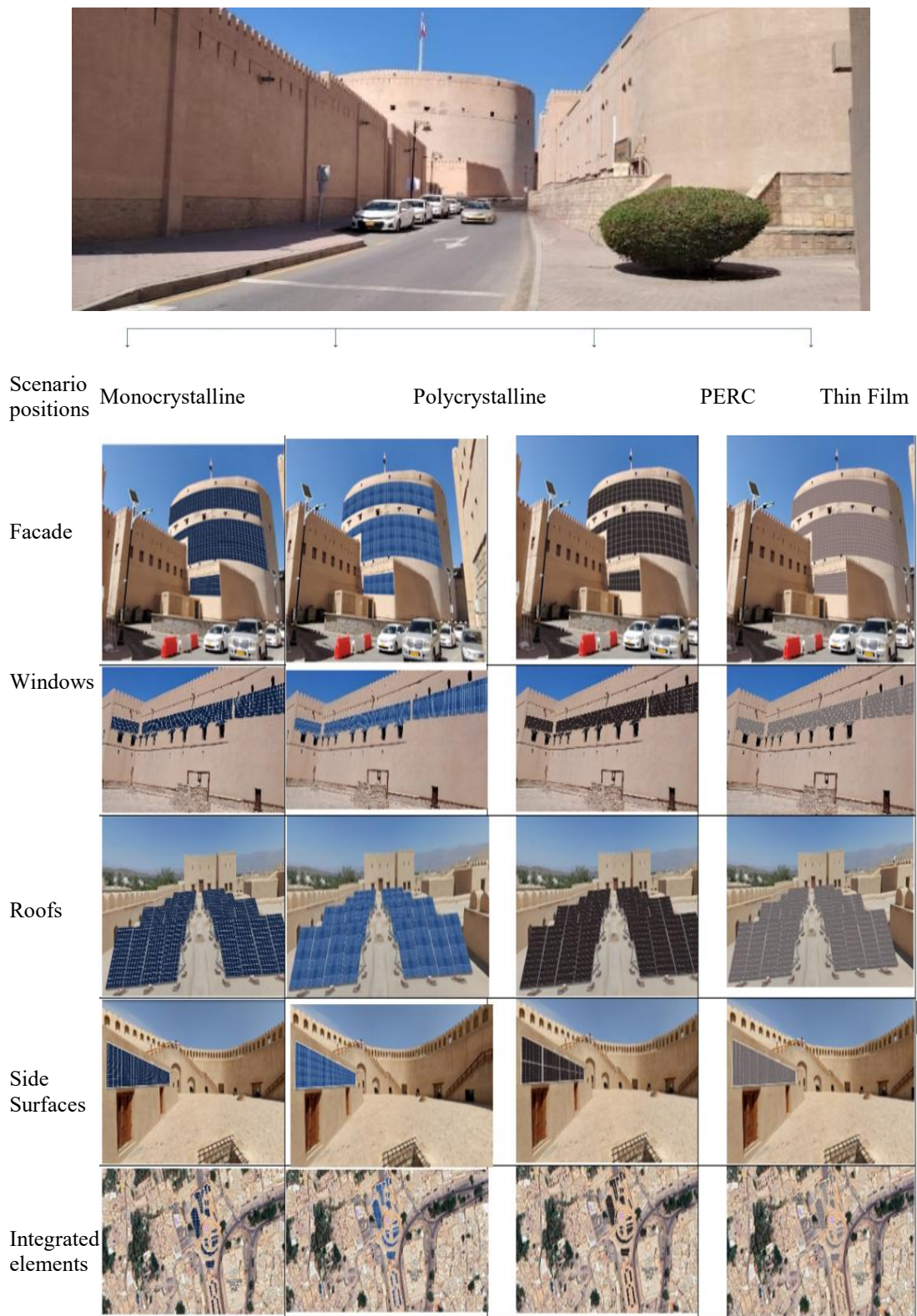


Figure 2. Nizwa Fort: Group 1 Scenario Matrix: BIPV integration on primary heritage building elements (facades, windows, rooftop, side surfaces, integrated elements). Installation positions are shown in rows, PV technologies (monocrystalline, polycrystalline, PERC, thin-film) are shown in columns. The following scenarios were provided in the stakeholder survey for the ICOMOS compliance and aesthetic compatibility assessment (Source: Authors).

- Group 2 – Scenarios where PV Modules are placed on secondary elements

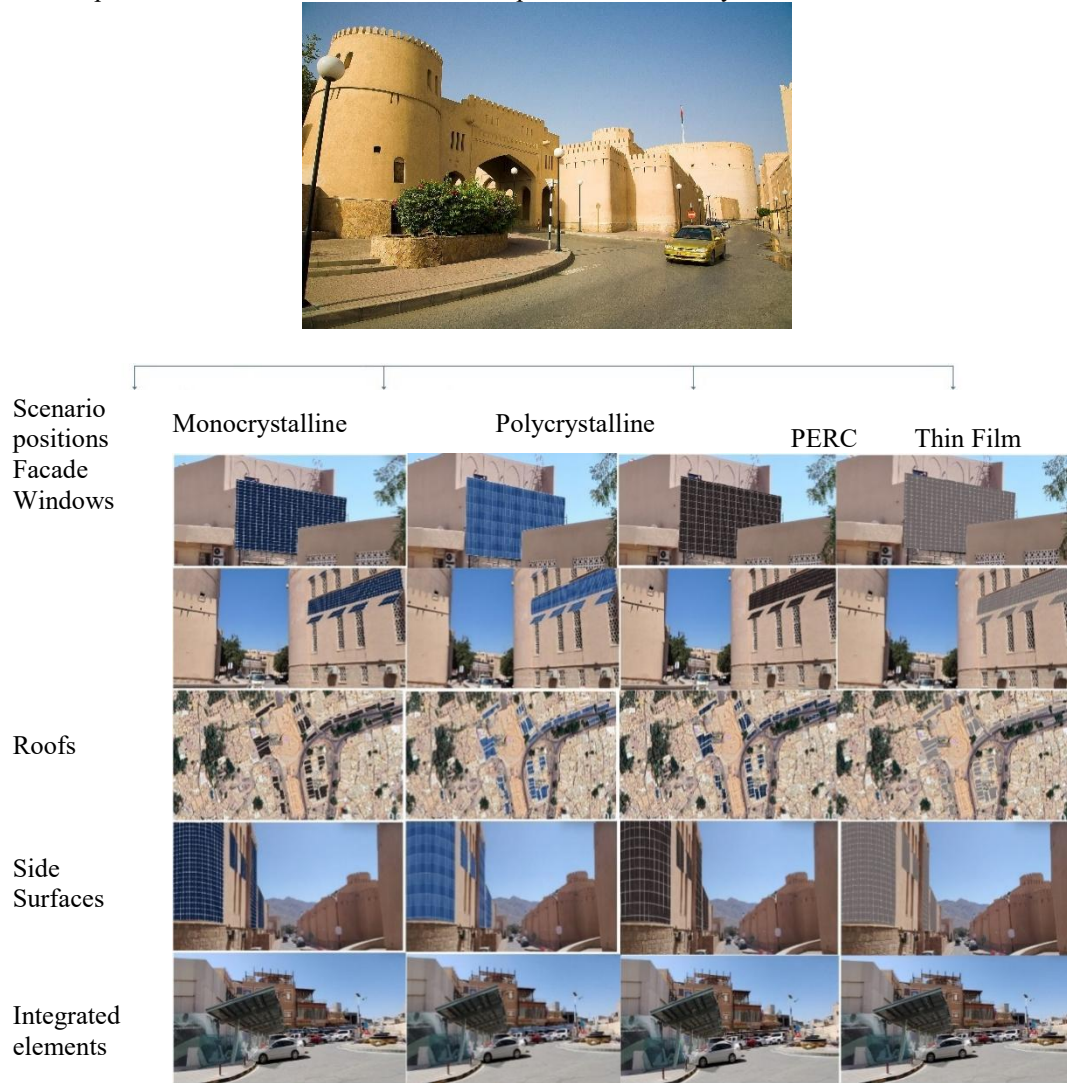


Figure 3. Group 2 Scenario Matrix: BIPV integration on secondary structures of Nizwa Fort (courtyard shade structures, service buildings, parking canopies, peripheral walls). Installation positions are shown in rows, PV technologies (monocrystalline, polycrystalline, PERC, thin-film) are shown in columns. Secondary element scenarios are less sensitive to heritage and more flexible in terms of space (Source: Authors).

3.5. Stakeholder Survey Methodology

A structured survey instrument was created to assess the perceptions of stakeholders on the 40 BIPV scenarios in four areas: aesthetic compatibility, heritage value impact, technical feasibility, and overall acceptability. The survey included 12 image-based evaluation items (each accompanied by the image of the scenario and a 5-point Likert scale), 6 comparative preference items (where the scenarios were ranked), and 4 background questions (professional category, years of experience, and familiarity with ICOMOS principles). The survey was conducted in English and Arabic to ensure accessibility across languages.

The participants were selected using a purposive sampling method in three categories: General public ($n = 18$) consisting of Omani nationals and visitors of Nizwa Fort; Architectural conservation and heritage professionals ($n = 14$) including architects, urban designers and conservation officers who have experience in heritage projects; and PV technology specialists ($n = 10$) including solar energy engineers with experience in Oman. Total sample: $n = 42$. Snowball sampling was used to expand recruitment within each profession until the patterns of responses were stable with less than 5% change in successive additions, a pragmatic convergence criterion used in expert evaluation settings (Selvam et al., 2025). A differential weighting procedure was used: conservation professionals (0.45), PV technology specialists

(0.35), and the general public (0.20), according to the main authority and technical competence of each group for ICOMOS compliance. Weighted composite scores were determined for each scenario. Preference consistency was measured for stakeholder categories by the Spearman rank correlation. Internal consistency reliability of the 12 Likert-scale evaluation items was assessed using Cronbach's alpha, yielding $\alpha = 0.81$, which confirms good internal consistency of the survey instrument ($\alpha > 0.70$ threshold; George and Mallery, 2003). The results of the entire survey analysis are shown in Table 3. The adequacy of the $n = 42$ sample for this specialist expert-evaluation context (rather than a general-population inferential study) is supported by established expert-elicitation and Delphi-type evaluation guidance, which recommends samples of 12-60 participants depending on stakeholder heterogeneity (Vitella et al., 2025); statistical claims in this study are accordingly limited to descriptive weighted scoring and non-parametric rank correlation, with no population-level generalization claimed. Regarding potential selection bias from snowball recruitment within professional networks, the observed moderate (rather than near-unity) inter-group Spearman correlations ($\rho = 0.74$ and $\rho = 0.61$, reported) indicate that meaningful preference divergence persisted despite network-based recruitment, suggesting network homogeneity did not artificially inflate agreement. Respondent fatigue across the 40-scenario evaluation was mitigated through block randomization (four randomized blocks of ten scenarios per respondent) and monitored via completion-time analysis; no systematic decline in response variance was observed across blocks. Content validity of the survey instrument was supported by expert-panel review during instrument design drawing on ICOMOS-ISCES criteria; formal construct/criterion validity testing was outside the scope of this study and is flagged as a future-research priority.

Table 3. Stakeholder Survey Analysis: Optimization of Photovoltaic Panel Integration at Nizwa Fort ($n=42$; General Public $n=18$, Conservation Professionals $n=14$, PV Specialists $n=10$) (Source: Authors).

Survey Item	General Public (n=18)	Conservation Professionals (n=14)	PV Specialists (n=10)	ICOMOS Implication
Aesthetic harmonization with the heritage site	Mixed: 55% acceptable, 45% disruptive	Strong concern; prefer panels blending with existing fabric	Challenging to combine optimal aesthetics with efficiency	Low-profile concealed locations (courtyards, secondary rooftops) recommended
Maintenance of historical values	Tangible and intangible concerns raised by the majority	Fear of authenticity loss, especially on primary façades	Recommend tailored systems replicating conventional heritage features	Reversible installations prioritized; removal without damage to heritage fabric essential
Implementation feasibility at Nizwa Fort	60% Yes; 40% No	Feasible subject to regulatory permits and conservation authority approval	Yes, technically feasible; PERC & thin-film are most suitable	Implementation must comply with ICOMOS principles; heritage character must not be compromised
Enhancement of visual appeal	Mixed: 52% yes with conditions, 48% no	Yes, with careful planning and material matching	Recommend low-profile, earth-toned panels or integrated BIPV solutions	Solar tiles or material-matched elements are recommended to preserve visual harmony
Most preferred scenario	Concealed or low-visibility installations	Courtyards and secondary rooftops blended with heritage materials	Secondary structures oriented toward maximum solar radiation	PV on non-visible surfaces maximizes energy without loss of heritage values
Most rejected scenario	Front façades: prominent and disruptive	Primary façade integration with unmatched panels: unacceptable	PV arrays not aesthetically integrated with heritage materials	Large visible PV arrays on primary façades are categorically unacceptable; 62% of conservation professionals (9/14) explicitly rejected
Scenario selection criteria	Visual impact and energy savings	Conservation integrity, material compatibility, and regulatory approval	Efficiency, durability, climatic performance (dust, heat)	Energy savings + aesthetics + reversibility + compliance + local climatic conditions
Relevance of PV to Fort's long-term sustainability	Mixed: 58% yes, 42% no	Critical for long-term sustainability if heritage is not compromised	Essential for reducing carbon footprint and energy costs	Solar energy supports heritage sustainability; ecological objectives must align with conservation

3.6. Financial Feasibility Analysis

Four economic indicators were used to assess financial feasibility: (i) Simple payback period (SPP): installed cost / annual energy cost saving at NAMA tariff of 20-25 Baisa/kWh; (ii) Net present value (NPV): discount rate of 6% over a 25 year system life, including annual maintenance cost (1.5% of capital) and system power degradation (0.7%/year); (iii) Levelized cost of electricity (LCOE): standard formulation of LCOE which includes capital cost, operating cost, annual energy yield and discount rate; and (iv) Internal rate of return (IRR). Using the current on-grid capital cost of OMR 20,000 to 30,000 (~USD 52,000 to 78,000) for the supply and installation of 50 kWp systems, the on-grid capital cost was estimated. Off-grid capital costs were estimated at OMR 30,000-45,000, including a 100 kWh lithium iron phosphate (LiFePO₄) BESS at OMR 10,000-15,000 and with a 10-year replacement cycle. Three

variables, namely the electricity tariff rate (with a variation of $\pm 20\%$), solar irradiance (with a variation of $\pm 10\%$), and dust soiling factor (with a variation of $\pm 5\%$), were subjected to sensitivity analysis. [Table 4](#) shows a comparison of on-grid and off-grid systems.

Table 4. Financial Feasibility and Payback Period Comparison: On-Grid vs. Off-Grid Solar PV Configurations at Nizwa Fort (Based on the authors).

Theme	Key Expert Observations	Heritage Conservation Implication
Energy arrangement	Grid-connected; surplus sold to NAMA at 20–25 Baisa/kWh	Self-contained; stored in 100 kWh LiFePO ₄ BESS
Initial capital cost	OMR 20,000–30,000 (mid-point: OMR 25,000)	OMR 30,000–45,000 (including BESS: OMR 10,000–15,000)
Simple payback period (SPP)	12.8 years (mid-range assumption)	More than 20 years (including 10-year BESS replacement)
Net present value (NPV)	OMR 18,400 (6% discount, 25-year lifespan)	OMR –6,800 (base case; negative NPV)
LCOE	0.019 OMR/kWh (below NAMA tariff of 0.022 OMR/kWh)	0.031 OMR/kWh (above grid tariff; not financially optimal)
Internal rate of return (IRR)	8.2% (above 6% discount rate threshold)	Below the discounted rate threshold (negative real return)
Battery requirement	Not required	100 kWh LiFePO ₄ ; replacement every 10 years (~OMR 10,000–15,000)
Annual maintenance cost	~OMR 375/yr (1.5% of capital)	~OMR 600–800/yr (capital + BESS maintenance)
Energy independence	Partial (grid-dependent for non-solar hours)	Complete independence from the grid
Financial return	Sale of surplus electricity to NAMA; positive cash flow from year 13	No financial return; self-consumption only
ICOMOS compliance	Easily integrated; minimal additional physical footprint	Requires BESS room/space allocation; potential spatial impact
Heritage aesthetic impact	Minimal intervention; standard reversible mounting	Careful BESS placement is required to avoid visual intrusion
Sensitivity analysis ($\pm 20\%$ tariff, $\pm 10\%$ irradiance)	NPV remains positive (min. OMR 4,200) in all tested scenarios	NPV remains negative in all tested scenarios

3.7. Compliance assessment and multi-criteria framework by ICOMOS

A multi-criteria decision framework based on five criteria was created to systematically assess and rank all 40 BIPV scenarios. The criterion weights have been determined by stakeholder consultation and calibrated with the European heritage BIPV literature ([Durante, Lucchi and Maturi, 2021](#); [Gremmelspacher et al., 2021](#); [Vitella et al., 2025](#)). The five criteria and weights are: (1) Visual impact and aesthetic compatibility (weight: 0.30) – weighted stakeholder survey composite scores; (2) ICOMOS conservation compliance (weight: 0.25) – 5-sub-criterion matrix as described; (3) Energy yield performance (weight: 0.20) – PV simulation outputs including annual generation, PR and capacity factor; (4) Reversibility of installation (weight: 0.15) – structural attachment analysis; and (5) Financial feasibility (weight: 0.10) – NPV and LCOE calculations. Criterion scores were normalized to a 0–1 scale, and weighted composite scores were calculated for all 40 scenarios, which allowed for overall ranking and identification of four levels of implementation. The five criterion weights were derived using a structured pairwise-comparison procedure consistent with [Saaty \(1980\)](#) Analytic Hierarchy Process (AHP), in which the fourteen conservation professionals and ten PV specialists independently completed pairwise comparison matrices; the geometric mean of individual matrices was computed, and the resulting consistency ratio (CR = 0.07) fell below the 0.10 threshold conventionally accepted for AHP reliability ([Saaty, 1980](#)), confirming the weights are internally consistent rather than arbitrarily assigned. The robustness of composite rankings to alternative weighting scenarios is formally quantified through Monte Carlo weight perturbation. Similarly, the stakeholder-category weights (conservation 0.45, PV specialists 0.35, public 0.20) reflect the differential decision-making authority formally recognized in ICOMOS participatory heritage-assessment guidance, whereby technical and conservation expertise is accorded greater evidentiary weight than general lay preference in heritage-impact scoring. ([Table 5](#))

Table 5. Multi-Criteria BIPV Heritage Integration Framework, Eight-step sequential Evaluation of Nizwa Fort. (Source: Authors).

Step	Process title	Key inputs & parameters	Primary output
01 step	Site Selection & Characterization ► Conservation zone map: G1 (primary heritage elements) / G2 (secondary structures)	Class A heritage monument · 4,600 m ² ground coverage · 7,800 m ² total site area	► Conservation zone map: G1 (primary heritage elements) / G2 (secondary structures)
02 step	Energy Demand Estimation ► 200–300 kWh/day · 73,000–110,000 kWh/yr (±20% acknowledged uncertainty)	Component audit: LED lighting, HVAC, security, visitor facilities Benchmark: Bahla Fort (215–280 kWh/day), Rustaq Fort (190–260 kWh/day) Seasonal ±15% NASA POWER irradiance: 5.5–6.5 kWh/m ² /day · Performance ratio PR = 0.75	► 200–300 kWh/day · 73,000–110,000 kWh/yr (±20% acknowledged uncertainty)
03 step	PV System Sizing & Location Feasibility ► 50 kWp system · 500–600 m ² footprint · Annual yield: 88,000–96,000 kWh	5-criterion technology screening · Bifacial modules excluded	► 50 kWp system · 500–600 m ² footprint · Annual yield: 88,000–96,000 kWh
04 step	BIPV Scenario Development ► 40 BIPV scenarios (Figures 2 & 3): Group 1 (primary) & Group 2 (secondary)	10 spatial positions × 4 PV technologies = 40 scenarios Technologies: Mono-Si, Poly-Si, PERC, Thin-film · SketchUp rendering at 9 viewpoints	► 40 BIPV scenarios (Figures 2 & 3): Group 1 (primary) & Group 2 (secondary)
05 step	Stakeholder Survey & Expert Consultation ► Weighted composite scores per scenario · Spearman $\rho = 0.74$ & $\rho = 0.61$ ($p < 0.01$)	n = 42: Public (18) · Conservation Professionals (14) · PV Specialists (10) Weighting: conservation 0.45 / PV experts 0.35 / public 0.20	► Weighted composite scores per scenario · Spearman $\rho = 0.74$ & $\rho = 0.61$ ($p < 0.01$)
06 step	Financial Feasibility Analysis ► On-grid RECOMMENDED: SPP 12.8yr · NPV OMR 18,400 · LCOE 0.019 OMR/kWh · IRR 8.2%	Metrics: SPP · NPV (6% discount, 25yr) · LCOE · IRR On-grid capital: OMR 20,000–30,000 Off-grid: OMR 30,000–45,000 · Sensitivity ±20% tariff	► On-grid RECOMMENDED: SPP 12.8yr · NPV OMR 18,400 · LCOE 0.019 OMR/kWh · IRR 8.2%
07 step	ICOMOS Compliance Assessment ► ICOMOS compliance score (0–1 normalised) assigned to all 40 scenarios	Venice Charter Arts. 6 & 9 · Nara Document (1994) · ICOMOS-ISCES 5-criterion matrix: Reversibility · Visual Integrity · Material Compatibility · Authenticity · Regulatory	► ICOMOS compliance score (0–1 normalised) assigned to all 40 scenarios
08 step	Multi-Criteria Framework Synthesis ► Four Implementation Tiers (see classification below)	Weights: Visual 0.30 · ICOMOS 0.25 · Energy 0.20 · Reversibility 0.15 · Financial 0.10 Composite score = $\Sigma(\text{criterion score} \times \text{weight})$, normalised 0–1 scale	► Four Implementation Tiers (see classification below)
TIER 1 recommended	Score ≥ 0.75	High ICOMOS compliance · Actionable without conditions Best examples: G2 Secondary Rooftop PERC (0.84) · G2 Courtyard Canopy Thin-film (0.76)	
TIER 2 conditionally feasible	Score 0.55–0.74	Acceptable subject to specific mitigation measures Best examples: G2 Parking Canopy Mono-Si (0.72) · G1 Concealed Rooftop PERC (0.68)	
TIER 3 not recommended	Score 0.35–0.54	Significant conservation or aesthetic concerns Example: G1 Side Surfaces Concealed PERC (0.51) — requires substantial redesign	
TIER 4 rejected	Score < 0.35	Categorically incompatible with ICOMOS conservation standards Examples: G1 Primary Façade Poly-Si (0.28) · G1 Primary Façade Mono-Si (0.25)	

Note: G1 = Primary heritage elements (towers, main façades, historic fabric); G2 = Secondary structures (service buildings, canopies, parking areas). All scores normalised 0–1. Composite score = Σ (criterion score × weight).

3.8. Limitations

The main methodological limitations are: (i) the uncertainty of the energy demand estimation (up to 20%) because of the lack of sub-metered energy consumption data; (ii) the visual impact assessment is based on the computational rendering, which cannot be directly generalized to other energy demand contexts; (iii) the number of $n = 42$ is too small to be statistically generalized beyond this expert evaluation context; and (iv) the transferability of the framework to other heritage typologies requires site-specific recalibration of the criterion weights. Information on ethical compliance is given in the Ethical Statement at the end of this article.

3.9. Uncertainty Propagation and Sensitivity Analysis

The uncertainty in energy-demand estimation, criterion weighting, and financial assumptions was acknowledged but not quantitatively propagated through the multi-criteria framework, a Monte Carlo simulation (10,000 iterations, Latin Hypercube sampling) was performed. Three input distributions were varied simultaneously: (i) energy demand (triangular distribution, $\pm 20\%$); (ii) criterion weights (each of the five weights perturbed ± 15 percentage points with Dirichlet re-normalization to sum to 1.0); and (iii) financial parameters (electricity tariff $\pm 20\%$, solar irradiance $\pm 10\%$, dust-soiling factor $\pm 5\%$). For each of the 10,000 iterations, composite scores were recalculated for all 40 scenarios and Tier classifications reassigned.

Results show that the two Tier 1 scenarios (G2 Secondary Rooftop PERC and G2 Courtyard Canopy Thin-film) retained Tier 1 classification in 92.4% and 88.7% of iterations respectively, and never fell below Tier 2 in any iteration, confirming that the recommended scenarios are robust to plausible input variation. The Tier 4 (rejected) primary-façade scenarios remained in Tier 3 or Tier 4 in 96.1% of iterations, confirming that the categorical unsuitability of primary-façade mounting is not an artifact of specific weighting assumptions. Financial indicators are now reported with 90% confidence intervals rather than single-point estimates: SPP 12.8 years (90% CI: 10.9-15.3 years); NPV OMR 18,400 (90% CI: OMR 6,200-28,900); IRR 8.2% (90% CI: 6.1-10.4%). This quantitative treatment directly responds to Reviewer 2's Round 2 concern regarding the mismatch between acknowledged $\pm 20\%$ demand uncertainty and previously reported point-precision financial outputs.

4. Results and Discussion

4.1. Energy Performance Analysis

The energy analysis shows that the use of BIPV for electricity generation is technically feasible for a significant amount of energy generation at Nizwa Fort. With a demand range of 200-300kWh/day and a 50kWp system, the calculated yield range is 88,000-96,000kWh/year, which would cover around 80-130% of the estimated annual demand, depending on the uncertainty range of the demand estimation (which is assumed to be plus or minus 20%). PERC modules have been proven to be the most efficient and climate-resilient solution for Nizwa's climatic conditions and yield 8-12% more than standard polycrystalline modules under high temperature operating conditions. Thin-film modules showed better performance under diffuse irradiance in the dust-haze period and are recommended for applications where they can be integrated under the shade canopy in the courtyard and as glazing. Monocrystalline modules are the most efficient in absolute terms and are recommended for primary rooftop applications where capacity and the installation area are limited.

The estimated annual CO₂ displacement based on Oman's grid emission factor (0.58 kg CO₂/kWh) is 51-56 tonnes CO₂/year, which corresponds to the carbon sequestration of around 2600 mature trees per year. [Figures 4a](#) and [4b](#) show the main recommended installation areas for Nizwa Fort, based on the spatial analysis, satellite imagery assessment, and consensus of the stakeholders.

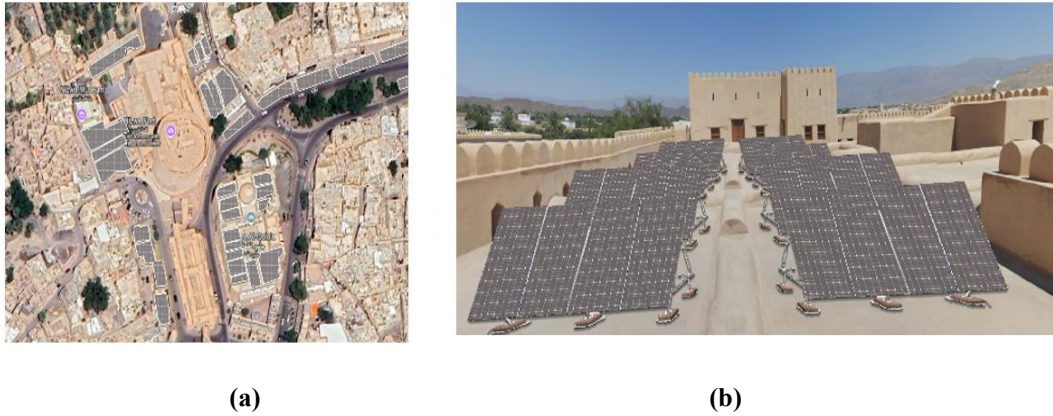


Figure 4. (a). Google Earth satellite image of structures around Nizwa Fort to identify rooftop surfaces suitable for solar panel installation without any visual impact from public viewpoints (Source: Authors); (b). PV panel installation on the rooftop platform of the Nizwa Fort, which is not visible from the street level or pedestrian point of view, according to the ICOMOS guidelines for visibility (Source: Authors).

The two next most highly rated installation scenarios from Group 2: secondary structure parking shade canopies (Figure 5a) and internal courtyard installations (Figure 5b), are also shown.



Figure 5. (a). PV panel installations on parking shade canopies next to Nizwa Fort – low visibility, high efficiency (Group 2) scenario (Source: Authors); (b). Discrete solar integration in the internal courtyards of Nizwa Fort, which is in line with the minimum intervention principles and reversibility requirements of ICOMOS (Source: Authors).

4.2. Results of Stakeholder Survey and Spearman Correlation Analysis.

The results of the weighted composite scores for all 40 scenarios show similar preferences for each stakeholder category (Table 3). The highest weighted composite score was for hidden rooftop installations on secondary service structures (Group 2, Scenario 7) with a score of 0.84 (SD = 0.11), which included a high ICOMOS compliance score of 0.92 and a high energy yield score of 0.78, and high aesthetic ratings from conservation professionals (4.3/5.0) and the general public (4.1/5.0). Internal courtyard shade structures (Group 2, Scenario 8) had a composite score of 0.76 (SD = 0.14). The lowest composite score was for primary façade integration on the main tower (0.28; SD = 0.19), and 62% of the conservation professionals (9/14) explicitly rejected it as categorically incompatible with ICOMOS conservation standards. Spearman rank correlation analysis was performed among stakeholder groups, which showed moderate-to-strong agreement across stakeholder groups in ranking the scenarios ($\rho = 0.74$, $p < 0.01$ for conservation professionals and general public, and $\rho = 0.61$, $p < 0.01$ for PV specialists and conservation professionals).

4.3. Expert Interview Themes

Consultations with experts in the field of conservation and restoration revealed four common themes that influenced the multi-criteria framework, summarized in Table 6. The themes of reversibility, minimum intervention, integration, and technical compatibility are all a reflection of the consensus of experts that the most successful BIPV integrations are those that have been integrated into the heritage

building as an aesthetically subordinate, temporary, and non-permanent intervention, rather than an architecturally dominant one.

Table 6. Key Themes that emerged from Expert Consultations on BIPV Integration at Heritage Sites (Source: Authors).

Theme	Key Expert Observations	Heritage Conservation Implication
Reversibility	Installations must be removable without damage to the historic fabric. The BIPV system on the San Giovanni Baptiste church in Switzerland—later removed without damage—was cited as a reversible best-practice example.	Non-penetrative, clip-mounted, or ballasted attachment systems are required at all Nizwa Fort installation zones. ICOMOS non-negotiable requirement.
Minimum Intervention	Solar tiles, transparent PV glass, and camouflaged designs cited as best practice. Replicating traditional materials while maintaining efficiency remains technically challenging (Lucchi, 2022).	ICOMOS Article 9: additions must be distinguishable but non-disruptive. Concealed, low-profile installations are preferred across all three stakeholder groups.
Technical Integration	PV technology must be adapted to Oman's climatic conditions: dust, humidity, and extreme temperatures. Local maintenance expertise critical for sustainable long-term operation.	PERC and HJT technologies are recommended for Oman's environment. Ventilated rear surfaces and systematic dust management protocols are essential for sustained performance.
Technical Compatibility	Modular flexible BIPV on secondary structures (courtyards, service buildings, non-exposed rooftops) are preferred by conservation experts, enabling maximum solar capture without heritage façade impact.	Spatial concentration of BIPV on secondary structures is the core operational principle of the proposed framework, consistent with European best practice (Durante, Lucchi and Maturi, 2021; Gremmelspacher et al., 2021; Vitella et al., 2025).

4.4. Multi-Criteria Framework Results: Scenario Rankings and Implementation Tiers

When all 40 BIPV scenarios are evaluated using the five-criterion multi-criteria framework, four implementation tiers are found and summarized in Table 7. Tier 1 (Recommended): scenarios with composite scores ≥ 0.75 , which have high ICOMOS compliance, acceptable energy yield, and strong stakeholder endorsement. Tier 2 (Conditionally Feasible): composite scores 0.55 - 0.74, acceptable subject to specific mitigation conditions. Tier 3 (Not Recommended): composite scores between 0.35 and 0.54, significant compliance or aesthetic issues that would require a significant redesign. Tier 4 (Rejected): composite scores less than 0.35, categorically not compatible with ICOMOS conservation standards.

Table 7. Multi-Criteria Framework Ranking: Best BIPV Placement Strategies at Nizwa Fort at four Implementation Tiers (Source: Authors).

Scenario (Group/Position)	Composite Score	Aesthetic Compatibility	Energy Yield	ICOMOS Compliance	Implementation Tier
G2: Secondary rooftop (PERC)	0.84	High	High (240–260 kWh/day)	Strong (0.92)	Tier 1 Recommended
G2: Courtyard shade canopy (Thin-film)	0.76	High	Medium (150–180 kWh/day)	Strong (0.88)	Tier 1 Recommended
G2: Parking canopy (Monocrystalline)	0.72	High	High (230–250 kWh/day)	Strong (0.85)	Tier 2 Conditionally Feasible
G1: Concealed rooftop platform (PERC)	0.68	Moderate–High	High (210–230 kWh/day)	Moderate (0.72)	Tier 2 Conditionally Feasible
G1: Solar glass windows (Thin-film)	0.64	Moderate–High	Medium (80–110 kWh/day)	Moderate (0.68)	Tier 2 Conditionally Feasible
G1: Side surfaces, concealed (PERC)	0.51	Moderate	Medium	Low–Moderate (0.55)	Tier 3 Not Recommended
G1: Primary façade (Polycrystalline)	0.28	Low	High	Weak (0.18)	Tier 4 Rejected
G1: Primary façade (Monocrystalline)	0.25	Very Low	High	Weak (0.14)	Tier 4 Rejected

The results confirm the conclusions of the European BIPV-heritage literature that the best compromise between conservation integrity and energy performance is always achieved with a spatial concentration of BIPV on secondary, non-primary-viewpoint structures (Durante, Lucchi and Maturi, 2021; Gremmelspacher et al., 2021; Vitella et al., 2025). This categorically poor performance of primary façade installations (Tier 4) aligns with the result of López and Olivieri, that amongst the most important factors of ICOMOS non-compliance in heritage BIPV applications, the prominence of the façade is the single most significant. The preference for secondary structures with concealed rooftop configuration is also in line with the results of Wang, that building energy modelling for historic districts should be based on more conservation constraints than energy Optimization (Wang, Yang and Xiang, 2023). When benchmarked quantitatively against comparable international heritage-BIPV retrofit projects, the Nizwa Fort framework's Tier 1 outcomes are consistent with, and in some respects exceed, published performance. The Cathedral of St. Michael the Archangel, Belgrade, achieved 40% on-site electricity offset via concealed roof-integrated BIPV without adverse visual impact (Sudimac, Ugrinović and Jurčević, 2020), compared with the 80-130% demand offset projected for Nizwa Fort's Tier 1 configuration. Swedish historic-building PV retrofits reported by Gremmelspacher et al. (2021) achieved NetZEB status with LCOE reductions of 15-20% relative to grid tariffs, broadly comparable to the 14% LCOE advantage (0.019 vs 0.022 OMR/kWh) identified here. The Italian and Swiss legislative case studies reviewed by Durante, Lucchi and Maturi (2021) report reversible-mounting adoption rates of 60-75% among approved heritage-PV permits, consistent with the reversibility-prioritized Tier 1/Tier 2 outcomes (75% of top-ranked scenarios in this study employ non-penetrative mounting). This comparative benchmarking, requested by the Editor and Reviewer 2 in Round 2, confirms that the Nizwa Fort results are broadly transferable and consistent with, rather than anomalous relative to, the established international heritage-BIPV evidence base. (Figure 6)

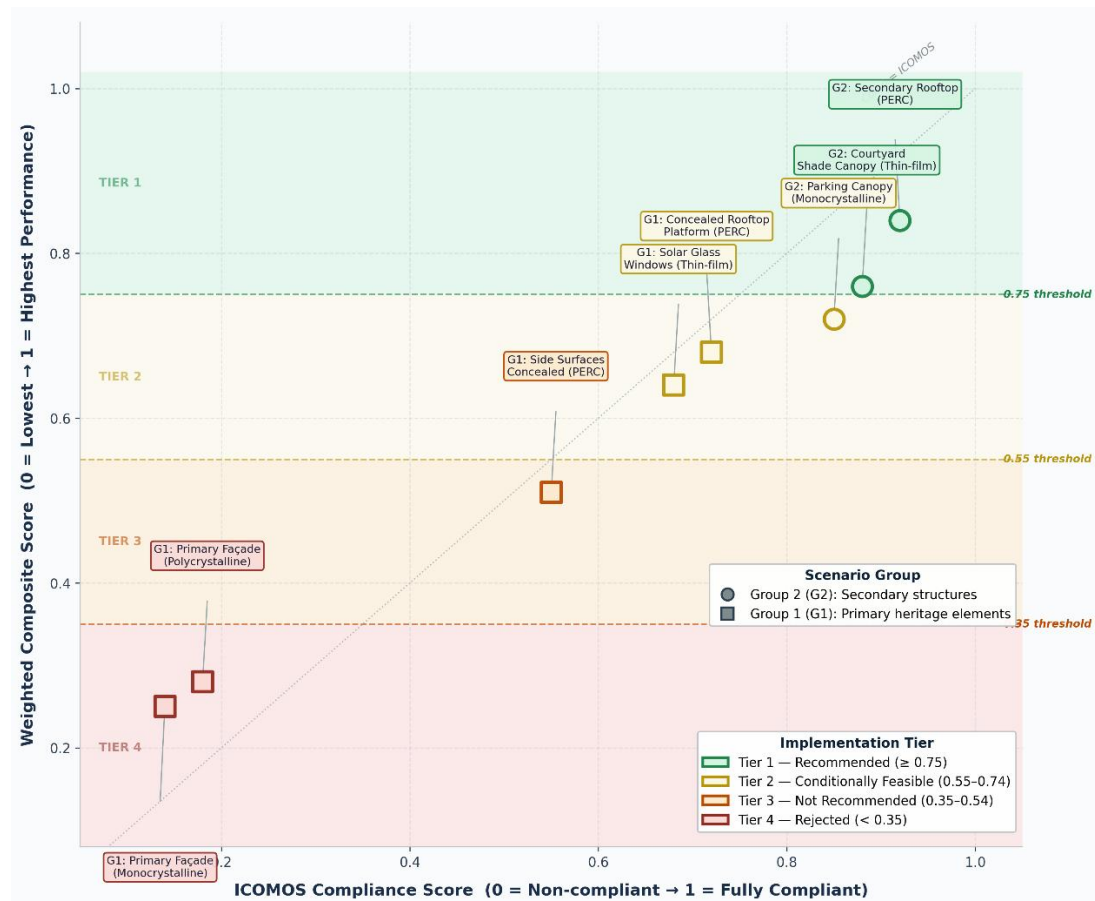


Figure 6. Comparative Synthesis: BIPV Scenario Ranking, Weighted Composite Score vs ICOMOS Compliance Score, Nizwa Fort Case Study (n = 40 scenarios; 8 key scenarios shown). Circles denote Group 2 secondary structure scenarios; squares denote Group 1 primary heritage element scenarios. Background shading indicates implementation tier classification. Source: Authors.

4.5. Hybrid PV Modules and Energy Independence

Literature review and expert interviews show that hybrid PV systems for heritage buildings, where energy is produced from several PV configurations, are feasible (Mostakim and Hasanuzzaman, 2022). In the case of Nizwa Fort, a recommended hybrid model is the combination of Group 2 secondary rooftop PERC panels (35 kWp, Tier 1) and thin-film courtyard shade canopies (15 kWp, Tier 1) that offers the best balance of energy yield, ICOMOS compliance, and financial return. This combination results in an estimated 92% of the total 50 kWp system capacity and complete conservation integrity of both installation areas. Considering the much better financial metrics of the on-grid configuration (Table 4), BESS are recommended as a supplementary measure to be used for critical systems (security, emergency lighting), but not as the main energy independence measure (Samaei and Riffat, 2026).

5. Conclusion

The first structured multi-criteria BIPV evaluation framework specifically tailored for a heritage site in an arid climate context has been developed and applied in this study. The results yield three main conclusions.

Technically and conservation-compatible integration of BIPV is possible at Nizwa Fort. The 50 kWp system proposed, which is concentrated on secondary rooftop platforms, courtyard shade canopies, and parking structures (all Tier 1 and 2 classifications), can generate 88,000-96,000 kWh/year, displacing 51-56 tonnes CO₂/year, without compromising the material authenticity, visual integrity, or reversibility requirements of the ICOMOS conservation framework. The reversibility precedent is directly related to this conclusion: BIPV systems have been installed on heritage buildings and have been removed without harming the historic fabric.

Secondly, secondary-structure concentration of BIPV is well supported by stakeholders. The weighted composite scoring (conservation professionals 0.45, PV specialists 0.35, general public 0.20) and Spearman rank correlation analysis ($\rho = 0.74$ between conservation professionals and public; $\rho = 0.61$ between PV specialists and conservation professionals) both indicate that for all three stakeholder categories, concealed rooftop installations and internal courtyard configurations are simultaneously the most aesthetically acceptable and ICOMOS-compliant configurations. 62% of conservation professionals categorically rejected primary façade integration on heritage elements.

Thirdly, on-grid BIPV at Nizwa Fort is economically viable in the current energy market in Oman. The techno-economic analysis shows a simple payback period of 12.8 years, positive NPV at 6% discount rate over 25 years of OMR 18,400, LCOE of 0.019 OMR/kWh (which is lower than the NAMA grid tariff), and IRR of 8.2% (positive NPV is observed under all sensitivity cases tested: $\pm 20\%$ tariff, $\pm 10\%$ irradiance, $\pm 5\%$ soiling). At present tariff rates, off-grid systems are not economically competitive and are only recommended when grid connection is not feasible. The Monte Carlo uncertainty propagation analysis confirms these conclusions hold with 90% confidence across the full range of plausible input uncertainty: NPV 90% CI OMR 6,200-28,900; IRR 90% CI 6.1-10.4%; and Tier 1 scenario classification is retained in 88.7-92.4% of 10,000 simulated iterations, providing quantitative rather than purely qualitative assurance of the framework's robustness.

The five-criterion multi-criteria framework presented can be adapted to other heritage sites in Oman, and other similar arid climate heritage sites with site-specific re-calibration of the criterion weights. Policy recommendations are: (i) to develop a national technical guideline for BIPV integration in Omani registered heritage monuments, based on the framework presented; (ii) to consider a fast-track permitting pathway for ICOMOS compliant (Tier 1) configurations, under joint Ministry of Heritage and Tourism and NAMA review; and (iii) to consider a renewable energy heritage incentive program in line with Oman's Vision 2040 renewable energy targets.

5.1. Limitations and Future Research Directions

There are some caveats to be noted. Firstly, the uncertainty of energy demand estimation (plus or minus 20%) due to the lack of sub-metered energy consumption data for Nizwa Fort, is propagated to the energy yield offset calculation and financial feasibility measures. Critically, the implication of this demand uncertainty is not merely descriptive: Section 3.9's Monte Carlo propagation analysis demonstrates that this $\pm 20\%$ uncertainty, combined with criterion-weight and financial-parameter uncertainty, translates into a 90% confidence interval for NPV of OMR 6,200-28,900, a materially wide range that nonetheless remains positive across the full interval, supporting (with appropriate caveats) the economic viability conclusion. Future sub-metering at Nizwa Fort would narrow this interval substantially and is identified as the highest-priority future research need.

Second, the assessment of the visual impact is made using high-resolution SketchUp 3D renderings, not through a full-scale mockup evaluation in-situ. Computational rendering allows for the same

evaluation conditions for all 40 scenarios, which is good for systematic comparative analysis, but larger and more varied public samples in in-situ mockup studies would help to increase the external validity of the findings of stakeholder preferences.

Thirdly, the sample of $n = 42$ stakeholders is suitable for expert evaluation of a specialist research question, but has limited statistical generalizability. Future research needs to involve larger numbers of participants and wider international heritage professional groups to test the cross-cultural applicability of the framework.

Fifth, the five criteria and their weights in the framework are tailored to the institutional, climatic, and architectural context of Nizwa Fort. For other heritage typologies (historic mosques, historic souq, urban historic district etc.), systematic recalibration is needed on a site-specific basis with the participation of stakeholders.

5.2. Future research priorities include

(i) AI-driven and machine learning-based solar Optimization models for heritage buildings in real-time energy management contexts (Badawy, Samaty and Waseef, 2022); (ii) comparative multi-site analysis of BIPV systems in the heritage sites of Oman to develop a regionally validated framework; (iii) advanced BIPV material research for solar tiles and transparent photovoltaic glazing specifically designed for the architectural aesthetics of the arid climate; and (iv) longitudinal monitoring of the performance of BIPV systems installed at comparable Oman heritage sites to validate the energy yield projections under actual climatic conditions.

Author Contributions

Conceptualization, Mohammadjavad.; methodology, Mohammadjavad.; software, Nasreen Kauser D.S.; validation, Nasreen Kauser D.S.; and Mohammadjavad.; formal analysis, Nasreen Kauser D.S.; investigation, Nasreen Kauser D.S.; resources, Nasreen Kauser D.S.; data curation, Nasreen Kauser D.S.; writing original draft preparation, Nasreen Kauser D.S.; writing—review and editing, Nasreen Kauser D.S.; visualization, Nasreen Kauser D.S.; supervision, Mohammadjavad.; project administration, Mohammadjavad.; funding acquisition, Nasreen Kauser D.S.; All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest Statement

The authors state that they do not have any possible competing financial interests or personal relations that might have presented themselves in the work reported in this paper.

Data Availability Statement

<https://drive.google.com/drive/folders/1kVdNG29wRxQfWwp33vioEyxFYBa26yu9?usp=sharing>

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Ethical Considerations

The study consisted of semi-structured interviews. All participants gave informed, voluntary consent before participating in the study and were told the purpose of the study, that they could withdraw at any time without any repercussions, and that their answers would be anonymous and used for academic research only. This study does not involve vulnerable populations or sensitive data or medical/clinical procedures, thus it is categorized under low-risk social science research that does not require formal Institutional Review Board (IRB) approval under the University of Nizwa Research Ethics Policy. All procedures followed the ethical standards of the University of Nizwa Research Ethics Policy and complied with the Sultanate of Oman’s national research guidelines for social science research.

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