Co-published by
Institute of Fluid-Flow Machinery
Polish Academy of Sciences
Committee on Thermodynamics and Combustion
Polish Academy of Sciences

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http://www.imp.gda.pl/archives-of-thermodynamics/

Dual-use PV canopies for public gardens: Performance, techno-economic feasibility and CO_2 mitigation of an 84.5 kWp grid-tied system in Baghdad, Iraq

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Received: 18.02.2026; revised: 13.05.2026; accepted: 30.06.2026

Abstract

This study presents a comprehensive energy, techno-economic and environmental assessment of a dual-use grid-connected photovoltaic canopy system implemented in a public urban garden in Baghdad, Iraq, under hot-arid climatic conditions. The photovoltaic system, designed as shading canopies integrated within recreational areas, has a total installed capacity of 84.5 kWp and operates under a net-metering configuration without battery storage. The system performance was evaluated using PVsyst simulation and independently cross-checked through a simplified analytical model developed in a spreadsheet-based framework using monthly solar-resource inputs and aggregate loss assumptions. The analytical model reproduced the same seasonal behaviour as the PVsyst simulation, with an annual deviation of only 1.51%. The results indicate an annual electricity generation of 133 189 kWh, corresponding to a specific yield of 1 577 kWh/kWp per year and a performance ratio of 79.6%, demonstrating reliable operation despite high ambient temperatures, dust exposure and other site-related losses. The irrigation demand of the public garden is supplied by a 4-hp electric pump requiring approximately 2 200 kWh per year, which represents only about 1.6% of the total annual photovoltaic production. Consequently, more than 130 MWh per year of surplus electricity is available for export to the national grid. The economic analysis revealed a levelised cost of electricity of approximately 44 IQD/kWh (≈ 0.034 USD/kWh), substantially lower than the prevailing commercial electricity tariff of about 120 IQD/kWh (≈ 0.092 USD/kWh), with a simple payback period of about 6 years and an internal rate of return of approximately 18%. Environmentally, replacing the previous diesel-based irrigation supply with the photovoltaic-supported electric system leads to an estimated annual reduction of approximately 113 tonnes of CO_2 emissions. Overall, the findings demonstrate that photovoltaic canopy systems provide a technically reliable, economically attractive and environmentally effective solution for urban irrigation while simultaneously delivering shading benefits, supporting grid interaction and improving the sustainability of public green spaces in hot-arid regions.

Keywords: Photovoltaic canopy; Urban solar irrigation; Grid-connected photovoltaic system; Techno-economic assessment; CO_2 mitigation; Hot-arid climate

Vol. 47(2026), No. 3, 79–88; doi: 10.24425/ather.2026.3657

Cite this manuscript as: Mahdi, E.J., Hussein, H.F., & Ata, A.I. (2026). Dual-use PV canopies for public gardens: Performance, techno-economic feasibility and CO_2 mitigation of an 84.5 kWp grid-tied system in Baghdad, Iraq. *Archives of Thermodynamics*, 47(3), 79−88.

1. Introduction

Urban green spaces such as public gardens and parks play a critical role in improving environmental quality, mitigating urban heat island effects and enhancing social well-being, particularly in densely populated cities located in hot-arid regions. However, maintaining these green infrastructures requires reliable and continuous irrigation, which in many developing countries still depends heavily on diesel-powered pumping systems. These systems are associated with high operational costs, fuel supply vulnerability, noise and significant greenhouse gas emissions [1–3]. As cities expand and climate conditions deteriorate,

Nomenclature

$E_{analytical}$ – energy estimated by the simplified analytical model, kWh
E_m – monthly electrical energy output, kWh
E_{PVsyst} – monthly or annual energy yield predicted by PVsyst, kWh
H_m – monthly in-plane solar irradiation, h
P_r – rated PV system capacity, kWp
PR_m – monthly effective performance ratio

Abbreviations and Acronyms

AC – alternating current
DC – direct current
IQD – Iraqi dinar
IRR – internal rate of return
LCOE – levelised cost of electricity
PV – photovoltaic
STC – standard test conditions

the energy–water nexus in urban irrigation has become an increasingly important challenge.

Photovoltaic (PV) energy has emerged as one of the most promising solutions for sustainable irrigation due to its modularity, declining costs, and suitability for regions with high solar irradiance [4–6]. In arid and semi-arid climates, solar energy availability often coincides with peak irrigation demand, making PV-powered irrigation systems particularly attractive. Nevertheless, most existing studies have focused on rural or agricultural irrigation schemes, frequently relying on off-grid configurations with battery storage, which increases system complexity, cost, and long-term maintenance requirements [7,8]. In contrast, grid-connected PV systems without storage, operating under net-metering schemes, remain underexplored for urban irrigation applications.

Recent research has emphasised the importance of system performance, degradation behaviour, and thermal effects on PV installations operating in harsh climates. Long-term exposure to high ambient temperatures, dust accumulation and thermal cycling can significantly affect PV efficiency and reliability [9–11]. Detailed performance assessment and loss analysis are therefore essential to ensure realistic energy yield predictions. Previous investigations have demonstrated that careful system design and monitoring can maintain high performance ratios even under challenging environmental conditions [12]. These aspects are particularly relevant for urban installations, where shading, architectural constraints and multifunctional land use must be considered.

An emerging concept in urban solar integration is the use of dual-use PV canopies, where PV modules are installed as shading structures over public spaces. Such systems offer multiple benefits: electricity generation, thermal comfort for users, reduced surface temperatures and improved land-use efficiency [13–15]. When applied to public gardens, PV canopies can simultaneously support irrigation energy demand and provide shaded recreational areas, contributing to both environmental sustainability and social value. Despite these advantages, quantitative assessments of PV canopy systems for urban irrigation, especially in hot-arid cities, remain limited in the literature.

In parallel, techno-economic analyses have become a cornerstone of evaluating renewable energy projects, particularly in regions where fossil-fuel-based solutions are still economically dominant. Studies conducted under Iraqi climatic conditions have demonstrated the critical role of thermal behaviour, material performance and system aging in determining the long-term viability of solar energy systems [16–18]. Moreover, replacing diesel-driven systems with electrically powered alternatives supplied by PV energy can yield substantial reductions in operating costs and carbon emissions, provided that system sizing and grid interaction are properly optimised [19].

Against this background, the present study addresses a clear research gap by providing a comprehensive energy, techno-economic and environmental assessment of a grid-connected PV canopy system used for urban irrigation in a hot-arid climate. The study is based on a real public garden located in Baghdad, Iraq, where a dual-use PV canopy system with an installed capacity of 84.5 kWp supplies a relatively small irrigation load while exporting most of the generated electricity to the national grid. Using PVsyst-based simulation, an independent simplified analytical model, realistic load profiles and detailed economic and emissions analysis, this work aims to:

(i) quantify the energy performance of the PV canopy system under local climatic conditions,
(ii) evaluate its economic feasibility in comparison with conventional diesel-based irrigation,
(iii) assess its contribution to CO_2 emission mitigation.

In addition to detailed software-based simulation, the study introduces an independent engineering cross-check model to enhance methodological transparency and improve the reproducibility of PV canopy performance estimation under hot-arid operating conditions. The analytical cross-check showed an annual deviation of only 1.51% relative to the PVsyst prediction, confirming acceptable agreement between the two approaches. The results provide practical insights for municipalities and decision-makers seeking scalable, multifunctional solar solutions for sustainable urban green infrastructure.

2. System description and methodology

2.1. Site description and climatic conditions

The investigated system is installed in a public urban garden located in Al-Ghazālīyah district, Baghdad, Iraq, at geographic coordinates of 33.33°N latitude and 44.27°E longitude, with an average altitude of approximately 28 m above sea level. The site lies within a hot-arid climatic zone, characterised by long, dry summers, high solar irradiance and elevated ambient temperatures during the irrigation season.

Baghdad receives high annual solar potential, with average global horizontal irradiation exceeding 1 800 kWh/m² per year, making it highly suitable for photovoltaic energy deployment. However, the same climatic conditions impose challenges related to thermal losses, dust accumulation and long-term system performance, which necessitate realistic modelling and conservative performance assumptions [9,11]. The geographical location of the public garden, the spatial arrangement of the PV canopy system, and the near-shading environment are illustrated in Fig. 1.

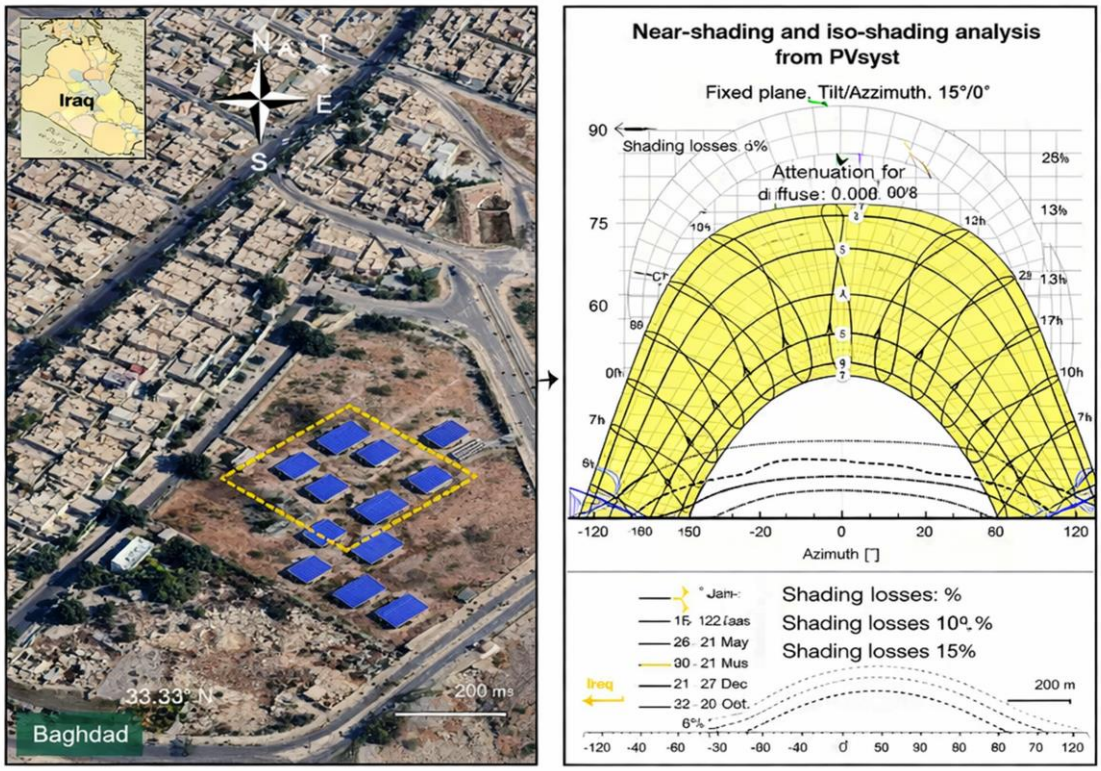


Fig. 1. Geographical location of the investigated public garden in Al-Ghazālīyah district, Baghdad, Iraq, showing the spatial layout of the PV canopy system and the corresponding near-shading and iso-shading analysis obtained from PVsyst.

2.2. Description of the PV canopy system

The photovoltaic installation is designed as a dual-use PV canopy system, where PV modules are mounted on shading structures integrated within the garden area. These canopies simultaneously provide electrical energy generation and shaded spaces for park users, thereby improving land-use efficiency and thermal comfort.

The total installed PV capacity of the system is 84.5 kWp, consisting of 128 monocrystalline PV modules, each rated at 660 Wp under standard test conditions (STC). The modules are arranged in eight strings of sixteen modules, mounted at a fixed tilt angle of 15° and an azimuth of 0°, optimised for annual energy production under local conditions. The total active module area is approximately 398 m². The structural configuration of the dual-use photovoltaic canopy system and its integration within the public garden are illustrated in Fig. 2.

Power conversion is achieved using two grid-connected inverters, each rated at 40 kWac, resulting in a direct current to alternating current (DC-to-AC) power ratio of approximately 1.06, which is consistent with best practices for minimising inverter clipping while enhancing energy yield. The system operates without battery storage and is directly connected to the national grid under a net-metering configuration.

The site characteristics and main technical specifications of the investigated grid-connected PV canopy system, including installed capacity, array configuration and inverter characteristics, are summarised in Table 1.

2.3. Irrigation load characterisation

The irrigation demand of the public garden is supplied by a single electric water pump rated at 4 horsepower (≈2.98 kW). Field inspection and operational assessment indicated that the garden requires approximately 10 000 litres of water per day, which can be delivered by operating the pump for two hours daily.

Under these operating conditions, the annual electricity consumption of the irrigation pump is approximately 2 200 kWh per year. Compared with the annual PV electricity



Fig. 2. Schematic configuration of the dual-use photovoltaic canopy system integrated within the public garden, showing the PV module arrangement, supporting structures, and the associated electrical components supplying irrigation and exporting surplus electricity to the grid.

Table 1. Site characteristics and technical specifications of the investigated grid-connected PV canopy system.

Parameter	Value	Unit
Location	Al-Ghazālīyah, Baghdad, Iraq	–
Latitude / Longitude	33.33° N / 44.27° E	–
Altitude	28	m
Climate zone	Hot-arid	–
PV system type	Grid-connected PV canopy (no storage)	–
Total installed capacity	84.5	kWp
Number of PV modules	128	units
Nominal power per module	660	Wp
PV module technology	Monocrystalline silicon	–
PV array configuration	8 strings × 16 modules	–
Tilt angle / azimuth	15° / 0°	–
Total module area	398	m^2
Number of inverters	2	units
Inverter rated power	40	kWac
Total inverter capacity	80	kWac
DC/AC ratio	1.06	–
Grid interaction	Net metering	–

production of the system, the irrigation load represents only about 1.6% of the total generated energy, allowing the majority of the PV output to be exported to the grid. This low load-to-generation ratio highlights the suitability of grid-connected operation and the economic importance of surplus energy export.

2.4. Performance modelling and simulation approach

The energy performance of the PV canopy system was evaluated using PVsyst (version 7.4.8), a widely validated simulation tool for photovoltaic system analysis. The model incorporates site-specific meteorological data derived from the Meteonorm database, including solar irradiance, ambient temperature and seasonal variability. The simulation accounts for the principal system losses, including soiling losses, thermal losses due to elevated module operating temperatures, light-induced degradation, module mismatch losses, ohmic losses in DC wiring, inverter conversion losses, and system unavailability. Near-shading effects caused by the canopy configuration were modelled using the linear shading approach implemented in PVsyst. The overall system performance was quantified using standard indicators, including annual energy yield, specific yield and performance ratio (PR).

2.5. Simplified analytical model and cross-validation approach

To complement the PVsyst-based simulation and improve methodological transparency, a simplified analytical model was developed to independently estimate the annual and monthly energy output of the PV canopy system. The analytical approach was based on the installed PV capacity, monthly solar resource and aggregate performance losses under local operating conditions.

The monthly electrical energy yield of the PV canopy system was estimated using the following simplified relationship:

$$E_m = P_r \times H_m \times PR_m, \quad (1)$$

where E_m is the monthly electrical energy output (kWh), P_r is the rated PV system capacity (kWp), H_m is the monthly in-plane solar irradiation expressed in equivalent peak-sun-hours, and PR_m is the monthly effective performance ratio. The term PR_m incorporates the main loss mechanisms affecting system operation, including thermal losses, soiling losses, mismatch losses, DC wiring losses, inverter losses and minor near-shading effects.

The simplified analytical model was implemented in a spreadsheet-based framework to provide an independent engineering cross-check of the simulation outputs. The purpose of this model is not to replace detailed photovoltaic simulation software, but rather to provide a transparent and reproducible validation tool for assessing the physical consistency of the predicted energy yield. The outputs of the analytical model were therefore compared with the PVsyst results at both monthly and annual scales in order to evaluate the agreement between the two approaches and strengthen confidence in the reported performance indicators.

To quantify the agreement between the analytical model and the PVsyst simulation, the relative deviation was calculated as follows:

$$Relative\ deviation\ (\%) = \\ = \left|E_{PVsyst} - E_{analytical}\right| / E_{PVsyst} \times 100, \quad (2)$$

where E_{PVsyst} is the monthly or annual energy yield predicted by PVsyst and $E_{analytical}$ is the corresponding value estimated by the simplified analytical model. This comparison was used to evaluate the consistency of the two approaches at both monthly and annual scales.

At the annual scale, the simplified analytical model showed a deviation of 1.51% relative to the PVsyst prediction, which indicates acceptable agreement for validation purposes under the adopted assumptions.

2.6. Techno-economic and environmental assessment methodology

The techno-economic and environmental evaluation was conducted after confirming the consistency of the PV energy output using both PVsyst simulation and the independent simplified analytical model. The economic assessment was performed using a life-cycle cost approach, considering capital investment, operation and maintenance costs, energy savings from diesel displacement and revenue from surplus electricity exported to the grid. The primary economic indicators used in this study include the levelised cost of electricity (LCOE), simple payback period, and internal rate of return (IRR). The environmental assessment focused on the reduction of greenhouse gas emissions achieved by replacing the diesel-powered irrigation system with an electrically driven pump supplied by photovoltaic energy. Carbon dioxide emission reductions were estimated using standard

emission factors associated with diesel fuel consumption and grid electricity generation [9].

2.7. Data reliability and assumptions

All system parameters, load profiles, and economic inputs were selected to reflect realistic operating conditions based on field observations, local climatic conditions and representative cost structures. Conservative assumptions were adopted where uncertainty existed in order to avoid overestimation of system performance or financial benefits. In addition, the simplified analytical model was intentionally formulated as an independent cross-check tool rather than a substitute for detailed PV simulation. This approach improves methodological transparency while maintaining consistency with the technical assumptions used in the PVsyst-based analysis.

3. Energy performance results and loss analysis

3.1. Annual energy yield and system productivity

The PV canopy system exhibits a high annual energy yield despite operating under hot-arid climatic conditions. The simulated annual electricity production reaches 133 189 kWh, corresponding to a specific yield of 1 577 kWh/kWp per year. This value is notably high for an urban installation and reflects the favourable solar resource of Baghdad combined with appropriate system sizing and orientation. The calculated performance ratio (PR) of 79.6% indicates efficient conversion of available solar irradiation into usable electrical energy, even when accounting for thermal losses, soiling and inverter inefficiencies. Such a PR value is comparable to, and in some cases higher than, those reported for PV systems operating in temperate climates, confirming the technical viability of PV installations in hot-arid urban environments when proper design practices are applied.

3.2. Monthly energy production profile

Monthly energy generation follows the expected seasonal solar irradiation pattern. Peak electricity production occurs between May and August, coinciding with maximum global horizontal irradiation and extended daylight hours. During this period, monthly energy output exceeds 13 MWh, with the highest contribution recorded in June and July. Lower production values are observed during winter months, particularly in December and January, due to reduced solar irradiance and shorter daylight duration. Nevertheless, even during these months, the system maintains stable operation and sufficient energy availability to fully cover the irrigation load. The consistency of the monthly production profile demonstrates the robustness of the canopy-mounted configuration against seasonal variability. A detailed month-by-month and annual energy balance of the investigated PV canopy system, including irrigation demand and surplus electricity exported to the grid, is presented in Table 2. A comparison between the monthly photovoltaic electricity generation and the irrigation energy demand is presented in Fig. 3, clearly showing that the irrigation load represents only a small fraction of the total PV production throughout the year.

Table 2. Monthly and annual energy balance of the investigated PV canopy system, irrigation demand, and surplus electricity exported to the grid.

Month	PV energy production, kWh	Irrigation energy demand, kWh	Energy exported to grid, kWh
January	9 139	187	8 952
February	9 209	169	9 040
March	11 725	187	11 538
April	13 224	181	13 043
May	13 831	187	13 644
June	14 648	181	14 467
July	14 322	187	14 135
August	13 246	187	13 059
September	12 522	181	12 341
October	10 324	187	10 137
November	8 772	181	8 591
December	8 138	187	7 951
Total (annual)	**133 189**	**2 200**	**130 989**

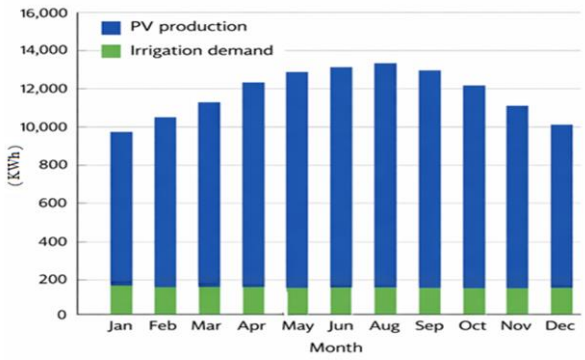


Fig. 3. Monthly photovoltaic electricity generation and irrigation energy demand of the investigated public garden, illustrating the large surplus electricity available for grid export throughout the year.

3.3. Load coverage and surplus energy export

The annual electricity demand of the irrigation system, estimated at 2 200 kWh, represents only approximately 1.6% of the total PV production. As a result, the system operates predominantly as an electricity-exporting installation, with more than 130 MWh per year of surplus energy injected into the national grid.

This pronounced mismatch between generation capacity and irrigation demand is intentional and reflects the dual-function design philosophy of the system. Rather than sizing the PV system solely to match the irrigation load, the canopy installation is optimised to maximise land-use efficiency and grid support while still fully satisfying local energy needs. From an operational standpoint, the irrigation load is entirely supplied by solar-generated electricity during daytime hours, while grid interaction ensures uninterrupted operation under all conditions.

3.4. Loss analysis and performance breakdown

A detailed loss analysis reveals the dominant mechanisms affecting system performance. Thermal losses constitute the larg-

est contribution, accounting for approximately 8.4% of the total energy reduction, which is consistent with the high ambient temperatures characteristic of Baghdad's climate. Soiling losses are estimated at 3%, reflecting conservative assumptions for dust accumulation under regular maintenance conditions.

Additional losses include light-induced degradation (approximately 2%), module mismatch losses (2%) and ohmic losses in DC cabling (approximately 1%). Inverter-related losses remain limited to around 2%, highlighting the suitability of the selected inverter configuration and DC-to-AC sizing ratio. Near-shading losses associated with the canopy geometry are negligible, contributing less than 0.3% to the overall energy reduction.

The cumulative impact of these losses results in an effective energy output that remains high relative to the available solar resource, confirming that no single loss mechanism critically undermines system performance. The key energy performance indicators and principal loss contributions affecting the investigated PV canopy system are summarised in Table 3.

Table 3. Key energy performance indicators and principal loss contributions of the investigated PV canopy system.

Indicator	Value	Unit
Annual energy production	133 189	kWh per year
Specific yield	1 577	kWh/kWp per year
Performance ratio (PR)	79.6	%
Global horizontal irradiation	1 818	kWh/m² per year
Effective irradiation on collectors	1 876	kWh/m² per year
Near-shading losses	0.26	%
Soiling losses	3.0	%
Thermal losses	8.36	%
Inverter losses	2.01	%
System availability	97.8	%

The contribution of the main loss mechanisms affecting the annual energy yield of the PV canopy system is summarised in the loss diagram presented in Fig. 4.

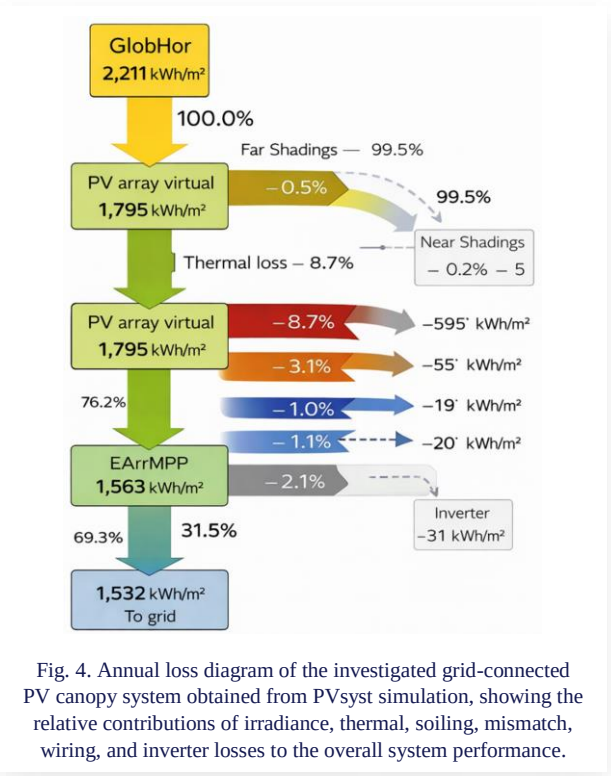


Fig. 4. Annual loss diagram of the investigated grid-connected PV canopy system obtained from PVsyst simulation, showing the relative contributions of irradiance, thermal, soiling, mismatch, wiring, and inverter losses to the overall system performance.

3.5. Cross-validation of PVsyst results using the simplified analytical model

To assess the robustness of the simulation results, the annual and monthly PV energy outputs predicted by PVsyst were independently cross-checked using the simplified analytical model described in Section 2.5. The analytical model reproduced the same seasonal production trend observed in the software simulation, with peak generation during late spring and summer and lower output during winter months.

At the annual scale, the analytical estimation showed acceptable agreement with the PVsyst result, with a total annual deviation of 1.51%. This indicates that the predicted energy yield is physically reasonable for the installed capacity, local solar resource and assumed loss conditions of the Baghdad site. Minor monthly deviations between the two approaches are expected because PVsyst incorporates more detailed sub-models related to thermal behaviour, incidence-angle effects and inverter operation, whereas the simplified analytical model applies aggregate monthly correction factors.

Overall, the comparison demonstrates that the reported performance indicators are not solely dependent on commercial software output, but are also supported by an independent engineering calculation framework. The simplified analytical model reproduced the same overall seasonal behaviour and annual performance trend obtained from PVsyst, and the annual deviation between the two approaches was limited to 1.51%, confirming the physical consistency of the predicted system output under the adopted operating assumptions. A detailed month-by-month comparison between the PVsyst predictions and the simplified analytical model estimates is presented in Table 4.

Note: The simplified analytical estimates were derived using monthly solar-resource inputs and aggregate loss assumptions to provide an independent engineering cross-check of the PVsyst results. The analytical model is intended for validation and transparency purposes rather than as an exact replacement for the detailed PVsyst simulation.

3.6. Reliability under hot-arid operating conditions

Operating in a hot-arid urban environment imposes challenges related to elevated module temperatures, dust exposure and prolonged summer operation. Despite these constraints, the system demonstrates stable performance indicators across the annual cycle. The acceptable agreement between PVsyst and the simplified analytical model, with an annual deviation of only 1.51%, further strengthens confidence in the reliability of the reported performance indicators under hot-arid operating conditions. The absence of battery storage also enhances system reliability by eliminating one of the most failure-prone components

in photovoltaic systems. The results indicate that grid-connected PV canopy systems can achieve high energy productivity and operational stability in extreme climates, provided that appropriate assumptions regarding losses and maintenance are incorporated into the design stage.

Table 4. Month-by-month comparison between PVsyst predictions and simplified analytical model estimates for the investigated PV canopy system.

Month	PVsyst energy, kWh	Analytical model energy, kWh	Absolute deviation, kWh	Relative deviation, %
January	9 139	8 152	987	10.80
February	9 209	8 643	566	6.14
March	11 725	10 883	842	7.18
April	13 224	12 524	700	5.29
May	13 831	13 372	459	3.32
June	14 648	13 614	1 034	7.06
July	14 322	13 654	668	4.66
August	13 246	13 304	58	0.44
September	12 522	12 417	105	0.84
October	10 324	9 639	685	6.64
November	8 772	8 024	748	8.52
December	8 138	6 948	1 190	14.62
Annual total	**133 189**	**131 174**	**2 015**	**1.51**

3.7. Summary of performance findings

Overall, the combined PVsyst simulation and independent analytical cross-validation confirm that the investigated PV canopy system not only satisfies the local irrigation demand with a large safety margin, but also functions as a significant distributed generation asset. The analytical model reproduced the seasonal and annual performance trends obtained from PVsyst, with an annual deviation of only 1.51%, supporting the physical consistency of the reported energy yield. The combination of high specific yield, favourable performance ratio and substantial surplus electricity export establishes the system as an effective model for integrating renewable energy into urban green infrastructure under hot-arid climatic conditions.

4. Techno-economic assessment

4.1. Economic framework and assumptions

The techno-economic evaluation of the proposed PV canopy system was conducted using a life-cycle cost approach that reflects realistic operating conditions and local market parameters. Capital expenditure includes PV modules, inverters, mounting structures, electrical accessories, and installation costs, while operational expenditure accounts primarily for routine maintenance and system supervision. In line with common practice for grid-connected PV systems without storage, annual operation and maintenance costs were assumed to be modest due to the absence of batteries and rotating mechanical components. All economic calculations were performed using conservative assumptions to avoid overestimation of financial benefits. Electricity tariffs, fuel prices and emission factors were selected based on prevailing local values and recent studies conducted under Iraqi climatic and economic conditions [9,11,16]. For clarity and international readability, selected monetary values originally expressed in Iraqi dinars (IQD) are also reported in equivalent U.S. dollars (USD) using a consistent representative exchange rate. An exchange rate of 1 USD = 1300 IQD was adopted for indicative currency conversion throughout the analysis.

4.2. Cost of electricity and competitiveness

The levelised cost of electricity (LCOE) produced by the PV canopy system was estimated at approximately 44 IQD/kWh (≈ 0.034 USD/kWh), considering the total life-cycle cost over an assumed system lifetime of 25 years. This value is significantly lower than the prevailing commercial electricity tariff of approximately 120 IQD/kWh (≈ 0.092 USD/kWh), indicating a cost reduction of nearly 63% per unit of delivered electricity.

This substantial difference highlights the economic advantage of photovoltaic energy in high-irradiance regions, particularly when systems are designed to operate without storage and are allowed to export surplus electricity to the grid. From a municipal perspective, such a reduction directly translates into long-term budgetary relief and improved energy cost predictability.

4.3. Diesel displacement and operating cost savings

Prior to PV system implementation, irrigation was supplied by a diesel-powered pump, characterised by high fuel consumption, frequent maintenance requirements, and sensitivity to fuel price fluctuations. Replacing this system with an electrically driven pump powered by solar-generated electricity results in immediate and sustained operating cost savings.

For the investigated case, the annual irrigation energy demand of 2 200 kWh is fully covered by PV generation, effectively eliminating diesel fuel consumption for irrigation purposes. The avoided cost of diesel fuel constitutes a significant portion of the annual savings, particularly when accounting for indirect costs associated with fuel transport, storage, and engine maintenance. These findings are consistent with previous studies demonstrating the economic vulnerability of diesel-based irrigation systems in comparison with solar-powered alternatives [6,7].

4.4. Revenue from surplus electricity export

A defining feature of the investigated system is the large surplus of electricity available for export to the national grid. Because the irrigation demand accounts for only a small fraction of the annual PV output, more than 130 MWh per year of electricity can be delivered to the grid under the adopted grid-connected operating scheme. This exported energy represents an important economic advantage of the system, as it improves overall electricity utilisation and enhances the financial value of the installation beyond its direct irrigation function. Unlike stand-alone systems, where excess generation may remain underutilised, the

grid-connected configuration enables productive use of the surplus electricity and strengthens the economic case for dual-use PV canopy deployment in urban public spaces.

4.5. Payback period and investment attractiveness

Based on the combined effects of reduced diesel dependence, lower electricity costs, and the economic value of surplus electricity export, the investigated PV canopy system achieves a simple payback period of approximately 6 years. This value falls within a practically acceptable range for municipal renewable energy investments and leaves a substantial portion of the system lifetime available for net economic benefit. The calculated internal rate of return (IRR) of approximately 18% further confirms the financial attractiveness of the project. These indicators show that the proposed system is not only environmentally beneficial, but also economically competitive as a long-term urban infrastructure investment.

4.6. Economic robustness and long-term perspective

One of the principal strengths of the investigated PV canopy system is its resilience to future economic uncertainty. In contrast to diesel-based irrigation systems, which remain highly sensitive to fuel price volatility and recurrent operating costs, the photovoltaic system is characterised by comparatively stable long-term operating expenses. This economic robustness becomes more pronounced when surplus electricity can be productively exported to the grid under a grid-connected operating scheme. In addition, the dual-use canopy configuration provides non-energy benefits, including shading and improved usability of public space, which further strengthen the overall value proposition of the system from a municipal planning perspective.

4.7. Summary of techno-economic findings

The techno-economic assessment confirms that the investigated PV canopy system represents a financially viable solution for urban irrigation in hot-arid regions. The combination of low electricity cost, productive utilisation of surplus generation through grid export, acceptable payback period, and favourable internal rate of return demonstrates that the system can deliver long-term economic value in addition to its environmental and functional benefits. The main techno-economic and environmental indicators of the investigated PV canopy system are summarised in Table 5.

Table 5. Main techno-economic and environmental indicators of the investigated PV canopy system.

Parameter	Value	Unit
System lifetime	25	years
Levelised cost of electricity (LCOE)	44 (≈ 0.034)	IQD/kWh (USD/kWh)
Commercial electricity tariff	120 (≈ 0.092)	IQD/kWh (USD/kWh)
Cost reduction compared to grid	63	%
Simple payback period	≈ 6	years
Internal rate of return (IRR)	≈ 18	%
Annual diesel fuel displacement	Fully eliminated	–
Annual CO_2 emission reduction	113	tonnes
Annual surplus energy exported	≈ 131	MWh

5. Environmental impact and CO_2 mitigation

5.1. Emission reduction through diesel replacement

The environmental benefits of the PV canopy system are primarily associated with replacing the previous diesel-powered irrigation supply with an electrically driven pump supported by photovoltaic energy. Diesel-based irrigation systems are a notable source of greenhouse gas emissions due to continuous fuel combustion and relatively low overall efficiency. In the investigated case, the transition to photovoltaic energy effectively eliminates diesel use for irrigation purposes.

Based on the adopted diesel displacement and grid-related emission assumptions, the avoided diesel fuel consumption corresponds to an estimated annual reduction of approximately 113 tonnes of CO_2. This reduction is achieved without compromising irrigation reliability or water delivery, highlighting the effectiveness of photovoltaic systems as a direct decarbonisation measure for urban service infrastructure. The environmental benefit of replacing diesel-powered irrigation with photovoltaic-powered irrigation is illustrated in Fig. 5, showing a substantial reduction in annual CO_2 emissions.

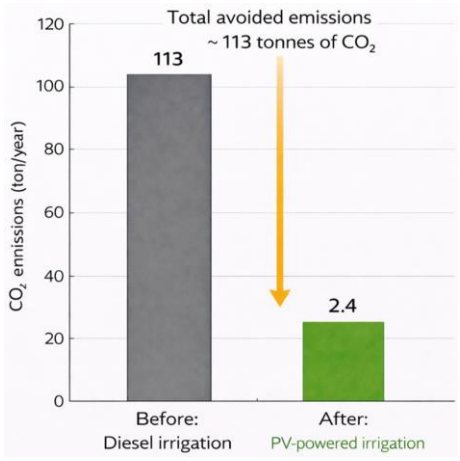


Fig. 5. Comparison of annual CO_2 emissions associated with diesel-based irrigation and photovoltaic-supported electric irrigation for the investigated public garden.

5.2. Contribution to grid decarbonisation

In addition to reducing local emissions through diesel displacement, the investigated PV canopy system contributes to grid decarbonisation by exporting more than 130 MWh per year of surplus solar electricity under the adopted grid-connected operating scheme. This exported electricity can offset part of the fossil-fuel-based generation that would otherwise be required to meet daytime demand. Although the carbon intensity of the national

grid may vary over time, the cumulative contribution of distributed photovoltaic generation remains environmentally significant, particularly in high-irradiance regions where daytime solar production is substantial. Accordingly, the environmental value of the system extends beyond the boundaries of the public garden itself and supports broader urban decarbonisation efforts.

5.3. Water–energy–climate co-benefits

The PV canopy configuration provides additional co-benefits that extend beyond direct electricity generation and carbon emission reduction. By functioning as shading structures within the public garden, the canopies can help reduce surface temperatures and limit direct solar exposure of soil and vegetation during peak summer conditions. This shading function may contribute to reduced evapotranspiration and improved local water-use efficiency, although these effects were not quantified in the present study. In addition, the integration of renewable energy generation into urban green spaces can support climate adaptation strategies by improving thermal comfort for users and enhancing the multifunctional value of public infrastructure.

5.4. Environmental significance at an urban scale

Although the present analysis focuses on a single public garden, the broader environmental implications become more significant when similar PV canopy systems are deployed across multiple urban parks and green spaces. Replication of this concept at the city scale could lead to cumulative reductions in diesel use, lower dependence on fossil-fuel-based electricity, and measurable decreases in urban carbon emissions. In addition to these direct energy-related benefits, wider deployment of PV canopies could support more climate-responsive urban infrastructure by combining renewable electricity generation with shading and improved public-space functionality. These considerations indicate that the environmental significance of the proposed system extends beyond the individual case study and may inform sustainable urban planning strategies in hot-arid cities.

6. Discussion

6.1. Comparison with existing studies

The performance indicators obtained in this study, particularly the specific yield of 1 577 kWh/kWp per year and the performance ratio of 79.6%, are consistent with, and in some cases superior to, values reported for PV systems operating in comparable hot-arid regions. Unlike many previous studies that focused mainly on ground-mounted or rooftop PV systems, the present work demonstrates that canopy-mounted configurations integrated into public urban spaces can achieve high productivity despite structural and near-shading constraints. In addition, the present study does not rely solely on commercial software output, as the PVsyst results were independently cross-checked using a simplified analytical model. This additional validation step improves the methodological transparency of the analysis and strengthens confidence in the reported energy performance trends. In particular, the annual deviation between the PVsyst output and the simplified analytical model was limited to 1.51%, indicating acceptable agreement between the two approaches for engineering validation purposes. From an economic standpoint, the reported LCOE of 44 IQD/kWh (≈ 0.034 USD/kWh) and payback period of approximately 6 years compare favourably with other solar irrigation solutions, particularly off-grid systems that rely on battery storage. The absence of storage not only reduces costs but also improves long-term reliability, which is a critical consideration for municipal infrastructure.

6.2. Design philosophy and system sizing

A key design insight emerging from this study is the deliberate oversizing of the PV canopy system relative to the direct irrigation load. Rather than minimising the installed PV capacity to match only the local pumping demand, the system was configured to maximise the functional value of the available urban space through simultaneous electricity generation, shading provision and grid interaction. This design philosophy differs from conventional solar irrigation configurations, which are typically sized to satisfy a specific agricultural or pumping load with limited consideration of broader urban functionality. In the investigated case, the relatively small irrigation demand enables most of the generated electricity to be exported to the grid, thereby improving the economic value of the installation while preserving its primary service role within the public garden. This multi-objective sizing strategy demonstrates that PV canopy systems can be planned not only as energy supply units, but also as integrated urban infrastructure assets.

6.3. Practical implications for municipalities

For municipalities in hot-arid regions, the results highlight a practical pathway for reducing dependence on diesel-based irrigation without introducing significant operational complexity. Grid-connected PV canopy systems offer predictable energy costs, minimal maintenance requirements and measurable environmental benefits while simultaneously improving the functional quality of public spaces through shading. In addition to supplying local irrigation demand, such systems can contribute surplus electricity to the grid, thereby enhancing the economic value of municipal solar investments. Importantly, the dual-use nature of the canopy installation may improve public acceptance by combining visible social benefits with clean energy generation. These features make PV canopy systems a promising option for sustainable urban green infrastructure planning in cities with high solar potential.

6.4. Limitations and future research

While the present study provides a comprehensive assessment based on detailed simulation and realistic operational assumptions, future work could extend the analysis through long-term monitoring of actual system performance under field conditions. Further research may also quantify microclimatic effects, water-saving potential and user comfort improvements associated with canopy shading, thereby strengthening the interdisciplinary value of such systems. Another limitation is that the independent analytical model was intentionally formulated as a simplified cross-check tool for validation purposes rather than as a repla-

cement for detailed dynamic PV simulation software. Nevertheless, its agreement with the PVsyst results, reflected by an annual deviation of only 1.51%, improves confidence in the physical consistency of the reported energy performance indicators.

7. Conclusions

This study evaluated the energy performance, techno-economic feasibility, and environmental impact of a grid-connected photovoltaic canopy system implemented for urban irrigation in a hot-arid climate using both detailed PVsyst simulation and an independent simplified analytical cross-check model. Based on a real public garden case in Baghdad, the system demonstrates high annual energy productivity, with 133 189 kWh per year of electricity generation, a specific yield of 1 577 kWh/kWp per year, and a performance ratio of 79.6%.

The irrigation load, accounting for only 1.6% of total PV production, is fully supplied by solar electricity, while the majority of generated energy is exported to the national grid. Economic analysis confirms the competitiveness of the system, with a levelised cost of electricity of 44 IQD/kWh (≈ 0.034 USD/kWh), a payback period of approximately 6 years, and an internal rate of return of about 18%. Environmentally, the system achieves an estimated annual reduction of approximately 113 tonnes of CO_2, primarily through diesel fuel displacement and grid support.

The close agreement between the software-based simulation and the independent analytical estimation enhances confidence in the reported results and improves the methodological transparency of the study. In particular, the annual deviation between the PVsyst prediction and the simplified analytical model was limited to 1.51%, confirming acceptable agreement between the two approaches for validation purposes. Overall, the findings demonstrate that PV canopy systems represent a technically reliable, economically viable, and environmentally effective solution for integrating renewable energy into urban green infrastructure. Beyond irrigation, such systems provide a scalable model for multifunctional solar deployment in hot-arid cities, supporting sustainable urban development and long-term decarbonisation strategies.

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