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A Comparative Study of the Techno-Economic Feasibility of Grid and Hybrid Solar Energy Systems Versus the Government Electricity Tariff in Duhok, Kurdistan Region

Semyan Omed Alyousifi[a,*], Mahir Ismael Ahmed[b]

[a]*Department of Mechanic and Solar Energy, Duhok Technical Institute, Duhok Polytechnic University, Duhok, Iraq*
[b]*Department of Energy Engineering, Technical College of Engineering, Duhok Polytechnic University, Duhok, Iraq*

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A B S T R A C T

A techno-economic assessment of distributed photovoltaic (PV) systems in Duhok, Kurdistan Region, was conducted under the newly implemented Government Electricity (Runakî) tariff using a 15-year discounted cash-flow (DCF) framework with a 10% real discount rate. On-grid and hybrid (PV + battery) configurations were evaluated using levelized cost of electricity (LCOE), net present value (NPV), and payback period indicators. Solar resource data from NASA POWER assumed a baseline performance ratio of 0.80, while hybrid systems accounted for battery round-trip efficiency losses ($\eta = 0.85$). Discounted LCOE values were 0.041 USD/kWh for on-grid PV and 0.1066 USD/kWh for hybrid systems. On-grid systems yielded positive NPVs and short payback periods across industrial and commercial sectors, while hybrid systems became economically viable primarily at high residential demand levels or when enhanced reliability and energy autonomy are prioritized. Sensitivity analysis identified capital expenditure and PV performance (PR/PVOUT) as dominant economic drivers, followed by discount rate and operation and maintenance costs. Overall, the results indicate that on-grid PV systems can economically complement the Government Electricity program under the Runakî tariff, whereas hybrid systems are justified where storage-based resilience, supply security, or diesel displacement provides additional value beyond cost minimization.

*Corresponding Author Email:semyan.omed@dpu.edu.krd

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1. Introduction

The Kurdistan Region of Iraq is currently undergoing a major electricity sector reform through the Government Electricity (Runakî) program, which aims to modernize metering, restructure tariffs, and expand 24-hour power availability across the region. Recent official releases indicate that millions of customers have already been served under this framework, with full regional deployment expected by 2026 (GOV.KRD) [1] . In this context, Duhok represents a strategic case for assessing the economic viability of distributed photovoltaic (PV) systems as an alternative or complementary supply option to grid electricity.

The region exhibits strong solar resource potential typical of Upper Mesopotamia. In the present study, solar irradiation is characterized using long-term NASA POWER satellite datasets, and a practical yield assumption of approximately 6 sun-hours/day is applied, coupled with a baseline performance ratio (PR) of 0.80, which aligns with previously validated regional PV assessments Atlas [2] NASA Langley Research Center [3] For hybrid PV configurations, energy delivery losses during storage and night usage are incorporated through an explicit battery round-trip efficiency (η = 0.85), consistent with conservative values reported by National Renewable Energy Laboratory- NREL [4].

Prior literature confirms a growing interest in techno-economic analyses of PV and hybrid systems in Iraq and the broader MENA region. A recent study examined a solar/wind multi-generation plant with hydrogen and ammonia pathways, emphasizing the need for realistic modeling of storage efficiency, degradation, and operating conditions Hashemian and Noorpoor [5]. Complementary thermal investigations comparing polycarbonate and glass covers for solar collectors demonstrated how optical and thermal losses directly affect system efficiency under high-irradiance conditions Chinnappan et al. [6]. Rooftop hybrid systems have been examined in several studies for both residential and institutional users, with results indicating that they can be economically feasible under local climate conditions and tariff structures, as noted by Falih et al. [7]. Other work has shown that on-grid PV systems generally perform better than off-grid alternatives in educational buildings when evaluated using HOMER Pro. In addition, ground-based irradiance measurements for Duhok have been reported by Kabao and Omar [8] helping confirm the accuracy of local solar resource estimates used in performance calculations. Utility-scale PV feasibility under Iraqi climatic and grid conditions has also been quantified, highlighting competitive LCOE and measurable CO_2 reductions Al-Mamory et al. [9] Alomar et al. [10]. Further analyses have examined techno-financial performance of hybrid renewable plants Qasim et al. [11], night-load dispatch using storage S. Ahmed and F. Ameen [12], and the influence of tariffs on grid-connected PV economics Ali Saleh et al. [13] Mohammad et al. [14]. Similar LCOE sensitivity trends driven by PR, CapEx, and discount rates have been reported regionally Ayed et al. [15] Ayadi et al. [16]. Net-metering viability in Iraq has also been linked to sectoral tariff break-even points, echoing the threshold-based approach adopted in the present study Hunehen et al. [17]. A consolidated policy and economic assessment for solar adoption in the Kurdistan Region further supports the strategic relevance of PV deployment in this context Vaziri [18].

1.1 Research gap and innovation

While extensive literature exists on the techno-economic feasibility of photovoltaic (PV) systems in the Middle East and Iraq, a critical research gap remains regarding the applicability of these analyses under the newly implemented Government Electricity (Runakî) tariff in the Kurdistan Region. This gap has become increasingly significant due to recent structural changes in electricity pricing that directly affect investment decisions for distributed PV systems.

First, most previous feasibility studies were conducted under older fixed or uniform tariff schemes that no longer reflect the current regulatory environment. The new Runakî tariff introduces differentiated block rates across residential, commercial, and industrial sectors, fundamentally altering the economic performance of both on-grid and hybrid PV systems. To date, no published studies have quantified the impact of these revised tariff blocks on key economic indicators such as break-even points, payback periods, and net present value (NPV).

Second, existing regional studies commonly rely on generalized financial frameworks that do not adequately capture sector-specific electricity consumption patterns or tariff escalation pathways. In practice, electricity demand profiles differ substantially between households, commercial facilities, and industrial users. This study addresses this limitation by conducting sector-specific comparisons that directly link actual demand profiles with the Government Electricity tariff structure.

Third, many available analyses do not employ a unified techno-economic framework that simultaneously incorporates practical system losses and long-term financial realism. In particular, performance ratio effects, battery round-trip efficiency losses, and realistic discount rates are often treated separately or omitted altogether. This work integrates these factors into a harmonized techno-economic model applied consistently over a standardized project lifetime.

The originality of this study is reflected in four main contributions. First, it presents the first comparative techno-economic evaluation of on-grid and hybrid PV systems explicitly under the new Runakî tariff in the Kurdistan Region of Iraq. Second, it establishes sector-specific break-even thresholds, defined in terms of both tariff rates and electricity consumption levels, providing clear decision boundaries for consumers and policymakers. Third, the research adopts a standardized 15-year discounted cash-flow (DCF) framework with consistent assumptions across all system configurations and sectors, enabling direct and transparent comparison. Fourth, a comprehensive sensitivity analysis is performed to identify the dominant economic drivers under the new tariff regime, including capital expenditure, performance ratio, discount rate, photovoltaic output, operation and maintenance costs, tariff escalation, and battery round-trip efficiency.

To address these research gaps and provide timely guidance to households, commercial entities, and policymakers, this study delivers the first integrated techno-economic and environmental assessment of distributed PV systems operating under the Government Electricity (Runakî) tariff in Duhok, Kurdistan Region. Using a harmonized DCF-based methodology, the analysis compares on-grid and hybrid PV configurations against sectoral tariff structures, identifies break-even decision thresholds, evaluates model robustness through two-way sensitivity analysis, and estimates cumulative CO_2 emissions reductions over a 15-year project lifetime while accounting for uncertainty in grid emission factors.

2. Materials and Methods

A harmonized techno-economic framework was employed to compare on-grid and hybrid photovoltaic (PV + battery) systems under the Government Electricity (Runakî) tariff in Duhok. The analysis was performed over a 15-year project lifetime using a real discount rate of 10%. All performance, cost, and tariff variables were parameterized using publicly available datasets, published literature, and validated engineering assumptions.

2.1 Solar Resource and Energy Yield Estimation

Long-term solar irradiance data were obtained from the NASA POWER database for the period 1999–2023. Monthly global horizontal irradiation (GHI) and PV power output (PVOUT, kWh/kWp·month) were used to characterize the solar resource. A baseline performance ratio (PR = 0.80) was adopted in accordance with regional PV assessments and IEC International Electrotechnical Commission [19]. The monthly energy yield for the on-grid configuration was computed using the standard irradiance-to-energy conversion structure provided by the Langley Research Center NASA [٢٠]. The formulation for estimating monthly and annual PV energy output follows the classical photovoltaic performance modeling framework described by Duffie and Beckman [21] as well as the NREL System Advisor Model (SAM) National Renewable Energy Laboratory [22] ensuring accurate temperature, irradiance, and loss-pathway representation for Duhok's climatic conditions.

$$E_{PV} = PV_{rated} \times PVOUT \quad (1)$$

Hybrid systems incorporated storage losses through battery round-trip efficiency Lavey et al. [23]:

$$E_{hybrid} = E_{PV} \times \eta_{battery} \quad (2)$$

Where $\eta_{\text{battery}} = 0.85$

2.2 Load Characterization and Tariff Structure

Electricity consumption was evaluated according to sector-specific Government Electricity tariff slabs (residential, commercial, industrial). For each sector, monthly demand D_m and tariff p_m were used to derive the reference cost of grid consumption International Energy Agency [24] World Bank[٢٥] :

$$C_{grid} = \sum_{m=1}^{12} D_m \times p_m \quad (3)$$

Break-even consumption thresholds (m^*) were later identified where PV NPV equals zero.

2.3 System Configurations

Two system configurations were modeled

1. On-grid PV**:** No storage; all generated energy directly offsets grid consumption.

2. Hybrid PV + Battery**:** Batteries sized to meet a fraction of nighttime demand, with losses captured through round-trip efficiency. Battery depth of discharge (DoD = 0.8), cycle life, and usable capacity were incorporated in sizing.

The total capital expenditure (CapEx) included PV modules, inverters, mounting structures, wiring, and battery units (for hybrid). Operation and maintenance (O&M) costs were modeled as an annual percentage of CapEx Lavey et al. [23], IEA Photovoltaic Power Systems Programme [26].

2.4 Economic Analysis

A discounted cash-flow (DCF) framework was employed to evaluate the techno-economic performance of the on-grid and hybrid PV systems. The analysis included computation of the

- Levelized Cost of Electricity (LCOE)
- Net Present Value (NPV)
- Simple Payback Period (SPP).

The discounted present value of annual cash flows was calculated using the standard financial formulation defined in corporate finance literature The present value of annual costs over the 15-year project lifetime was computed as Ross et al. [27]:

$$PV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \qquad (4)$$

where C_t is the annual cost in year t, r is the real discount rate, and n =15 years, r = 0.10 (10%) is the real discount rate. The LCOE was obtained by dividing the discounted cost stream by the discounted energy output following National Renewable Energy Laboratory (NREL) [28] IEA Photovoltaic Power Systems Programme [29]. The LCOE was obtained from:

$$LCOE = \frac{PV_{energy}}{PV_{cost}} \qquad (5)$$

NPV relative to the reference grid cost was calculated as Ross et al. [27]:

$$NPV = PV_{avoided} - PV_{cost} \qquad (6)$$

Break-even tariff (p^*) and consumption (m^*) thresholds were identified numerically by solving:

$$NPV(p^*, m^*) = 0 \qquad (7)$$

2.5 Environmental Assessment

CO_2 emissions avoided by PV generation were estimated using the grid emission factor Eggleston H.S. et al. [30,International Energy Agency [31]:

$$CO2_{saved} = E_{PV} \times EF \qquad (8)$$

A ±20% uncertainty band for the emission factor (EF) was considered to reflect variability in Iraq's thermal-generation mix. Cumulative 15-year CO_2 reduction was computed using discounted energy yield.

2.6 Sensitivity Analysis

Two-way sensitivity tests were performed for:

- CapEx × PR
- Discount rate × tariff escalation
- Battery efficiency × hybrid LCOE

Each parameter was varied ±20% around its baseline value to evaluate model robustness and identify dominant economic drivers.

3. Results and Discussion

3.1 Solar Resource Results

Long-term solar resource characteristics for Duhok were evaluated using NASA POWER satellite derived datasets. The region demonstrates strong potential for photovoltaic generation, although seasonal variability is pronounced. Figure 1 provides a spatial overview of solar resources across Iraq, showing that the Kurdistan Region exhibits moderate-to-high PV power potential compared with the western and southern parts of the country. Although Duhok's solar radiation values are relatively lower compared with other regions in Iraq, PVOUT data obtained from Solargis [32], show that the region still receives enough sunlight to support stable distributed PV system.

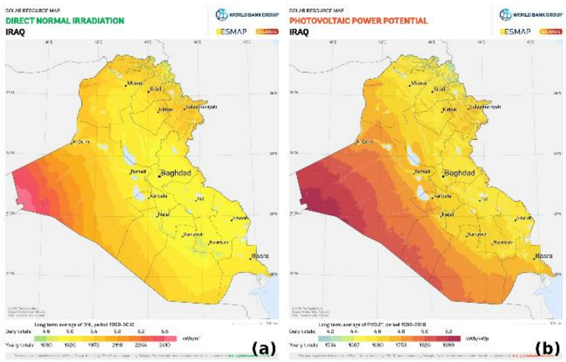

Figure 1. Long-term solar resource conditions in Iraq. Demonstrations of (a) average direct normal irradiation (DNI), and (b) average photovoltaic power potential (PVOUT, kWh/kWp) for the period 1999–2018. Source: Solargis [32]

Figure 2 shows the geographical location of Duhok (36.8632° N, 42.9885° E), which lies within the northern Upper Mesopotamia (northern Iraq) climatic zone. This location is characterized by clear-sky summer months and cooler winters, resulting in distinct variations in monthly irradiation profiles.

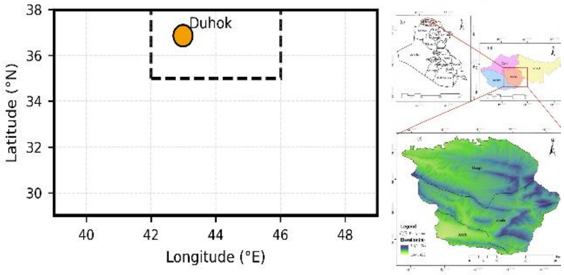

Figure 1. Study area: Duhok, Kurdistan Region (northern Iraq), with a locator map and administrative boundaries

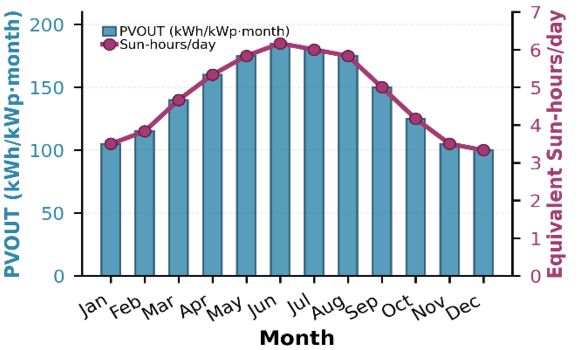

Figure 3. Monthly solar resource profile for Duhok Monthly PVOUT (kWh/kWp·month) and equivalent sun-hours/day derived from NASA-POWER (2025) and World Bank (2024). The profile shows strong seasonal variation with peak output during June–July and minimum values in December–January using a baseline performance ratio PR = 0.80 and optimal fixed tilt

.

The monthly PVOUT values were derived from NASA POWER satellite-based solar irradiance data for northern Iraq (Duhok) combined with Global Solar Atlas guidance on PV power potential NASA Langley Research Center [3] World Bank [33] , is illustrated in Figure 3. The equivalent sun hours range from approximately 4.0–4.5 hours/day during December–January to 7.5–8.0 hours/day in June–July. Corresponding PVOUT values vary from around 95–110 kWh/kWp-month in winter to 170–185 kWh/kWp-month in summer. These seasonal shifts reflect regional atmospheric patterns, including temperature fluctuations, dust concentration, and humidity.

A baseline performance ratio of PR = 0.80 was applied, consistent with IEC 61724-1 guidelines International Electrotechnical Commission [19] .

Overall, the results confirm that Duhok receives an annual average of approximately 6.0 sun hours/day, making it well-suited for on-grid PV deployment and providing a strong foundation for the subsequent techno-economic evaluation. Seasonal changes matter especially for hybrid systems, since the shorter winter days increase reliance on battery storage during nighttime hours.

3.2 System Performance (On-Grid vs Hybrid)

Residential electricity use in Iraq generally peaks during the evening. After sunset, demand increases due to lighting, cooling, and normal household activities. This pattern is reported in national demand studies, including those by the World Bank [34]. For this reason, the hybrid system was modeled by assuming that part of the daily electricity demand occurs at night and is supplied through the battery, while daytime needs are met directly from the PV array. This assumption enables realistic representation of storage-related losses and their impact on system performance.

The performance of the on-grid and hybrid PV systems was evaluated using monthly PVOUT values, a baseline performance ratio of PR = 0.80, a baseline round-trip battery efficiency of 0.85 was adopted for all hybrid PV calculations. In the sensitivity analysis, a wider efficiency range (0.80–0.90) was considered to reflect realistic variability in lithium-battery performance under field conditions, as reported by recent Cole and Karmakar [35] and Rosenfeld et al. [36]. The annual energy yield of the on-grid PV system reached approximately 1,950–2,150 kWh per installed kWp, consistent with previously reported values for northern Iraq.

Strong seasonal variation was observed, with peak generation occurring during June–July and minimum levels during December–January, reflecting the solar resource patterns discussed earlier

Marked seasonal differences were observed, with the highest PV generation occurring in June and July, and the lowest levels during December and January. This pattern follows the solar resource trends described earlier. For the hybrid system, the amount of delivered energy was lower because of battery conversion losses. Under typical residential load patterns, about 25–35% of the yearly PV energy passed through the battery, which led to an overall reduction of roughly 15–18% in usable energy compared with the on-grid system. This reduction was more noticeable in winter, when shorter daylight hours increased reliance on stored electricity. As a result, the hybrid system produced a lower effective energy yield and a higher levelized cost than the on-grid alternative.

Taken together, the performance results show that on-grid PV offers the highest usable output since it avoids battery-related losses. Hybrid systems, while providing nighttime autonomy and greater reliability, experience energy penalties that must be compensated for through tariff savings or resilience needs to remain economically reasonable. These performance patterns form the basis for the techno-economic comparison presented in the next section. Figure 5 provides an overview of the Government Electricity tariff structure, showing the residential block tariff and the fixed per-kWh rates applied to non-residential sectors.

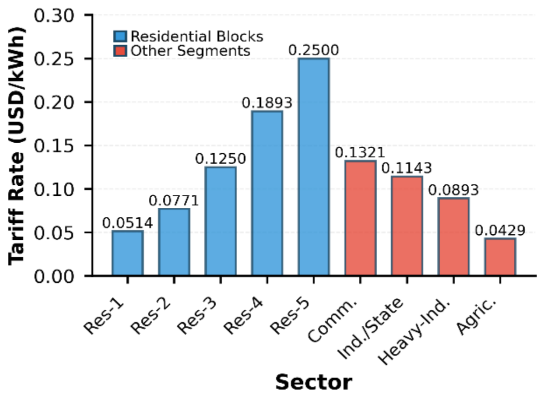

Figure 4. Government Electricity tariff structure showing per-kWh rates by sector. Residential charges are divided into five 400-kWh blocks (Res-1 to Res-5), while other sectors use fixed rates. Exchange rate: 1 USD = 1,400 IQD

3.3 Techno-Economic Results

The techno-economic analysis was carried out using a discounted cash-flow approach over a 15-year lifetime. For both the on-grid and hybrid PV systems, the levelized cost of electricity (LCOE), net present value (NPV), and simple payback period (SPP) were calculated and then compared with the Government Electricity (Runakî) tariff. These indicators provide a practical measure of how cost-effective each system is under the performance conditions and tariff structure found in Duhok. Household electricity costs rise sharply at higher consumption levels because of the increasing block tariff. As shown in Figure 5, residential users reach a point of cost equivalence with the commercial tariff at roughly 1,890 kWh/month. Once consumption exceeds 2,000 kWh/month, the unit price for households increases to 350 IQD/kWh, (≈0.25 USD/kWh), which is noticeably higher than the commercial rate. This behavior explains the steep upper slope of the residential curve and shows why high-demand households face stronger incentives to consider on-grid PV systems. Where Household becoming higher than the commercial tariff of 185 IQD/kWh (≈0.132 USD/kWh). This transition explains the steep upper segment of the residential curve at high consumption levels.

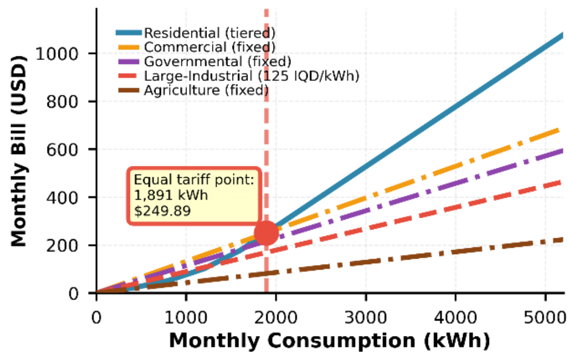

Figure 5. Monthly electricity bill under the Government Electricity tariff for all sectors over the range 0–5,200 kWh/month. Residential service uses an increasing block tariff; other sectors apply fixed per-kWh rates. 1 USD = 1,400 IQD

The on-grid PV system recorded a discounted LCOE of about 0.041 USD/kWh. This low value reflects the absence of storage losses and the relatively strong annual energy yield in Duhok's climate. The hybrid system, however, showed a much higher LCOE of around 0.106–0.108 USD/kWh due to battery-related conversion losses, higher upfront costs, and lower usable output. These results indicate that the on-grid option is the more cost-effective choice under current conditions, unless the user requires significant nighttime supply or additional resilience that justifies the extra cost of storage. Figure 6 compares the discounted LCOE values for both systems with the Government Electricity tariff levels across the main consumer categories in Duhok

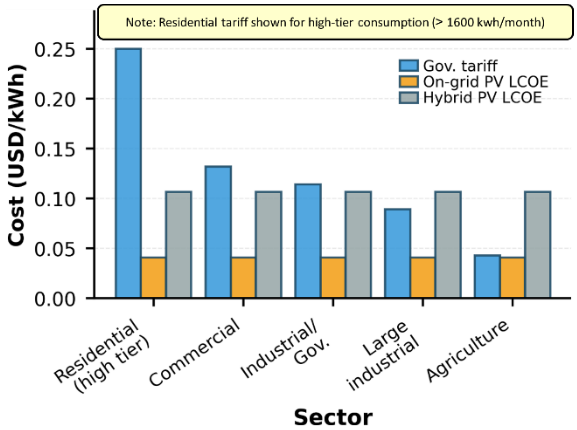

Figure 6. Comparison of Government Electricity tariffs with discounted LCOE for on-grid and hybrid PV systems across representative consumer categories in Duhok (Residential high-tier, Commercial, Industrial/Governmental, Large-industrial, and Agriculture

When compared with the current sectoral tariff structure, on-grid PV produced consistently positive NPVs across commercial and industrial loads, with payback periods ranging from 2 to 6 years, depending on consumption level and tariff bracket. The hybrid configuration delivered negative or marginal NPVs for most residential users under moderate consumption, becoming financially attractive only at higher monthly consumption levels or when frequent nighttime autonomy is required.

A break-even analysis was performed to identify the tariff p^* and consumption threshold m^* at which NPV becomes zero. Results indicate that for residential customers, cost parity with the Government Electricity tariff occurs when monthly consumption exceeds approximately 2000 kWh.

Figure 7 compares the residential monthly electricity bill under the tiered Government Electricity tariff (Runakî) with the levelized monthly cost of on-grid and hybrid PV systems. The government electricity bill increases sharply with rising consumption due to the progressive tariff structure, whereas on-grid PV consistently exhibits the lowest cost across all demand levels. Although hybrid PV systems involve higher costs due to battery investment, they become economically competitive beyond a break-even consumption of approximately 1540 kWh/month, outperforming the government tariff for high-demand users and those prioritizing supply reliability and energy autonomy.

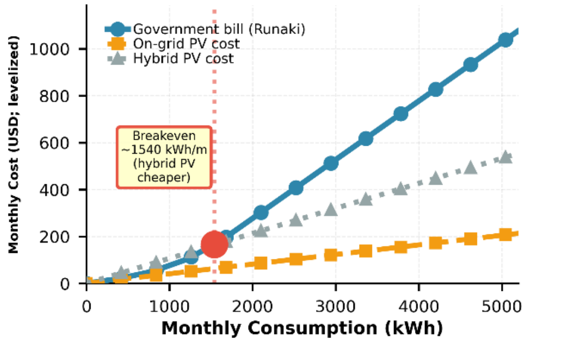

Figure 7. Residential monthly electricity cost under the Government Electricity tariff compared with on-grid PV (LCOE = 0.041 USD/kWh) and hybrid PV (LCOE = 0.1066 USD/kWh)

At higher consumption levels, the on-grid PV system is able to recover its initial investment within about 6–7 years. For smaller residential users, however, grid electricity remains the cheaper option because of the subsidized blocks in the lower tariff ranges. In contrast, commercial and industrial consumers reach break-even much earlier, as their electricity charges start from higher base tariffs.

To demonstrate how the lower levelized cost of on-grid PV translates into actual financial returns, cumulative cash-flow curves were generated for a representative residential load of 2,200 kWh/month. These curves present both discounted and undiscounted savings over the 15-year project lifetime, enabling a direct comparison between on-grid and hybrid PV systems. Figure 8 illustrates the respective payback points and confirms the superior long-term financial performance of the on-grid configuration.

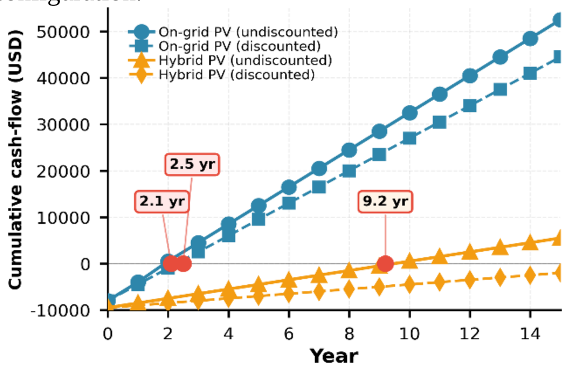

Figure 8. Discounted and undiscounted cash-flow profiles over 15 years for on-grid and hybrid PV systems serving a residential load of 2,200 kWh/month. The on-grid option reaches discounted break-even at about 2.5 years; the hybrid system at about 9.2 years

Overall, the techno-economic results indicate that on-grid PV systems deliver strong financial returns under the current tariff structure. In contrast, hybrid systems become cost-effective mainly in cases of high electricity demand or when they provide additional benefits that compensate for their higher cost. These outcomes are consistent with prior regional analyses and form a basis for the sensitivity evaluation.

3.4 Sensitivity Analysis

A structured sensitivity analysis was conducted to evaluate the robustness of the techno-economic results and to identify the parameters with the greatest influence on LCOE, NPV, and the break-even tariff p^*. The analysis followed standard renewable-energy economic assessment guidelines recommended by the NREL Ramasamy et al. [37] and methodologies of IEA Photovoltaic Power Systems Programme [29], with parameter uncertainty ranges informed by international cost benchmarks IRENA [38] and Sustainable Energy Advantage [39]. Furthermore, the physical basis for PV energy variability including temperature dependence, irradiance response behavior, and system derating was cross-checked using the standard photovoltaic performance formulations of Duffie and Beckman [21] and the performance modelling structure implemented in the National Renewable Energy Laboratory [22]. These sources provide the established relationships for PV-module temperature modelling, POA-to-DC energy conversion, and system derating factors, which justify the selected sensitivity bounds for PR, PVOUT, and temperature-related effects.

3.4.1 One-Way Sensitivity (Tornado Analysis)

Key input parameters were varied around their baseline values using realistic uncertainty ranges derived from regional market data and international benchmarks IRENA [38]:

- Capital cost (CapEx): ±20%
- Performance ratio (PR): ±15%
- Discount rate: 8–12%
- O&M rate: 2–3% of CapEx
- Battery round-trip efficiency (η): 0.80–0.90 (hybrid only)

To identify the parameters that most significantly affect the economic performance of the PV systems, a one-way sensitivity analysis was performed following standard guidelines recommended by IEA-PVPS and NREL. Results showed that capital expenditure (CapEx) and the performance ratio (PR/PVOUT) are the dominant drivers of uncertainty in LCOE, consistent with international PV cost literature IEA Photovoltaic Power Systems Programme [29] Ramasamy et al. [37]. Figure 9 presents the tornado diagram summarizing the percentage impact of each parameter on the baseline LCOE.

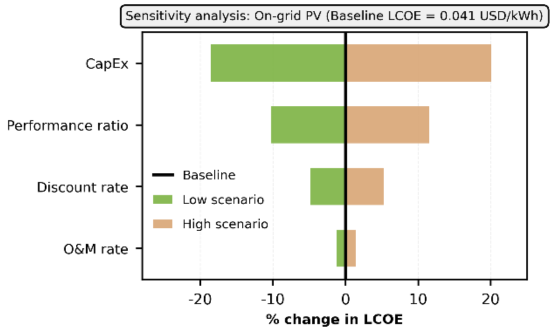

Figure 9. One-way sensitivity -tornado diagram showing the percentage impact of variations in CapEx, performance ratio, discount rate, and O&M rate on the LCOE of the on-grid PV system (baseline LCOE = 0.041 USD/kWh). CapEx and PR represent the dominant uncertainty drivers

A 20% reduction in CapEx decreased LCOE by approximately 17–19%, while a 15% improvement in PR reduced LCOE by 11–14%. Variations in discount rate showed moderate impact, while O&M exerted minimal influence due to its relatively low magnitude.

For the hybrid system, battery efficiency introduced a substantial effect: shifting η from 0.85 to 0.80 increased LCOE by 6–9%, reflecting the compounding impact of storage-related losses on delivered energy Sustainable Energy Advantage [39].

3.4.2 Two-Way Sensitivity (CapEx × PR and Discount × Escalation)

Two-dimensional sensitivity matrices were constructed to capture interaction effects. The CapEx × PR map demonstrated that on-grid LCOE remains below the Government Electricity tariff for most realistic combinations, except under low-PR/high-CapEx conditions IEA Photovoltaic Power Systems Programme [29]. In contrast, hybrid systems require near-optimal PR and low CapEx to achieve parity.

The Discount rate × Tariff escalation map confirmed that on-grid systems maintain positive NPVs even under high discount rates when tariff escalation is zero. Hybrid systems achieve NPV ≥ 0 only when escalation is ≥2% or when η ≥ 0.90.

3.4.3 Threshold Identification (Break-Even Tariff and Consumption)

The break-even tariff p^* satisfying NPV = 0 simplifies to: $p^* = \text{LCOE}$

This result follows directly from standard discounted cash-flow formulation as defined in NREL's LCOE financial modeling framework Sustainable Energy Advantage [39]. Break-even tariff estimates were:

On-grid: $p^* \approx 0.041$ USD/kWh

Hybrid: $p^* \approx 0.1066$ USD/kWh

Consumption thresholds m were derived for the residential tiered tariff. Results showed that households consuming: ≥ 2000 kWh/month achieve payback within 6–7 years for on-grid PV Hybrid systems do not reach parity unless consumption exceeds 3000 kWh/month or battery efficiency improves beyond current market levels.

3.4.4 Interpretation

The sensitivity analysis shows that the economic performance of PV systems in Duhok is mainly influenced by the initial investment cost (CapEx) and the performance ratio (PR). For hybrid systems, the results depend strongly on battery efficiency and the rate of tariff escalation. These patterns are consistent with international assessments of PV system economics and support the validity of the main conclusions reached in this study. Table 1 summarizes the baseline techno-economic performance of the on-grid and hybrid systems, while table 2 presents an overview of the sensitivity analysis outcomes.

Table 1. Baseline techno-economic indicators for on-grid and hybrid PV systems in Duhok (15-year) project life, r = 10%).

Parameter	Sensitivity Range Used	Impact on LCOE (%)	Impact on NPV (%)	Influence Level	Notes
Capital cost (CapEx)	−20% to +20%	On-grid: −19% to +21% Hybrid: −17% to +23%	On-grid: +38% to −42% Hybrid: +32% to −40%	High	Most influential parameter for both systems
Performance ratio (PR)	−15% to +15%	On-grid: −14% to +12% Hybrid: −11% to +13%	On-grid: +25% to −22% Hybrid: +18% to −20%	High	Direct effect on annual energy yield
Discount rate	8% to 12%	On-grid: +6% to −5% Hybrid: +4% to −6%	On-grid: −18% to +15% Hybrid: −14% to +12%	Medium	Stronger effect on NPV than on LCOE
O&M cost	2% to 3% of CapEx	On-grid: +1% to +2% Hybrid: +1% to +2%	On-grid: −3% to −5% Hybrid: −3% to −5%	Low	Minor due to small proportion of costs
Battery round-trip efficiency (η)	0.80 to 0.90	—	Hybrid: +9% to −8% (NPV) Hybrid: +7% to −6% (LCOE)	High (Hybrid only)	Significant due to storage losses
Tariff escalation (g)	0% to 3%	No effect on LCOE	Strong positive effect on NPV, especially hybrid	Medium–High	Raises future savings

Table 2 Summary of one-way sensitivity analysis for the key techno-economic parameters of on-grid and hybrid PV systems

Indicator	On-Grid PV System	Hybrid PV System (PV + Battery)
Annual energy yield (kWh/kWp·year)	1950–2150	1600–1800 (after storage losses)
Baseline LCOE (USD/kWh)	0.041	0.1066
Net Present Value (NPV)	Positive for commercial/industrial sectors; break-even for large residential consumers	Negative under baseline tariff; becomes positive only at high consumption or with tariff escalation ≥ 2%
Simple payback period (years)	2–6 years (commercial/industrial); 6–7 years for residential users consuming ≥ 2000 kWh/month	Not achieved under baseline conditions (payback > project lifetime)
CO_2 reduction (annual)	1.3–1.5 tons CO_2 per kWp	1.1–1.3 tons CO_2 per kWp
15-year cumulative CO_2 reduction	19–22 tons per kWp	16–19 tons per kWp

3.5 Environmental Impact Assessment

Photovoltaic deployment in Duhok provides measurable environmental benefits through avoided grid electricity consumption. The environmental assessment in this study focused on quantifying annual and long-term CO_2 emissions reductions resulting from the operation of the on-grid and hybrid PV systems. Emission abatement was calculated using a regional grid emission factor of 0.55 kg CO_2 /kWh, consistent with values reported for Iraq and neighboring Middle Eastern power systems, with an uncertainty range of ±20% to account for variability in fuel mix and seasonal operation International Energy Agency [31], IRENA [40].

3.5.1 Annual CO_2 Reduction

Annual CO_2 abatement was determined by multiplying the delivered PV energy by the assumed grid emission factor, Intergovernmental Panel on Climate Change [41]. The on-grid system, with an annual yield of approximately 1950–2150 kWh per kWp, achieved an annual reduction of:

$$1.3-1.5\,\textit{tons}\,CO_2\ \textit{per kWp per year}$$

In contrast, the hybrid system, due to storage-related energy losses, delivered a lower effective annual output, resulting in a slightly reduced annual CO_2 reduction of approximately:

$$1.1-1.3\,\textit{tons}\,CO_2\ \textit{per kWp per year}$$

3.5.2 15-Year Cumulative CO_2 Reduction

Over the 15-year project lifetime, cumulative CO_2 reductions were calculated by discounting annual delivered energy according to degradation and multiplying by the grid emission factor. The on-grid configuration achieved:

$$19-22\,\textit{tons}\,CO_2\ \textit{per kWp}$$

The hybrid configuration achieved:

$$16-19\,\textit{tons}\,CO_2\ \textit{per kWp}$$

These results indicate that although hybrid systems contribute significantly to emissions reduction, their performance remains lower than on-grid alternatives due to storage inefficiencies.

3.5.3 Sensitivity of CO_2 Abatement to Emission Factor Variability

Because the emission factor of the Iraqi national grid is not fixed and may vary from year to year, the analysis included a simple test to see how this uncertainty affects the estimated CO_2 reductions. For this purpose, the baseline value of 0.55 kg CO_2 /kWh was adjusted upward and downward by about 20%, giving a range between 0.44 and 0.66 kg CO_2 /kWh. When these alternative values were used the calculated emission reductions changed in a similar proportion. Lower emission factors resulted in smaller savings, while higher factors led to larger reductions. Even with these changes, the comparison between the two systems stayed the same. The on-grid option still produced the larger reduction in emissions because it supplies more usable energy without storage losses. The hybrid system continued to perform well but remained slightly lower in overall abatement. This indicates that the main environmental findings of the study remain valid and are not strongly affected by reasonable shifts in the grid emission factor.

3.5.4 Interpretation and Policy Implications

The environmental assessment shows that distributed photovoltaic systems are capable of reducing CO2 emissions in Duhok, even with conservative assumptions. The grid-tied system achieves the greatest reduction because it provides more usable energy over the project's lifetime. The hybrid system, while affected by storage losses, still offers clear environmental benefits and adds the advantage of improved reliability in areas with unreliable grid supply. To verify the sensitivity of these results to changes in the national grid's emissions coefficient, the analysis was repeated using values 20% higher and lower than the baseline estimate (0.55 kg CO2/kWh). Applying the lower value of 0.44 kg CO2/kWh resulted in a 20% reduction in total avoided emissions. Increasing the coefficient to 0.66 kg CO2/kWh resulted in a similarly higher estimated reduction. Despite this difference, the comparison between the two system types remained unchanged: the grid-tied option consistently achieved a higher reduction. This indicates that the key environmental findings remain stable within the uncertainty range regarding Iraq's projected emission factor.

These results also have political significance. The ability of distributed photovoltaic systems to achieve measurable reductions in CO2 emissions supports the broader objectives of the government's electricity program (Runakî), which seeks to modernize the electricity sector and promote clean energy sources. When the analysis is broken down by consumer category, the greatest long-term environmental gains are observed in the commercial and industrial sectors due to their high electricity consumption.

Figure 10 illustrates both the annual emissions avoided and the cumulative reductions over the system's 15-year lifespan. The figure also includes a ±20% uncertainty range to reflect potential variations in the emission factor.

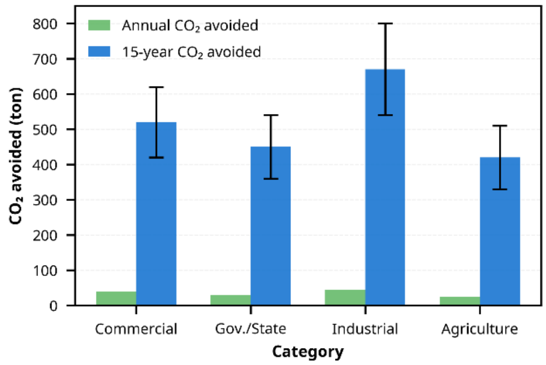

Figure 10. The cumulative and annual CO_2 reductions over 15 years for commercial, governmental, industrial, and agricultural users, including ±20% uncertainty in the grid emission factor

4. Discussion

The results of this study help clarify how on-grid and hybrid photovoltaic systems behave under the Government Electricity (Runakî) tariff used in Duhok. When the numbers are viewed together, the on-grid setup shows a clear advantage because the energy it produces is used directly, without passing through any storage stage. This direct transfer avoids the losses that occur in systems relying on batteries. The monthly solar pattern in the region—particularly the higher output in summer—supports this outcome, as more of the generated power is available during the hours of highest production.

Hybrid systems, by contrast, deliver less usable energy. The reduction is tied mainly to battery round-trip losses, which become more noticeable in warm climates. The assumed efficiency of 0.85, as well as the values tested in the sensitivity analysis, show how strongly storage performance can influence final output. Similar conclusions appear in earlier reports from the NREL- Ramasamy et al. [37] and IEA Photovoltaic Power Systems Programme [29], both of which highlight that storage losses and long-term degradation can weigh heavily on the economics of hybrid configurations.

Other studies help explain these trends. Work by Hashemian and Noorpoor [5], shows how temperature and storage behavior can shift energy delivery in hybrid or multi-generation setups. Likewise, the findings of Chinnappan et al. [6] llustrate how thermal and optical losses influence system performance under strong sunlight. These observations support the temperature-related assumptions used in this study for Duhok's conditions.

The outcomes observed here are also consistent with previous assessments of the region. Earlier analyses by Falih et al. [7], and Kabao and Omar [8], have identified on-grid PV as the more cost-effective option under northern Iraq's climate and tariff structures. Utility-scale studies (e.g., Al-Mamory et al. [9]., Alomar et al. [10]) point in the same direction, reporting competitive LCOE values for grid-connected systems. The behavior of hybrid systems in this study also follows the pattern found by Qasim et al. [11], and Ahmed et al. [42], where hybrid setups become appealing mostly when backup capability or diesel replacement is a priority.

A notable detail emerges when the residential tariff is examined more closely. Because of the steep increase in the upper consumption blocks, a household using around 1,890 kWh per month pays nearly the same unit cost as a commercial user paying a fixed rate. Once residential consumption passes 2,000 kWh/month, the unit price reaches 350 IQD/kWh, making household electricity more expensive than commercial rates. This explains the sharp slope of the upper residential tariff, as shown in Figure 6, and it also shows why high-consumption households have a strong incentive to consider on-grid PV.

Sector-level outcomes follow the same pattern. The discounted LCOE of the on-grid system (0.041 USD/kWh) stays below the effective electricity cost for most commercial and industrial consumers and for larger households. This leads to payback periods in the range of 2–6 years for non-residential users and about 6–7 years for high-consumption homes. The hybrid system, on the other hand, shows a higher LCOE (0.1066 USD/kWh), making it harder to justify economically unless tariffs rise, storage prices fall, or reliability is a major concern. The sensitivity analysis confirms how strongly storage efficiency and capital costs affect the hybrid case, while the on-grid case remains relatively stable.

From an environmental perspective, both systems contribute meaningfully to CO_2 reduction over the project lifetime. On-grid PV avoids roughly 19–22 tons of CO_2 per installed kWp over 15 years. Hybrid systems achieve slightly lower reductions, but they still support regional sustainability goals and offer additional resilience value.

Several limitations should be kept in mind. The analysis assumes stable PR values, fixed tariffs, and constant storage performance, while real projects may experience soiling, shading, tariff changes, or faster battery aging. The use of city-level solar data also means that micro-level variations were not captured. Future studies could explore degradation-based modeling, uncertainty analysis, or optimized storage dispatch. Overall, the evidence suggests that on-grid PV is currently the most favorable distributed-generation option for Duhok from both economic and environmental perspectives. Hybrid systems still have a role—mainly where backup power or autonomy is essential—but their feasibility depends heavily on storage-related factors and the evolution of tariff and cost conditions.

5. Conclusions

This study compared the techno-economic performance of grid-connected and hybrid photovoltaic (PV) systems under the newly implemented Government Electricity (Runakî) tariff in Duhok, Kurdistan Region, using a harmonized 15-year discounted cash-flow (DCF) framework. The results demonstrate that, under current tariff structures and market conditions, grid-connected PV systems provide the most economically attractive solution in most practical scenarios. Their low levelized cost of electricity (US$0.041/kWh) and full utilization of generated energy without storage requirements allow for shorter investment recovery periods, particularly for consumers with medium to high electricity demand.

The analysis further reveals that the progressive structure of the residential electricity tariff plays a decisive role in shaping PV investment outcomes. As household electricity consumption increases, the effective tariff approaches and in some cases exceeds commercial electricity prices, significantly widening the cost gap between grid electricity and PV-generated energy. This dynamic explains why grid-connected PV systems become increasingly favorable for high-consumption households, as break-even thresholds are reached at lower system capacities and shorter payback periods.

Hybrid PV systems remain a technically viable alternative; however, their economic competitiveness is constrained by higher capital costs associated with battery storage and energy losses during charging and discharging processes. Despite this limitation, hybrid systems retain strategic value for users requiring higher reliability, nighttime energy availability, or backup power conditions under which grid-connected systems alone may not satisfy operational needs.

From an environmental perspective, both system configurations contribute to long-term reductions in CO_2 emissions. Grid-connected PV systems achieve the highest cumulative emission savings due to their greater usable energy output over the project lifetime. Although the assessment relies on simplified assumptions such as fixed performance ratios and tariff parameters the results provide a robust and policy-relevant indication of PV system performance as the Runakî tariff continues to expand across the region.

Overall, the findings indicate that grid-connected solar PV currently represents the most suitable and cost-effective option for electricity consumers in Duhok and, more broadly, the Kurdistan Region, while hybrid PV systems are best reserved for applications where energy autonomy and reliability are prioritized over minimum electricity cost. The methodological framework and sector-specific insights developed in this study offer a practical basis for informed household investment decisions, commercial energy planning, and future regional energy policy formulation.

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Nomenclature

$A(r,T)$	Present-worth factor over T years at discount rate r	—
$B(M)$	Total monthly electricity bill for consumption M	USD
$CapEx$	Capital expenditure (initial cost)	USD
Co_{2t}	Avoided CO_2 emissions in year t	kg
C_o	Initial capital outlay (CapEx)	USD
CUM_t	Undiscounted cumulative cash flow at year t	USD
DCF	Discounted cash-flow	—
D_t	Discount factor for year t	—
d	Annual PV degradation rate	%/year
DoD	Depth of discharge (battery)	%
E_t	Annual energy yield at year t	kWh/year
$E_{hybrid,t}$	Adjusted hybrid PV energy considering battery efficiency	kWh/year
EF	Grid emission factor	kg CO_2 /kWh
g	Annual tariff escalation rate	%
H	Average daily solar hours	h/day
η	Battery round-trip efficiency	—
$kWp(DC)$	Installed PV capacity (DC side)	kW□
$LOCE$	Levelized cost of electricity	USD/kWh
M	Monthly electricity consumption	kWh
m^*	Consumption threshold where NPV = 0	kWh/month
NPV	Net present value	USD
$O\,\&\,M$	Operation and maintenance cost (as fraction of CapEx)	%/year
P_t	Electricity tariff in year t	USD/kWh
$P_{eff\,(M)}$	Effective tariff for monthly consumption M	USD/kWh
p^*	Tariff threshold (price at which NPV = 0)	USD/kWh
PB	Simple payback period	years
PR	Performance ratio	—
$PVOUT$	Annual PV energy yield per kWp	kWh/kWp·yr
Q_t	Annual electricity supplied by PV to load	kWh
r	Real discount rate	—
ROI	Return on investment	%
S_{DC}	System size in DC kWp	kWp
Sav_t	Annual savings at year t	USD/year
STC	Standard test conditions	—
T	Project lifetime	years
η_{RTE}	Round-trip efficiency (battery)	—
Φ	Parameter analyzed in sensitivity (LCOE, NPV, etc.)	—

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