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THE OPTIMIZATION OF BUILDING INTEGRATED PHOTOVOLTAIC (BIPV) ROOF IN RESIDENTIAL BUILDINGS IN YOGYAKARTA

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ABSTRACT

Solar panel technology is expected to mitigate the impact of global warming with the use of Building Integrated Photovoltaic (BIPV) that incorporates solar panels into buildings. However, the application of BIPV still has limitations in architectural design, especially for housing in Yogyakarta. This study uses a quantitative approach with a design-based simulation method through exploration of the best roof shape for BIPV type-72 houses in Yogyakarta. This study aims to identify the most optimal roof shape of type-72 houses in utilizing solar energy potential through the application of the BIPV system in residential areas in Yogyakarta. Through a quantitative design-based simulation approach, 72 combinations of roof models integrated with variations in orientation, plot shape, and floor plan shape are analyzed to measure the estimated annual energy production per installed PV area (kWh/m²/year). On average, the gable roof shape has the highest value in the application of BIPV on the roof for each orientation scenario, plot shape and floor plan shape. While the most optimal design per scenario is a sloping roof shape facing north, a 10m x 12m plot shape, and a single building mass floor plan with a garden in the middle. The optimal condition is obtained by combining all scenarios which gives 10.4% better performance compared to the average of all simulation results.

KEYWORDS: building-integrated photovoltaic, house design, roof, simulation, solar analysis

Teknologi solar panel diharapkan dapat memitigasi adanya dampak dari pemanasan global dengan penggunaan Building Integrated Photovoltaic (BIPV) yang menggabungkan solar panel kedalam bangunan. Namun penerapan BIPV masih memiliki keterbatasan dalam rancangan arsitektural khususnya pada perumahan di Yogyakarta. Penelitian ini menggunakan pendekatan kuantitatif dengan metode simulasi berbasis desain melalui eksplorasi bentuk atap terbaik untuk BIPV rumah tipe 72 di Yogyakarta. Penelitian ini bertujuan untuk mengidentifikasi bentuk atap rumah tipe 72 paling optimal dalam pemanfaatan potensi energi surya melalui penerapan sistem BIPV pada kawasan perumahan di Yogyakarta. Melalui pendekatan simulasi kuantitatif berbasis desain, 72 kombinasi model atap yang diintegrasikan dengan variasi orientasi, bentuk kavling, dan bentuk denah dianalisis untuk mengukur estimasi produksi energi tahunan per luas terpasang PV (kWh/m²/tahun). Secara rata-rata bentuk atap pelana memiliki nilai tertinggi dalam pengaplikasian BIPV pada atap untuk setiap skenario orentasi, bentuk kavling dan bentuk denah. Sedangkan untuk rancangan paling optimal per skenario adalah bentuk atap miring yang menghadap utara, bentuk kavling 10m x 12m, dan bentuk denah satu masa bangunan dengan taman ditengahnya. Kondisi optimal didapatkan dari penggabungan semua skenario yang memberikan performa 10.4% lebih baik dibandingkan dengan rata-rata keseluruhan hasil simulasi.

KATA KUNCI: *building-integrated photovoltaic, desain rumah, atap, simulasi, analisis matahari*

INTRODUCTION

Climate change, driven by rising greenhouse gas emissions, necessitates the adoption of clean, renewable energy solutions. Solar panels (photovoltaic, or PV, systems) harness solar energy to generate electricity without burning fossil fuels, making them one of the key solutions for mitigating global climate change (Zhang et al., 2025). The integration of solar energy systems into urban environments offers considerable potential to reduce reliance on fossil fuels, mitigate greenhouse gas emissions, and enhance energy self-sufficiency. (Liu et al, 2023) PV systems convert solar radiation into electricity through the photovoltaic effect in silicon cells or other semiconductor materials (Kazem et al., 2023). As a result, no emissions are produced during energy generation, making it a clean energy source. In terms of implementation, solar panels can be installed in most locations worldwide as long as sufficient sunlight is available, and they are applicable across various building scales, from small residential houses to large high-rise buildings.

However, solar panels are still not widely adopted, primarily due to aesthetic considerations, which are often perceived as lacking flexibility (Basher et al., 2023; Celadyn & Filipek, 2020). The limited variety of solar panels available on the market is often considered insufficient in addressing architectural design needs. Architects require PV systems to offer versatility in terms of color, transparency, size, and reflectivity (Haghighi et al., 2021). Therefore, further exploration is needed to enhance the aesthetic value of PV systems to support their broader application.

Building-Integrated Photovoltaics (BIPV) refers to the physical integration of photovoltaic components (typically solar panel modules) into the building structure. From an architectural perspective, this integration also encompasses aesthetic values (Marchwiński, 2023). Building-Integrated Photovoltaic (BIPV) systems have been proven to be among the most effective solutions for reducing thermal and cooling energy consumption while simultaneously generating renewable energy (Rababah et al., 2021). The application of BIPV is considered a crucial step in incorporating PV systems into buildings. Therefore, it is important to identify and elaborate on design criteria for BIPV implementation to determine the key factors to be considered during the design process. This development is accompanied by growing interest in emerging sustainable energy technologies and increasing aesthetic possibilities offered by BIPV systems (Maghrabie et al., 2021).

Based on research by Haryadi et al. (2021), Indonesia has experienced a significant increase in market demand for rooftop solar power systems (PLTS) in residential buildings, with growth of up to 700% between 2018 and 2020. This surge has been influenced by several key factors, including easier access to solar PV systems, increasing public awareness of pollution reduction, shifts in lifestyle trends toward clean energy, and changing public perceptions of renewable energy. Research has shown that the integration of green technologies in residential developments is well accepted by consumers (Thadani & Go, 2021).] [At the community level, awareness regarding the development and adoption of renewable energy has also been established (Mutaqi et al., 2023). Furthermore, research by Putri et al. (2024) indicates that larger residential buildings, particularly those classified as type 60 and above, are more economically feasible for rooftop PV installation than smaller houses (types 21–54). In the context of housing typology classification in Indonesia, type 72 houses are categorized as the upper limit of simple housing with a single floor, according to regulations issued by the Ministry of Public Works and Housing (PUPR, 2011). Therefore, type 72 houses can be considered as having optimal potential for the economic and functional implementation of rooftop PV systems.

Yogyakarta, as ones of the major cities in Indonesia, remains a primary destination for urbanization, as noted by Mubarrak et al. (2025). This condition has led to a continuous increase in the number of households, which in turn has contributed to the rising demand for residential housing (Ayuningtyas & Astuti, 2018). BIPV can be effectively implemented in high-density urban environments. It is an important factor in enabling tropical buildings to achieve green building standards, including ultra-low-energy buildings, net-zero-energy buildings, and positive-energy buildings (Chen et al., 2022). Along with the growing need for housing, roof forms in Yogyakarta have become increasingly diverse, reflecting the influence of local culture, functional requirements, and adaptation to a humid tropical climate. Traditional roof forms such as *limasan* and joglo roofs are still commonly found in houses that adopt Javanese architectural values, The use of modern materials, such as solar panels, does not diminish the traditional significance of roof architecture as long as the original roof form remains unchanged (Wibowo, 2021). while gable and hip roofs are widely used in modern housing due to their construction efficiency and effective rainwater drainage performance.

Previous studies have demonstrated that roof form has a significant impact on sustainable building design (Miao et al., 2022). Therefore, further research focusing on residential roof typologies commonly found in Yogyakarta is necessary.

METHODS

This study adopts a quantitative, design-based simulation approach. The initial stage involved conducting a comprehensive literature review and field observations to identify the defining characteristics of the type 72/120 housing prototype, in accordance with the regulatory framework established by the Indonesian Ministry of Public Works and Housing (Permen PUPR). In addition, an inventory of roof forms commonly employed in residential areas of Yogyakarta was compiled. Several representative housing design examples were sourced from widely used online platforms, such as (rumah123.com, reijogja.or.id, and brighton.com) to supplement the data collection process. Although the Joglo roof form is rarely associated with type 72 housing, it was incorporated into the study due to its prevalence in vernacular and traditional residential architecture in Yogyakarta, as evidenced by both field observations and scholarly references. Figure 1. illustrates the overall research workflow, beginning with the literature review and field observations, followed by the identification of housing prototype characteristics and roof form typologies, and culminating in the integration of these findings into the design-based simulation model. This structured workflow ensures methodological rigor and provides a clear framework for analyzing housing prototypes within the local architectural context.

Based on the findings from the literature review, a floor plan for a type 72/120 house was developed as the base building model for simulation. This model was subsequently transformed into a three-dimensional simulation design, enabling the application of various roof-form variations identified during the observation stage.

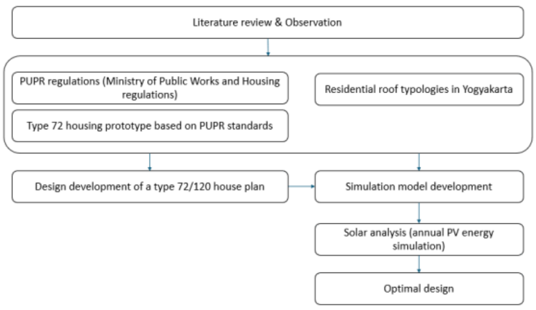

Figure 1. Research flow diagram
(Source: Author's Document, 2025)

In the next phase, each roof variation was analyzed using solar simulation (Solar Energy – Annual PV) to measure the annual solar energy potential. The simulation was conducted using geographic coordinates at latitude -7.763947486877 and longitude 110.37196350097. The results were then compared to evaluate the energy performance of each roof configuration. Ultimately, the study identifies the most optimal roof design in terms of solar energy potential for type 72 residential buildings in the Yogyakarta region.

Previous research by Roosandriantini et al. (2019) classified roof forms in Javanese architecture, while Hamka and Winarni (2023) mapped vernacular roof typologies across Java, identifying forms such as joglo, *limasan*, and kampung. Additionally, Kapita and Mahabella (2020) identified roof types in the Kauman settlement in Malang, including gable, mono-pitch (sloped), and hip roofs. Based on these studies, field observations were conducted to identify roof typologies commonly found in Yogyakarta. The results indicate eight predominant roof forms, as illustrated in Figure 2, including joglo, kampung, *limasan*, gable, mono-pitch, hip, and hybrid combinations such as gable–*limasan*.

In developing the type 72 house floor plan, several design parameters were considered: a land area of 120 m², a minimum frontage width of 6 meters, a setback distance of 3 meters from the road, and a minimum carport length of 4 meters. Three plot configurations were examined: 6 m × 20 m, 8 m × 15 m, and 10 m × 12 m. These configurations were further developed into nine floor plan variations, incorporating three design approaches: a single building mass, a single mass with an internal courtyard, and a two-mass configuration. Figure 3 presents the resulting floor plan designs.

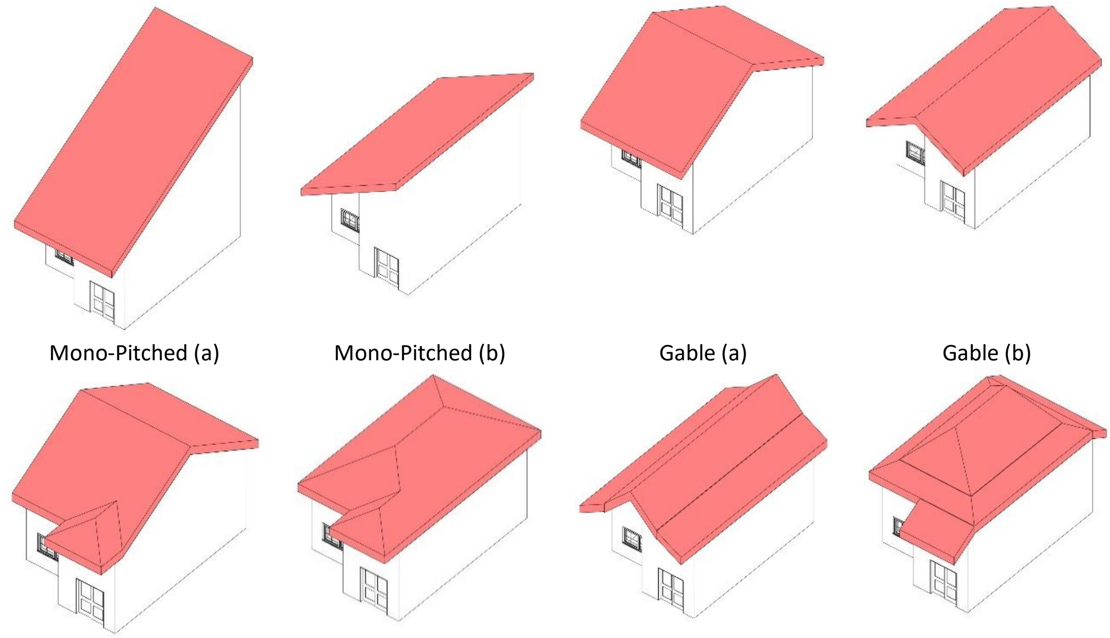

Figure 2. Roof typologies in Yogyakarta
(Source: Author's Document, 2025)

Figure 3. Spatial configuration designs
(Source: Author's Document, 2025)

Table 1. Design variables for variation scenarios

Grid Form	Room Config.	Orient.	Roof Form
(A) 6 x 20 m^2	(1) Single-mass building	(1) North	(1) *Limasan*
(B) 8 x 15 m^2	(2) Single-mass building with a void (courtyard)	(2) East	(2) *Gable* (a)
(C) 10 x 12 m^2	(3) Two-mass building config.	(3) South (4) West	(3) *Gable*(b) (4) *Mono-pitched* (a) (5) *Mono-pitched* (b) (6) Joglo (7) *Kampung* (8) Hybrid

Each floor plan was then combined with different roof variations, resulting in a total of 72 distinct roof models. Table 1 describes the variables used in generating the roof variations and the coding system applied to the simulation models.

The simulation models were arranged as row houses, with the tested unit positioned in the middle of the row, reflecting the common condition in residential developments. Table 2 presents the combinations of the Variables used in this study, organized into a coding system for the simulation models. Figure 4 illustrates an example simulation model labeled C136.

Table 2. Table of simulation model codes

Model Code								
A111	A211	A311	B111	B211	B311	C111	C211	C311
A112	A212	A312	B112	B212	B312	C112	C212	C312
A113	A213	A313	B113	B213	B313	C113	C213	C313
A114	A214	A314	B114	B214	B314	C114	C214	C314
A115	A215	A315	B115	B215	B315	C115	C215	C315
A116	A216	A316	B116	B216	B316	C116	C216	C316
A117	A217	A317	B117	B217	B317	C117	C217	C317
A118	A218	A318	B118	B218	B318	C118	C218	C318
A121	A221	A321	B121	B221	B321	C121	C221	C321
A122	A222	A322	B122	B222	B322	C122	C222	C322
A123	A223	A323	B123	B223	B323	C123	C223	C323
A124	A224	A324	B124	B224	B324	C124	C224	C324
A125	A225	A325	B125	B225	B325	C125	C225	C325
A126	A226	A326	B126	B226	B326	C126	C226	C326
A127	A227	A327	B127	B227	B327	C127	C227	C327
A128	A228	A328	B128	B228	B328	C128	C228	C328
A131	A231	A331	B131	B231	B331	C131	C231	C331
A132	A232	A332	B132	B232	B332	C132	C232	C332
A133	A233	A333	B133	B233	B333	C133	C233	C333
A134	A234	A334	B134	B234	B334	C134	C234	C334
A135	A235	A335	B135	B235	B335	C135	C235	C335
A136	A236	A336	B136	B236	B336	C136	C236	C336
A137	A237	A337	B137	B237	B337	C137	C237	C337
A138	A238	A338	B138	B238	B338	C138	C238	C338
A141	A241	A341	B141	B241	B341	C141	C241	C341
A142	A242	A342	B142	B242	B342	C142	C242	C342
A143	A243	A343	B143	B243	B343	C143	C243	C343
A144	A244	A344	B144	B244	B344	C144	C244	C344

A145	A245	A345	B145	B245	B345	C145	C245	C345
A146	A246	A346	B146	B246	B346	C146	C246	C346
A147	A247	A347	B147	B247	B347	C147	C247	C347
A148	A248	A348	B148	B248	B348	C148	C248	C348

All roof models were simulated using Autodesk Revit with the Solar Analysis plugin for Solar Energy production by Annual PV. Figure 5 shows the screenshot of simulation results of B123 facing orientations. Note that in this paper, the simulations were conducted under four possible building orientations from facing north, east, south, and west.

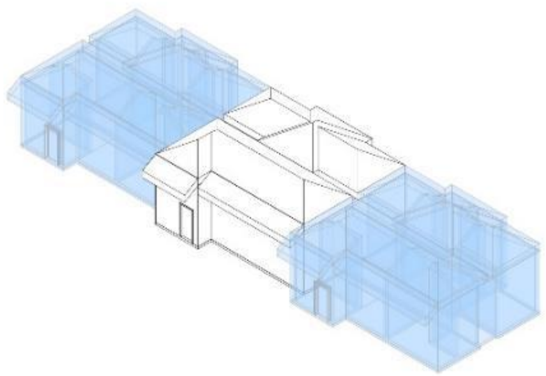

Figure 4. Simulation model C136
(Source: Author's Document, 2025)

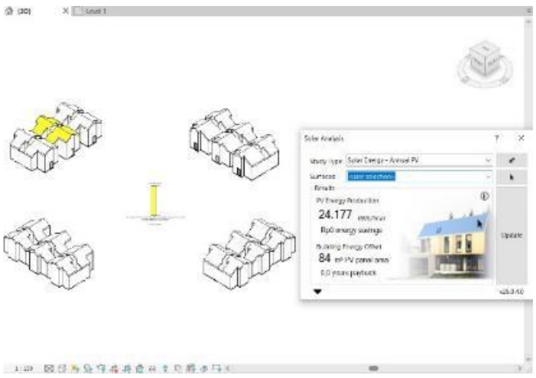

Figure 5. Solar energy simulation of Annual PV energy production for east west orientation.
(Source: Author's Document, 2025)

RESULTS AND DISCUSSION

The simulation results provide estimates of total annual energy generation and the installed PV surface area. The installed surface area then normalized the annual energy output to obtain the annual energy yield per square meter (kWh/m²/year), as presented in Table 3. Model A1 is a single-mass building configuration on a 6 m × 20 m plot. Model B1 is a single-mass building configuration on an 8 m × 15 m plot, while C1 is a single-mass building configuration on a 10 m × 12 m plot. Model A2 is a single-mass building configuration with an internal courtyard on a 6 m × 20 m plot, B2 is a single-mass building configuration with an internal courtyard on an 8 m × 15 m plot, and C2 is a single-mass building configuration with an internal courtyard on a 10 m × 12 m plot. Furthermore, Model A3 is a two-mass building configuration on a 6 m × 20 m plot, B3 is a two-mass building configuration on an 8 m × 15 m plot, and C3 is a two-mass building configuration on a 10 m × 12 m plot.

Table 3. Simulation results of roof forms (kWh/m²/year)

		A 1		
	North	**East**	**South**	**West**
Limasan	289.12	289.96	289.11	289.97
Gable (a)	289.42	294.14	289.40	294.14
Gable (b)	286.46	286.05	286.46	286.05
Mono-pitched (a)	310.04	296.45	271.39	294.40
Mono-pitched (b)	241.69	249.89	240.79	270.50
Joglo	261.48	264.14	261.39	264.14
Kampung	262.87	262.55	262.87	262.55
Hybrid	292.94	289.69	285.63	289.31
		B1		
	North	**East**	**South**	**West**
Limasan	290.17	292.50	290.16	292.50
Gable (a)	291.11	295.90	291.09	295.91
Gable (b)	287.87	287.76	287.87	287.76
Mono-pitched (a)	309.98	296.44	271.36	294.37
Mono-pitched (b)	244.33	251.85	243.28	273.35
Joglo	273.60	277.14	273.59	277.14
Kampung	265.11	264.23	265.11	264.24
Hybrid	294.34	290.38	283.50	289.81
		C1		
	North	**East**	**South**	**West**
Limasan	290.62	293.78	290.60	293.78
Gable (a)	291.07	295.84	291.05	295.85
Gable (b)	288.69	288.08	288.68	288.08
Mono-pitched (a)	309.86	296.29	271.23	294.24
Mono-pitched (b)	247.68	253.90	246.50	277.38
Joglo	278.54	283.15	278.53	283.17
Kampung	276.31	284.04	276.65	284.07
Hybrid	297.27	291.50	282.13	290.71
		A2		
	North	**East**	**South**	**West**
Limasan	285.21	282.28	289.97	288.14
Gable (a)	289.69	294.24	294.14	294.22
Gable (b)	286.67	286.98	286.05	285.40

	North	East	South	West
Mono-pitched (a)	309.30	295.74	294.40	293.70
Mono-pitched (b)	244.41	251.05	270.50	272.66
Joglo	263.51	265.35	264.14	268.21
Kampung	263.58	268.23	262.55	268.08
Hybrid	289.56	289.84	289.31	288.67
		B2		
	North	**East**	**South**	**West**
Limasan	289.60	291.97	289.62	291.96
Gable (a)	289.95	295.37	291.28	295.45
Gable (b)	287.68	288.02	287.73	286.70
Mono-pitched (a)	310.20	296.61	271.54	294.53
Mono-pitched (b)	248.65	253.93	246.49	276.94
Joglo	260.87	265.46	261.89	268.69
Kampung	260.59	262.82	260.64	263.39
Hybrid	289.95	294.98	290.76	295.04
		C2		
	North	**East**	**South**	**West**
Limasan	288.92	291.01	287.43	290.73
Gable (a)	290.88	296.35	292.32	296.44
Gable (b)	289.23	288.02	289.17	289.17
Mono-pitched (a)	310.41	296.83	271.72	285.58
Mono-pitched (b)	248.79	254.48	247.18	278.10
Joglo	260.00	263.82	260.21	270.82
Kampung	258.75	267.86	258.63	274.59
Hybrid	293.93	295.87	288.37	295.58
		A3		
	North	**East**	**South**	**West**
Limasan	289.25	291.14	288.81	291.19
Gable (a)	290.76	293.37	289.50	293.30
Gable (b)	288.92	289.45	289.05	287.03
Mono-pitched (a)	299.89	277.99	267.00	276.36
Mono-pitched (b)	243.82	250.53	242.55	271.89
Joglo	271.11	274.55	271.08	274.55
Kampung	272.55	277.86	272.59	277.85
Hybrid	289.25	292.15	288.78	292.12
		B3		
	North	**East**	**South**	**West**
Limasan	289.55	288.50	284.84	289.04
Gable (a)	287.35	290.48	287.98	290.54
Gable (b)	286.48	286.84	286.55	285.61
Mono-pitched (a)	286.26	263.75	258.07	262.33
Mono-pitched (b)	248.93	252.52	248.35	277.34
Joglo	271.59	274.27	269.19	275.25
Kampung	268.52	274.38	266.18	276.09
Hybrid	289.59	285.69	284.49	285.66
		C3		
	North	**East**	**South**	**West**
Limasan	292.19	292.57	287.90	292.36
Gable (a)	287.79	290.07	286.88	290.06
Gable (b)	287.21	287.21	287.10	286.95
Mono-pitched (a)	282.87	262.38	255.70	261.01
Mono-pitched (b)	246.20	251.84	243.70	274.38
Joglo	279.68	281.66	276.42	281.49
Kampung	273.72	277.23	270.15	277.05
Hybrid	288.78	287.89	283.58	287.61

Based on the simulation results, it was found that, on average, houses with gable roofs oriented front-to-back exhibit the highest performance across all plot configurations and spatial arrangements, with a value of 292.04 kWh/m²/year. This performance is influenced by the relatively stable solar exposure received by this roof form throughout the year, as well as minimal shading from adjacent buildings. In contrast, mono-pitch roofs extending along the left–right axis demonstrate the lowest average performance, at 255.18 kWh/m²/year, primarily due to shading effects caused by the height of neighboring buildings, which obstruct portions of the PV-installed roof surface.

Hybrided roof types (*limasan*–gable) and *limasan* roofs also show relatively high potential, with values of 289.85 kWh/m²/year and 289.90 kWh/m²/year, respectively. This is attributed to their multi-directional roof orientations, which allow for more consistent solar exposure under varying conditions. On the other hand, gable roofs oriented left–right and mono-pitch roofs oriented front–back demonstrate more limited performance. These roof types achieve high values only under specific conditions. For example, a mono-pitch roof facing front–back performs optimally when oriented northward, reaching 303.20 kWh/m²/year, but decreases significantly when oriented southward, to 270.27 kWh/m²/year. This variation is due to the higher annual solar exposure received by north-facing orientations, while south-facing orientations receive comparatively less. As a result, the overall average performance of this roof type remains moderate, at 286.11 kWh/m²/year. Similarly, gable roofs oriented left–right produce relatively stable results across scenarios but remain within a moderate range, with an average of 287.47 kWh/m²/year.

Joglo and kampung roof models are generally less recommended due to their lower average performance, at 270.82 kWh/m²/year and 269.01 kWh/m²/year, respectively. Although these roof types often have larger surface areas, their complex geometries and varying roof inclinations result in suboptimal solar exposure angles, thereby reducing their overall PV efficiency.

When analyzing each scenario individually rather than relying solely on average values, several additional considerations emerge based on orientation, plot configuration, and spatial layout. As illustrated in Figure 6, north-facing orientation yields the highest energy performance, with a rating of 310.41 kWh/m²/year. This is because Yogyakarta is located South of the equator, resulting in greater annual solar exposure on north-facing surfaces. Conversely, south-facing orientation produces the lowest value, at 292.32 kWh/m²/year. East- and west-facing orientations show relatively similar performance, at 296.83 kWh/m²/year and 296.44 kWh/m²/year, respectively. Therefore, residential developments implementing rooftop BIPV systems should prioritize north-facing building orientations whenever possible.

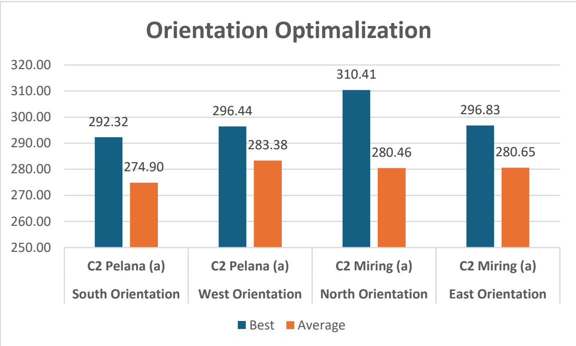

Figure 6. Orientation optimization diagram
(Source: Author's Document, 2025)

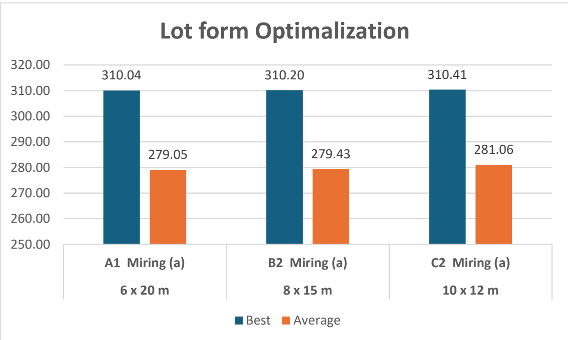

Figure 7. Lot Form optimization diagram
(Source: Author's Document, 2025)

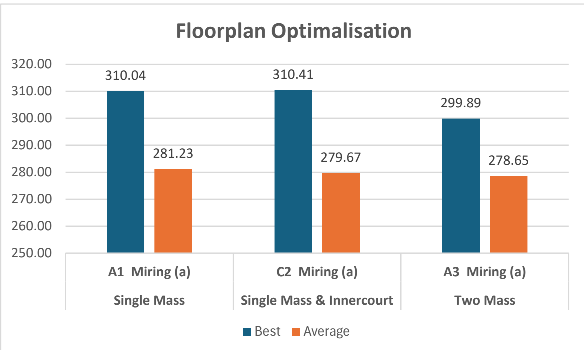

Figure 8. Floorplan optimization diagram
(Source: Author's Document, 2025)

In terms of plot configuration (Figure 7), no significant differences were observed among the three plot types. Although the 10 m × 12 m plot yields the highest value (310.41 kWh/m²/year), the differences compared to the 6 m × 20 m (310.04 kWh/m²/year) and 8 m × 15 m (310.20 kWh/m²/year) plots are negligible. Thus, no specific recommendation is required regarding plot shape in BIPV-oriented housing design.

Regarding spatial configuration (Figure 8), single-mass layouts and single-mass layouts with an internal courtyard demonstrate similarly high performance, at 310.04 kWh/m²/year and 310.41 kWh/m²/year, respectively. In contrast, two-mass configurations yield the lowest performance, at 299.89 kWh/m²/year. This is due to shading effects, where one building mass obstructs solar exposure to the PV-installed roof surfaces of the other mass. Therefore, it is recommended to prioritize single-mass configurations, with or without an internal courtyard, while avoiding two-mass layouts.

Based on the combined optimization of orientation, plot configuration, and spatial layout, the optimal scenario is identified as a mono-pitch roof oriented front-to-back, facing north, on a 10 m × 12 m plot, with a single-mass layout incorporating a central courtyard (as illustrated in Figure 9). Accordingly, designers focusing on rooftop BIPV implementation for type 72 housing in Yogyakarta are encouraged to consider this configuration as a design reference.

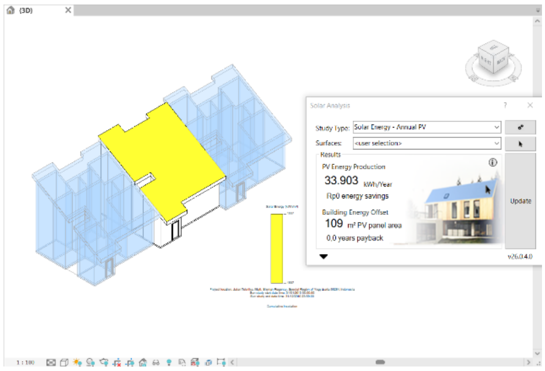

Figure 9. Optimal design model
(Source: Author's Document, 2025)

CONCLUSION

This study aims to identify the most optimal roof form for type 72 residential buildings in maximizing solar energy potential through the implementation of BIPV systems in housing developments across Central Java and Yogyakarta. Using a quantitative design-based simulation approach, 72 roof model combinations which were integrated with variations in building orientation, plot configuration, and spatial layout, were analyzed to evaluate annual energy production per installed PV area (kWh/m²/year).

The simulation results indicate that gable roofs oriented along the front–back axis achieve the highest average energy performance, with a value of 292.04

kWh/m²/year. In contrast, mono-pitched roofs extending along the left–right axis yield the lowest average performance at 255.18 kWh/m²/year, primarily due to shading effects from adjacent buildings. *Limasan* and Hybrided gable–*limasan* roof forms demonstrate relatively high and consistent performance, as their multi-directional geometry allows for more uniform solar exposure.

In terms of building orientation, north-facing configurations produce the highest energy output at 310.41 kWh/m²/year, approximately 10.4% above the overall simulation average. This is attributed to the geographic position of Central Java and Yogyakarta, which lie south of the equator, where north-facing surfaces receive greater annual solar exposure. Conversely, south-facing orientations result in the lowest performance (292.32 kWh/m²/year). Regarding plot configuration, no significant differences were observed among the three typologies (6 × 20 m, 8 × 15 m, and 10 × 12 m). Meanwhile, the spatial layout analysis indicates that single-mass configurations, both with and without a central courtyard, demonstrate superior performance compared to two-mass configurations, whose efficiency is diminished by shading interactions between adjacent building masses.

Based on the optimal combination of variables, the best-performing scenario consists of a mono-pitched roof oriented front–back, facing north, located on a 10 m × 12 m plot, and utilizing a single-mass layout with a central courtyard. Therefore, for the application of BIPV systems in type 72 housing in Yogyakarta, designers are recommended to prioritize north-facing orientations, avoid multi-mass layouts, and select roof forms with consistent inclinations and minimal shading potential from surrounding structures.

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