Indian Journal of Engineering & Materials Sciences
Vol. 33, April 2026, pp. 243-251
DOI: 10.56042/ijems.v33i02.29179

Optimization of rooftop PV layouts in Baghdad using 3D shading and PVsyst with energy-density approach

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Received: 26 February 2026; accepted: 18 March 2026

This study has addressed a common rooftop PV challenge in Baghdad, where roof space has been limited and has usually included obstacles such as rooftop rooms, parapet walls, water tanks, and service structures. These objects have created near-shading that has reduced annual energy yield and has even changed how PV design options have ranked against each other. Because of this, comparing alternatives using annual energy only has been misleading, as a design may have appeared better simply because it has installed more capacity and occupied more roof area. To address this issue, several rooftop PV variants have been evaluated using an integrated workflow that has linked detailed 3D roof-and-obstacle modeling with PV performance simulation. A near-shading scene has been built in 3D and imported into PVsyst, so the annual results have included shading impacts together with practical loss terms such as soiling, system unavailability, and aging. The tested variants have represented common rooftop strategies, including fixed shading-aware layouts, seasonal adjustment, and tracking. The results have shown that the highest-energy option has not always been the most feasible choice. The maximum annual production, 272,308 kWh/yr, has been achieved by the tracking configuration (Variant 4: HJT_680_L_Tracking), while the highest performance ratio, 85.22%, has been achieved by the seasonal-adjustment configuration (Variant 3: HJT_680_L_Seasonal). Considering practicality and economics, the fixed shading-aware design (Variant 5: HJT_680_P_Shading) has been recommended as a balanced rooftop solution, producing 181,510 kWh/yr with LCOE = 0.0245 USD/kWh and a payback period of 2.8 years.

Keywords: HJT modules, Payback period, PVsyst, Shading analysis, SketchUp

1 Introduction

Rooftop photovoltaic (PV) systems have become a commonly discussed option for producing clean electricity close to the point of use, reducing emissions, and supporting the transition to sustainable energy systems. Renewable-energy research has expanded globally, from health and economic links to broader development and political-economy considerations, as reported by Rizzi–Ang[1-5], and these developments have made PV a key option in modern energy planning, as discussed by Kazem6. This global momentum is especially important in countries where electricity supply is uncertain, because PV can be deployed more rapidly than many conventional projects and can be sized incrementally to meet demand.

Renewable energy, particularly solar energy, has gained increasing attention in Iraq because of the need to diversify the energy mix and reduce reliance on conventional generation. The role and future potential of renewables in Iraq have been discussed by Kazem[6], who has indicated that solar PV can support energy security and strengthen the national power sector. More recent work by Alomar[7] has further examined PV systems under different Iraqi climates and has confirmed the strong link between local climate, energy yield, and feasibility. Ahmed[8] has also investigated the relationship between irradiance and temperature in Iraq and its implications for sustainable development. At the same time, PV performance in Iraq cannot be evaluated from irradiation values alone. Lower cell and ambient temperatures have improved PV efficiency, and studies by Ebhota[9] and Al-Ghezi[10] have shown that the combined effects of orientation, irradiance, tilt, and operating temperature can become much more pronounced in hot regions such as Iraq. These effects become even more critical for urban rooftop systems, where heat, dust, and practical installation restrictions interact with each other.

A major practical constraint for rooftop PV systems is the limited roof area and the presence of rooftop obstructions such as rooftop rooms, parapet

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walls, tanks, and service equipment. These constraints create near-shading and mismatch losses that reduce annual energy yield and may change the ranking of design options. Therefore, annual energy should not be treated as the only competitive metric when one configuration appears better merely because it installs more capacity and occupies a larger roof footprint. In Baghdad, urban context strongly influences design choice, and simulation-based studies have investigated distributed PV plants and rooftop cases under local conditions, such as Shneishil[11], Mahmood[12]–Tariq[14], Kumar[15] and Islam[16], Hussain[17] and Tuama[18], as well as Kasim[19], Mahmood[12], Abed[13], and Hussein[20].

Elsewhere in the Middle East and in other climates with similar conditions, PVsyst applications have also supported confidence in PVsyst as a comparative simulation tool when it has been applied consistently, as shown by Alkahtani[21] and Moustafa[22]. In addition, Mishra[23] has emphasized its value in evaluation workflows for grid-connected PV systems supported by real-time or monitoring-based assessment methods. Collectively, these studies have shown that PVsyst is well suited for comparing variants when consistency of assumptions is essential, particularly when the goal is not only maximum theoretical energy yield but also practical viability.

Modern PV assessments have increasingly combined technical performance with economic indicators because any rooftop project must also remain feasible in practice. Feasibility studies such as Sami[24] have shown how cost of energy, investment level, and payback period can change the preferred option even when energy yield is high. More generally, design and optimization tools discussed by Kumar[25] and Horvat[26] have reinforced the need to evaluate performance and feasibility together. Accordingly, a comprehensive rooftop PV study for Baghdad should couple loss modeling, including shading- and temperature-related losses, with economic evaluation indicators such as payback period and LCOE so that the final recommendation can be realistically designed, built, operated, and maintained under local constraints..

Several simulation-based studies have assessed PV system performance in Baghdad using PVsyst as the main evaluation tool. Hussain[17] has addressed tilt-angle optimization for grid-connected PV systems in Baghdad and has shown how tilt selection can increase annual solar capture without changing the technology or system size. Tuama[18] has examined the effects of tilt angle, azimuth, and configuration on PV productivity in Baghdad and has provided useful guidance on the sensitivity of system output to design choices such as fixed, seasonal, and tracking configurations. Mahmood[12] has also investigated a 20 kW rooftop PV system installed at MTU University and has reported practical rooftop-scale performance indicators and losses under Baghdad conditions.

Similarly, Abed[13] has examined an on-grid mono-Si PV solar system in Baghdad and has provided a local reference for system operation under harsh climatic influences, including temperature effects, seasonal conditions, and loss factors that affect performance ratio and capacity factor. These studies have reinforced that idealized assumptions are not sufficient for Baghdad-based PV assessment, because actual PV performance can vary markedly between winter and summer under high-temperature conditions.

Hussein[20] has compared four on-grid PV technologies under Baghdad climatic conditions. Such comparisons are valuable because they directly test different PV technologies within the same climate context in terms of thermal sensitivity and relative performance. This evidence has further supported the view that, in hot climates, technology choice matters not only because of nominal efficiency, but also because of temperature coefficient and operational-loss behavior.

Lastly, Mahdi[27] has investigated the solar potential at Al-Khwarizmi College of Engineering, Baghdad, using both PVsyst and HelioScope. This study is especially relevant because it has demonstrated a multi-tool simulation approach, combining HelioScope for 3D visualization, layout understanding, and shading/orientation exploration with PVsyst for structured yield simulation. It therefore provides a useful example of integrating tools to improve design clarity and evaluation confidence for Baghdad sites.

Overall, these studies have provided a strong foundation through tilt optimization by Hussain[17], configuration and orientation analysis by Tuama[18], rooftop performance modeling by Mahmood[12], localized on-grid evaluation by Abed[13], technology comparison by Hussein[20], and multi-tool simulation by Mahdi[27]. However, simple comparison of annual energy or energy per roof area can still be misleading when roof space is limited and rooftop obstructions cause near-shading, especially when the compared configurations do not use roof area in a similar way. This gap has motivated the present work to adopt a structured, variant-based comparison under the same conditions while explicitly accounting for realistic rooftop limitations.

2 Materials and Methods

Recent advances in heterojunction (HJT) solar cell technology have combined crystalline silicon with ultra-thin amorphous silicon layers, as described by Machín[28]. This structure has reduced carrier recombination and has enabled higher open-circuit voltage and higher efficiency, as illustrated in Fig. 1. In a conventional HJT structure, an n-type silicon wafer has been sandwiched between amorphous silicon layers on both sides, and this configuration has provided strong electrical characteristics together with improved resilience under harsh conditions, according to Machín[28]. Reported HJT efficiencies have reached about 25% in laboratory demonstrations and around 22% in mass production, while the technology has also been associated with a low temperature coefficient (approximately −0.25%/°C), which is beneficial in hot climates where cell temperature rise reduces PV output, as noted by Machín[28] and Breyer[29]. Although HJT modules have involved higher manufacturing cost, ongoing industrial improvements have continued to enhance their viability as high-efficiency options for high-irradiance regions, as discussed by Breyer[29].

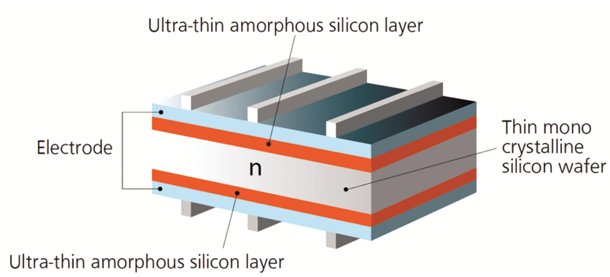


Fig. 1 — Structure of heterojunction (HJT) solar cell[30].

PVsyst is a popular tool for PV system modeling and yield assessment because it has enabled the design of grid-connected systems within an organized framework for evaluating annual energy yield together with the main loss components, as reported by Kasim[19], Hasan[31], and Kumar[15]. These loss components generally include temperature-dependent power loss, inverter conversion loss, mismatch loss, ohmic wiring loss, and shading loss, thereby allowing direct comparison of different PV designs using the same site and meteorological inputs. PVsyst has also generated standardized reports with monthly and annual summaries and has supported economic evaluation through indicators such as LCOE and payback period, as described by Kumar[15].

SketchUp is a practical 3D modeling platform for rooftop PV projects because it can represent roof geometry and rooftop obstacles and can support solar and shadow analysis across the day and seasons, as discussed by Kadeval[32] and Jaiswal[33]. This capability is essential in urban rooftops, where limited area and rooftop objects can create near-shading and mismatch effects that reduce annual yield, as explained by Kadeval[32]. A robust workflow has connected the 3D rooftop model in SketchUp to PVsyst near-shading

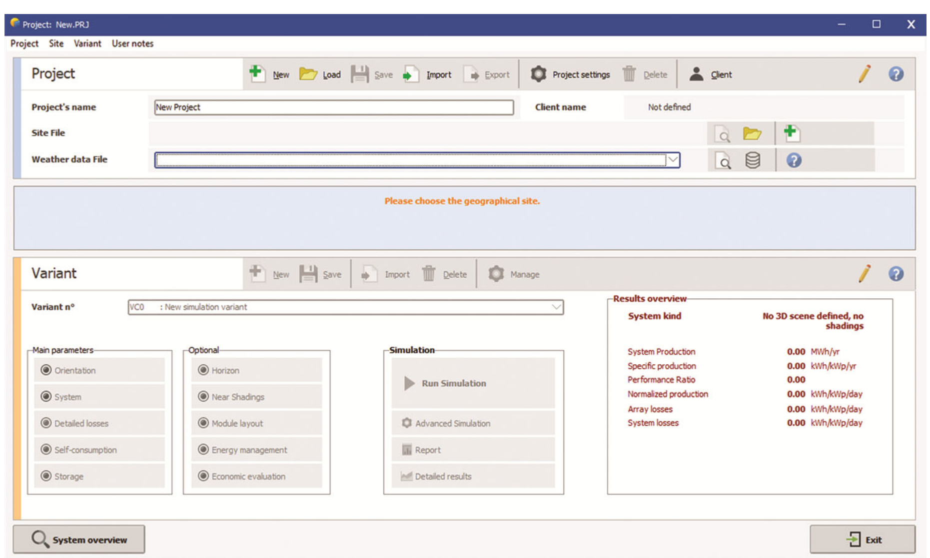


Fig. 2 — PVsyst starting interface.

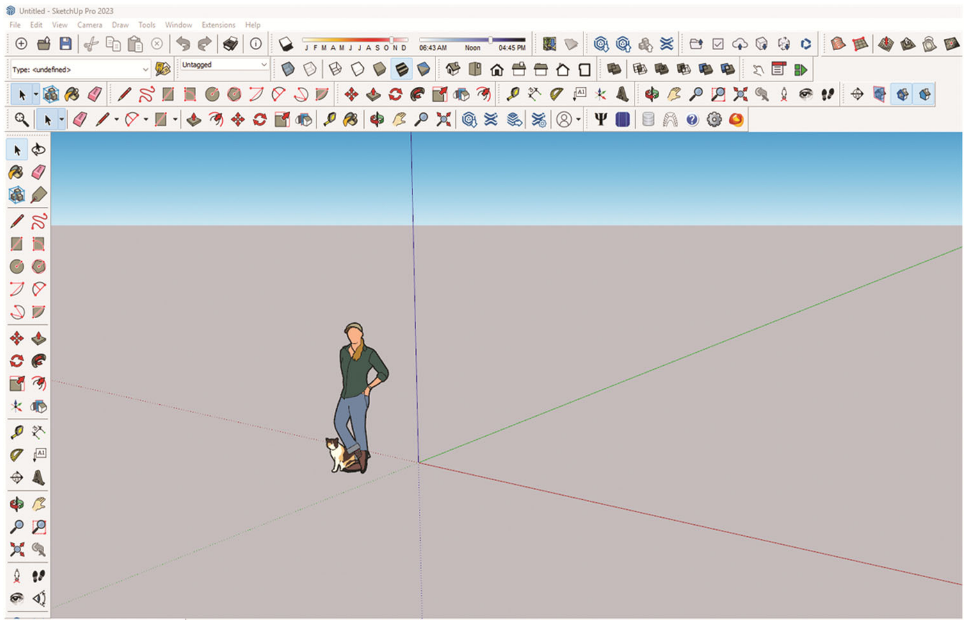


Fig. 3 — SketchUp interface.

calculations by exporting the complete 3D scene in a compatible format, such as .3ds, and then importing it into the PVsyst near-shading module. PVsyst has then computed annual shading losses and integrated them into the energy simulation, providing a realistic basis for comparing rooftop PV design alternatives under space and shading constraints, as reported by Kumar[15] and Kadeval[32].

A realistic 3D rooftop model (including all obstacles) is created in SketchUp, then the 3D shading scene is exported to PVsyst to run the same annual simulation for each design variant. Technical and economic outputs are then compared to identify the most suitable option. Detailed steps are summarized in the methodology flowchart (Fig. 4).

(i) Setting site and weather conditions: The Baghdad site is defined and all variants are simulated using one meteorological dataset (TMY/NSRDB) to ensure a fair comparison.

(ii) Define the design variants (scenarios): A set of variants (e.g., 17 cases) is prepared. Each variant changes only the intended design factors such as:

- Module technology (Mono vs. HJT)
- Module orientation (portrait vs. landscape) and spacing rules (row distance/clearance)

(iii) 3D rooftop modeling in SketchUp: The rooftop geometry and all obstacles (walls, tanks, rooftop rooms, service structures) are modeled. PV tables are then placed for each configuration while respecting rooftop constraints (clearances and access routes).

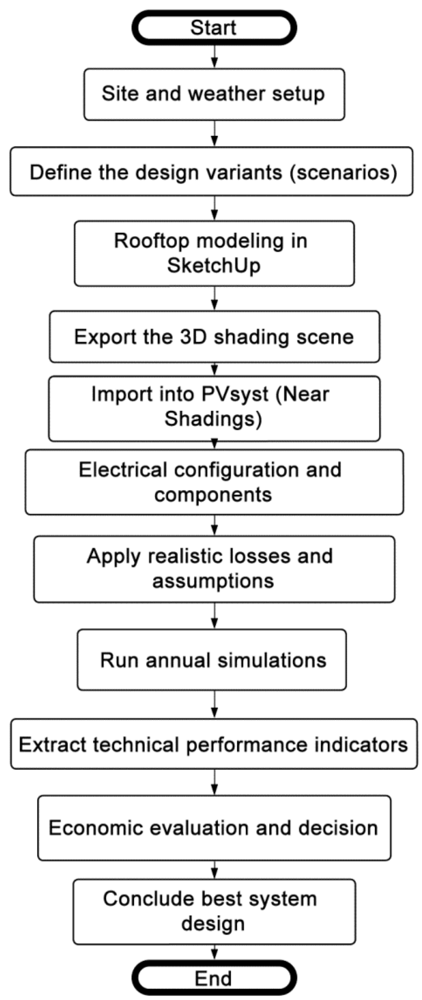


Fig. 4 — Proposal flow chart.

(iv) Export the 3D shading scene: The complete 3D scene (roof + obstacles + PV layout) is exported to a compatible format (commonly .3ds) for shading calculations in PVsyst.

(v) Import into PVsyst (Near Shadings): The 3D scene is imported into PVsyst Near Shadings, the scale/orientation is verified, and annual shading-loss calculation is enabled so rooftop obstructions are included in the annual results.

(vi) Electrical configuration and components: For each variant, PV modules and inverters are defined (from the PVsyst database or inserted specifications) and string/MPPT configuration is set using consistent rules across variants.

(vii) Apply realistic losses and assumptions: The same loss factors are applied across variants unless a loss factor is inherently variant-specific. Assumptions include soiling, thermal losses, mismatch, wiring, inverter losses, unavailability, and aging/degradation.

(viii) Annual simulation for all variants: PVsyst annual simulations are performed for each variant under the same site and weather conditions to produce standard PVsyst reports.

(ix) Extract technical performance indicators: The main comparison indicators are extracted, including annual energy (kWh/yr), specific production (kWh/kWp/yr), PR (%), and shading-loss share.

(x) Economic evaluation and decision: Cost assumptions are entered and indicators such as LCOE and payback period are extracted. The recommended design is the option that provides the best balance between realistic energy output, PR, and economic feasibility.

The following definitions and formulas can be used to evaluate the data analysis in terms of days, months, and years

(i) Energy Production (E, kWh/year)

Energy production is the quantity of electricity produced by the PV system during a specific period such as a day, month, or year. Although E is directly related to rooftop energy output, it should be interpreted carefully because larger installed capacity can increase E without necessarily indicating a more efficient design, as noted by Fezzani[34]. AC energy output over hours, days, and months can be calculated using the computation approach reported by Gulkowski[35] within the IEC-based performance assessment framework discussed by Haydaroğlu[36].

The amount of AC (alternating current) power produced by the system within a specific time period has represented the energy output, as described by Gulkowski[35].

$$E_{AC},M=\sum E_{AC},D \quad \dots (1)$$

where

E_{AC},H: Alternating current (AC) energy output per hour.
E_{AC},D: Alternating current (AC) energy output per day.
E_{AC},M: Alternating current (AC) energy output per month
N : Number of days in the month.

(ii) Reference Yield (Yr, kWh/kWp/year)

Reference yield has represented the effective full-sun hours received by the PV array. It has been calculated by dividing the total in-plane irradiation by the reference irradiance under STC (1 kW/m²), so it has primarily described the solar resource and geometric configuration rather than the internal system losses, as reported by Femin[37]. The definition of reference irradiance has followed the same standard framework discussed by Haydaroğlu[36].

$$Y_R= H_t(KWh/m^2)/ G(KW/m^2) \quad \dots (2)$$

where H_t is total solar radiation received by a specific platform with unit (KWh/m^2)(, G is reference radiation with unit (KW/m^2) Haydaroğlu[36].

(iii) Final Yield / Specific Production (Yf, kWh/kWp/year)

Final yield or specific production has represented the useful delivered AC energy per installed kWp. It has been defined as the quotient of the total AC energy delivered to the grid or load and the installed PV capacity, and it has therefore reflected actual operating performance after losses, as explained by Hazem[38]. Accordingly, Yf has served as an important criterion for evaluating practical system effectiveness, as noted by Elsaadawi[39], and it has remained consistent with the standard performance definitions reported by Haydaroğlu[36]. Final yield can be expressed as the amount of energy delivered in a given unit of time divided by the installed power.

$$Yf= E_{use,PV} / P_o \quad \dots(3)$$

where P_o is the installed power, $E_{use,PV}$ denotes the energy delivered to the system Haydaroğlu[36].

(iv) Performance Ratio (PR, %)

Performance ratio relates the final yield with the reference yield (a reference yield is a quality indicator). This shows the electricity generated that was converted from the available solar resource, after all losses and is a basis for fair comparison between systems and sites Haydaroğlu[36]. Researcher report PR so much as this comparison makes fair PR available for different solar plants with different sizes or location Haydaroğlu[36].

$$PR = Yf / Yr \quad \ldots (5)$$

(v) Energy-per-Area / Space Utilization (PE, kWh/m²/year)

A second measure for rooftop PV is PE, the area-specific annual yield of AC power generated (Energy/Area). PE (Performance Efficiency) reflects the efficiency of resource use within the installation area, an important indicator for roofs, given that they are nearly never one large unobstructed space, but are exposed to spacing limitations. In this study, PV area is the whole surface area of installed modules (total area of modules), so PE is energy produced per square meter of modules installed in an year Femin[37].The metric is calculated as PE = E_AC,year / A_PV (kWh/m²/year), where E_AC,year is the total energy generated (kWh/year) and A_PV is the area of all installed PV modules (m²).

(vi) Economic Indicators (LCOE and Payback)

Economic evaluation complements the technical assessment: LCOE (USD/kWh) represents the levelized cost of producing electricity over the system lifetime, while payback period (years) indicates how quickly the initial investment is recovered. These indicators allow comparing variants not only by energy performance but also by feasibility and financial attractiveness.

3 Results and Discussion

All variants were simulated in PVsyst, and the values in Table 1 were extracted directly from the PVsyst technical and economic reports (Fig. 5). In the configuration labels, "L" denotes a landscape module orientation, while "P" denotes a portrait module orientation.

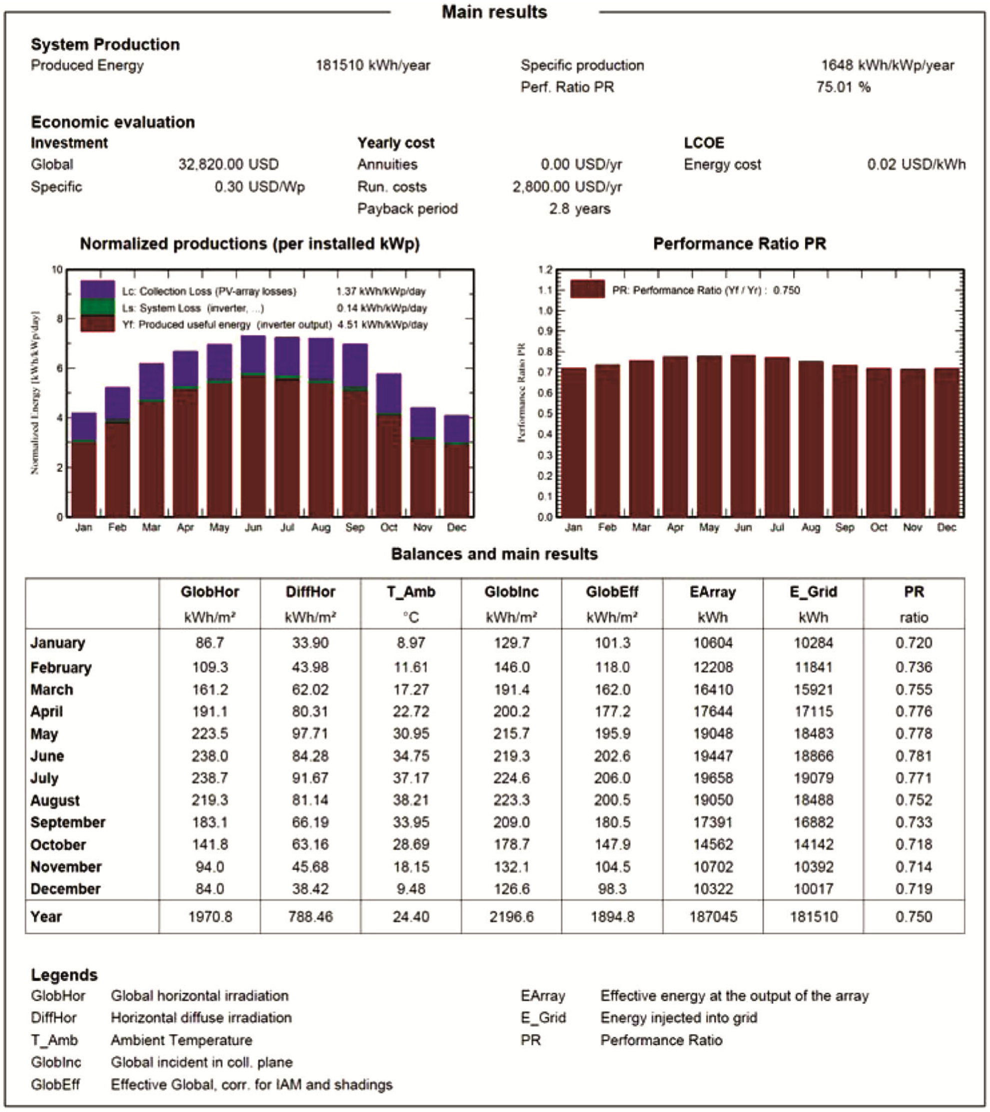
Table 1: Summary of the key performance and Economics parameters for variants 1–10 For the best case (non-shaded) scenario, the tracking configuration (Variant 4 (HJT_680_L_Tracking) yields the highest annual energy of 272,308 kWh/yr based on annual energy alone, in addition to leading in kWh/kWp/yr (specific production: 2086 kWh/kWp/yr), and land use (space utilization, PE = 456.6 kWh/m2/yr). Yet this technical advantage comes at a distinctly lower PR (73.63%) and much less favorable economics (LCOE = 0.0323 USD/kWh, payback = 4.7 years), showing that the increased complexity and cost outweigh the praticality benefits.

Specifically for the fixed/adjustable non-shaded scenarios, the strongest balanced technical performance reflected by the PR (85.22%) in the dataset is provided by Variant 3 (HJT_680_L_Seasonal) at 253,304 kWh/yr and at the same time achieves the highest specific production (1940 kWh/kWp/yr) and PE (424.7 kWh/m²/yr). In Variant 2, the fixed HJT baseline is also a top performer (244,305 kWh/yr, PR = 85.19%) and outperforms the mono fixed baseline (Variant 1) in energy, specific production and PR, confirming the benefit of HJT with the conditions analyzed.

In Baghdad, rooftops include obstacles that cause near-shading, so the shaded configurations (Variants 5–10) provide the closest reflection of realistic rooftop performance. Within this group, Variant 6

Table 1 — Main result for all variants.

Variant	Configuration	Produced Energy (kWh/yr)	Specific Production (kWh/kWp/yr)	PR (%)	PE (kWh/m2/yr)	LCOE (USD/kWh)	Payback (yrs)
1	Mono_680_L_Fixed	239314	1833	83.44	401.3	0.0296	3.2
2	HJT_680_L_Fixed	244305	1871	85.19	409.6	0.0291	3.1
3	HJT_680_L_Seasonal	253304	1940	85.22	424.7	0.028	3
4	HJT_680_L_Tracking	272308	2086	73.63	456.6	0.0323	4.7
5	HJT_680_P_Shading	181510	1648	75.01	360.8	0.0245	2.8
6	HJT_680_L_Shading	201576	1544	70.29	338	0.0352	4.1
7	HJT_680_L_shadding_Soiling	195810	1500	68.28	328.4	0.0363	4.2
8	HJT_680_L_Shading_Soiling_Aging	185522	1421	64.69	311.1	0.0383	4.6
9	HJT_680_L_Shading_Soiling_Aging_Unavailability	182410	1397	63.6	305.8	0.0389	4.7
10	HJT_680_L_Shading_Soiling_Aging_Unavailability_Auxiliaries	181982	1394	63.45	305.2	0.039	4.7



Main results

System Production
Produced Energy 181510 kWh/year
Specific production 1648 kWh/kWp/year
Perf. Ratio PR 75.01 %

Economic evaluation

Investment
Global 32,820.00 USD
Specific 0.30 USD/Wp

Yearly cost
Annuities 0.00 USD/yr
Run. costs 2,800.00 USD/yr
Payback period 2.8 years

LCOE
Energy cost 0.02 USD/kWh

Balances and main results

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	kWh	kWh	ratio
January	86.7	33.90	8.97	129.7	101.3	10604	10284	0.720
February	109.3	43.98	11.61	146.0	118.0	12208	11841	0.736
March	161.2	62.02	17.27	191.4	162.0	16410	15921	0.755
April	191.1	80.31	22.72	200.2	177.2	17644	17115	0.776
May	223.5	97.71	30.95	215.7	195.9	19048	18483	0.778
June	238.0	84.28	34.75	219.3	202.6	19447	18866	0.781
July	238.7	91.67	37.17	224.6	206.0	19658	19079	0.771
August	219.3	81.14	38.21	223.3	200.5	19050	18488	0.752
September	183.1	66.19	33.95	209.0	180.5	17391	16882	0.733
October	141.8	63.16	28.69	178.7	147.9	14562	14142	0.718
November	94.0	45.68	18.15	132.1	104.5	10702	10392	0.714
December	84.0	38.42	9.48	126.6	98.3	10322	10017	0.719
Year	1970.8	788.46	24.40	2196.6	1894.8	187045	181510	0.750

Legends
GlobHor Global horizontal irradiation
DiffHor Horizontal diffuse irradiation
T_Amb Ambient Temperature
GlobInc Global incident in coll. plane
GlobEff Effective Global, corr. for IAM and shadings
EArray Effective energy at the output of the array
E_Grid Energy injected into grid
PR Performance Ratio

Fig. 5 — Main results in the PVsyst report.

(HJT_680_L_Shading) is the best technical performer, with the highest produced energy (201,576 kWh/yr), the highest specific production (1544 kWh/kWp/yr), and the highest PE (338 kWh/m²/yr). At the same time, Table 1 shows that Variant 5 (HJT_680_P_Shading) delivers the best economic performance, achieving the lowest LCOE (0.0245 USD/kWh) and the shortest payback period (2.8 years), although its annual energy (181,510 kWh/yr) is lower than several other shaded variants. This supports a dual recommendation: Variant 6 is preferred when maximizing energy under shading is the priority, while Variant 5 is preferred when minimizing cost and payback is the main objective.

In order to make the study closer to the real operation, extra loss layers were added on the top of shading. The decline in produced energy (201,576 down to 181,982 kWh/yr), specific production (1544 down to 1394 kWh/kWp/yr), PR (70.29% down to 63.45%), and PE (338 down to 305.2 kWh/m²/yr) as one progresses from Variant 6 (shading only) to Variant 10 (shading + soiling + aging + unavailability + auxiliaries) is accompanied by a rise in the LCOE (0.0352 up to 0.039 USD/kWh) and the payback period (4.1 up to 4.7 years). Such a stepwise process illustrates the essential nature of ensuring that the contributing operating elements used within the studies are realistic, such that final conflicting conclusions mirror the performances of rooftops under real-world conditions and not idealistic assumptions.

With the full results now presented, Variants 1–4 will be seen not as realistic rooftop options, but as

Table 2 — Comparison table with previous PVsyst-based studies.

Work / Ref. No.	Produced Energy (kWh/year)	Specific production (kWh/kWp/year)	PR (%)	PV Module Area (m²)	PE = Energy/Area (kWh/m²/year)	System size (kWp) (computed)
This work	244,305	1,871.0	85.19	559.00	437.04	130.57
Islam [40]	318,200	1,591.0	83.92	1,003.00	317.25	200.00
Ghlaim [41]	458,800	1,835.3	81.00	1,796.20	255.43	249.99
Al-Khazzar [42]	9,820	1,964.0	82.00	32.50	302.15	5.00
Al-Sarraj [43]	6,080	1,448.0	72.00	19.00	320.00	4.20
Al Sarhan [44]	70,230	1,734.0	84.00	176.00	399.03	40.50
Sawner [45]	144,200	1,442.0	69.02	598.00	241.14	100.00
Ahmad [46]	346,692	1,387.0	75.00	1,858.00	186.59	249.96
Satish [47]	352,600	1,757.0	81.67	1,180.00	298.81	200.68

benchmark cases (Reference cases 1–4), because they represent the unshaded or mechanically expensive configurations (seasonal adjustment and tracking), and would often be restricted by rooftop obstructions, access restrictions, and maintenance concerns in real-world urban installations.

Table 2 compares PVsyst-based indicators from this study with selected published works that report Produced Energy, Specific Production, Performance Ratio (PR), and PV array area. In addition, the PE indicator (kWh/m²/year) is included to reflect rooftop space utilization, defined as yearly AC energy divided by PV module area. Overall, Table 2 highlights the strength of this study as a decision-oriented assessment: near-shading is explicitly modeled on a realistic rooftop geometry, performance is reported using normalized indicators (Yf/Specific Production and PR), and economic feasibility (LCOE and payback) is evaluated within the same PVsyst workflow. This combined technical–economic perspective supports actionable recommendations for Baghdad rooftops under practical shading constraints.

4 Conclusion

A PVsyst-based workflow, supported by detailed 3D shading modeling, is used to help choose suitable rooftop PV layouts for Baghdad. PVsyst reports provide both technical and economic results, including annual produced energy, specific production (final yield), performance ratio (PR), energy-per-area (PE), LCOE, and payback period. Variants 1–4 are kept as benchmark cases (unshaded fixed, seasonal adjustment, and tracking). They represent an upper bound of what a system can achieve, but they are not considered the most practical rooftop choices because typical Baghdad roofs have obstacles, limited access paths, and strong near-shading effects.

For the practical, shading-dominated group (Variants 5–10), Variant 6 (HJT_680_L_Shading) is the best technical option. It delivers the highest produced energy under shading (201,576 kWh/yr) and also shows the strongest specific production and PE among Variants 6–10. On the other hand, Variant 5 (HJT_680_P_Shading) is the best economic option, with the lowest LCOE (0.0245 USD/kWh) and the shortest payback (2.8 years) in the table. A main conclusion is that realistic operating losses must be included to avoid overestimating rooftop PV performance. Adding soiling, aging, system unavailability, and auxiliary consumption on top of shading gradually reduces produced energy, specific production, PR, and PE, while it increases LCOE and payback. If these losses are modeled unrealistically, the results can look closer to ideal conditions than to real rooftop operation in Baghdad, which can lead to misleading design decisions.

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