Multi-objective optimization of BIPV envelope design: BIPV Cladding application

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Abstract:

This extended abstract presents optimization results obtained for a BIPV cladding application utilizing a novel multi-objective optimization framework for Building-Integrated Photovoltaic (BIPV) envelope design. The aim of this study is to concurrently address multiple objectives, including energy performance and economic viability in the process of BIPV envelope design optimization.

Introduction: As global energy demands continue to rise and environmental concerns escalate, the synergy between sustainable architecture and renewable energy technologies has emerged as a pivotal approach to mitigate energy consumption and carbon emissions in the built environment (IEA, 2022). BIPV systems, which integrate solar panels directly into building components such as facades and roofs, offer a promising solution to transform buildings into energy-generating assets. The integration of photovoltaic (PV) technology into building envelopes has gained significant attention to harness solar energy while enhancing building aesthetics and functionality. BIPV is an excellent renewable energy source to generate free electricity, reduction of CO_2 emissions and building material cost offset and improve the aesthetics of buildings (Alim et al., 2019; Amoruso & Schuetze, 2022; Azami & Sevinç, 2021; Gholami & Røstvik, 2020). The process of designing Building-Integrated Photovoltaic (BIPV) envelopes encompasses an extensive array of parameters associated with both the envelope itself and the photovoltaic elements. Additionally, these parameters intersect with conflicting performance criteria, rendering BIPV envelope design an intricate undertaking. Given this complexity, the optimization of multiple objectives concurrently emerges as a notable approach to assist in BIPV façade design, particularly during the early stages of building conceptualization, an approach that has been scarcely employed (Wu, Ng, & Skitmore, 2016). Optimizing BIPV envelope designs involves intricate trade-offs among conflicting objectives, making it a challenging task that requires a comprehensive multi-objective optimization approach.

However, there is a lack of BIPV specific multi-objective optimization frameworks which address both building and PV related requirements of BIPV projects in early design stage. The aim of this study is to employ a multi-objective optimization framework (Tharushi Imalka Samarasinghalage, 2022) to optimize BIPV cladding envelope design considering multiple objectives, including energy performance and economic viability.

Methodology: The utilized multi-objective optimization framework incorporates diverse aspects of BIPV envelope design, aiming to balance energy efficiency and economic viability. The framework employs an evolutionary algorithm, the Non-dominated Sorting Genetic Algorithm (NSGA-II), to efficiently explore the trade-off space and identify a set of Pareto-optimal solutions. The optimization objectives include maximizing energy generation while minimizing life-cycle cost through architectural quality indicators.

The BIPV envelope design space is defined by numerous parameters, such as PV module type, orientation, Window-to-Wall ratio (WWR), tilt angle, and BIPV product type. These parameters interact with climatic conditions, building geometry, energy demands, and economic factors. Net Present Value (NPV), and payback period are used as optimization constraints to filter the optimization solutions.

Table 1 illustrates the design variable configuration utilized in the optimization process. Following this configuration, a total of 4000 distinct Building-Integrated Photovoltaic (BIPV) designs were subjected to simulation and optimization using the developed framework (Tharushi I Samarasinghalage, Wijeratne, Yang, & Wakefield, 2022).

Results and Discussion: The application of the multi-objective optimization framework to a BIPV cladding application type case study demonstrates its effectiveness in generating a diverse set of BIPV envelope design alternatives. The Pareto optimal solutions obtained from the optimization process (Table 2) reveal the trade-offs between conflicting objectives. Each alternative design represents a unique solution, offering a range of design choices for decision-makers.

The analysis of the optimal solutions allows stakeholders to make informed decisions based on their preferences and priorities. A detailed comparison of the solutions showcases the intricate relationships among energy performance and economic viability.

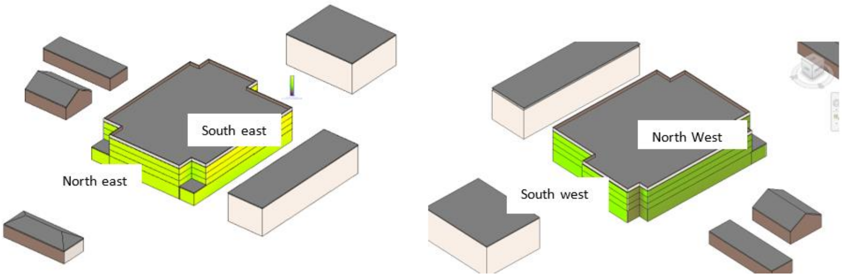

Figure 1. Case study building

Table 1. Parameters of the optimization process

Design variable	**Values**
BIPV products	16 products
WWR	0.3, 0.4, 0.5, 0.6
PV placement	YES/NO
Façade Tilt angle	75, 80, 85, 90 degrees
Objective function	**Aim**
LCC	Minimization
LCE	Maximization
Constraints	**Values**
NPV	> 0
Payback period	< PV life span

As per Table 2, it is noteworthy that the optimal results uniformly discourage the placement of BIPV modules on the southeast façade of the building. Interestingly, a consistent recommendation for an optimal tilt angle of 75 degrees is observed across nearly all outcomes. The calculated payback periods within the results demonstrate a range of 12 to 16 years, suggesting the potential for even more favorable payback periods under varying irradiance conditions. Notably, designs featuring a higher Window-to-Wall Ratio (WWR) correspond to shorter payback periods, implying a positive correlation between the two factors.

Table 2. BIPV cladding design optimization results

	Southeast tilt (degrees)	Southeast PV placement	Southeast WWR	Southeast No of PVs	Northeast tilt (degrees)	Northeast PV placement	Northeast WWR	Northeast No of PVs	PV Type	PV Color	PV Life Span	LCC (AUD)	LCE (kW)	Payback Period (years)	NPV	Capital Cost (AUD)	LCOE	Total PV area (m^2)	Life cycle saving (AUD)
ALT 1	90	-	NA	0	75	•	0.3	313	501	grey	25	53107	1003426	14.88	13674	44170	0.06	225.36	66781.63
ALT 2	90	-	NA	0	75	•	0.6	179	401	blue	25	30371	573844	12.70	11566	25260	0.06	128.88	41938.11
ALT 3	90	-	NA	0	75	•	0.5	224	204	black/blue/custom	25	39945	718107	14.46	10766	32551	0.06	161.28	50711.61
ALT 4	90	-	NA	0	80	•	0.4	268	201	black	25	45472	839572	14.64	12252	37820	0.06	192.96	57724.53
ALT 5	90	-	NA	0	75	•	0.3	313	505	blue	25	53107	1003426	14.88	13674	44170	0.06	225.36	66781.63
ALT 6	90	-	NA	0	75	•	0.6	179	512	bronze	25	30371	573844	12.70	11566	25260	0.06	128.88	41938.11
ALT 7	90	-	NA	0	75	•	0.6	179	914	silver	25	30371	573844	12.70	11566	25260	0.06	128.88	41938.11
ALT 8	90	-	NA	0	75	•	0.5	224	507	orange	25	39945	718107	14.46	10766	32551	0.06	161.28	50711.61

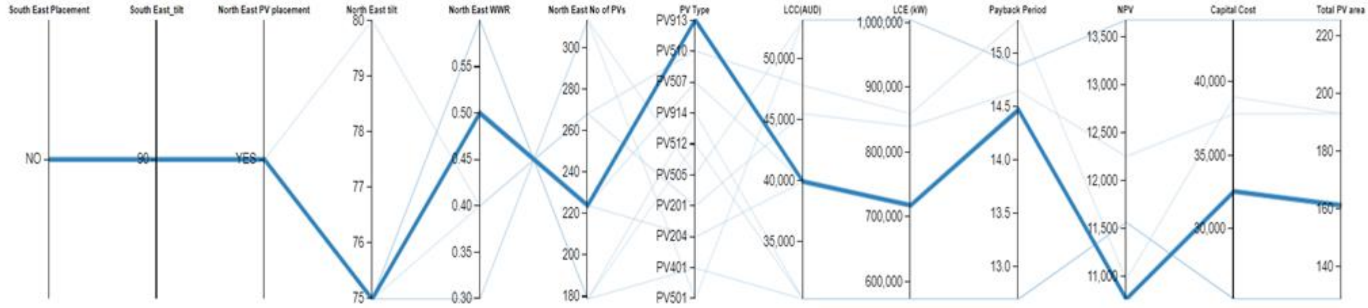

Figure 2. Optimal alternative design solutions

The analysis further reveals that the achieved Net Present Value (NPV) across the results is positive, signifying the feasibility of a cost-benefit advantage over the lifecycle of the BIPV design scenarios. This observation implies that the optimization process has yielded BIPV designs capable of offering positive economic returns. To visually encapsulate the values attributed to optimal design variables within the array of alternative designs identified through the framework, Figure 2 is presented as an illustrative representation. This depiction aids in comprehending the distribution and relationships of the design variables among the optimal design solutions. In essence, the collective findings emphasize the robustness of the framework and its ability to consistently generate BIPV designs that avoid southeast-facing modules, favor a tilt angle of 75 degrees, demonstrate diverse payback periods, and exhibit positive NPV values. These results underscore the economic viability and potential benefits of BIPV design scenarios, paving the way for sustainable and economically prudent building solutions. The study can expand to consider additional factors like, thermal effects,daylighting and carbon emissions. Further investigations should address conflicts between technical, aesthetic, and social design needs in real-world design and optimization scenarios.

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