

Economic and environmental imperative of solar PV in post-conflict Iraq: A data-driven case study of Anah

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ABSTRACT

This study presents a comparative analysis of solar photovoltaic (PV) systems with battery storage versus diesel generators in Anah, a post-conflict district in western Iraq. Using 30-year of local climate data and observed market electricity tariffs, the study evaluates economic and environmental feasibility over a 25-year project horizon, the analysis employs the Levelized Cost of Energy (LCOE) and life-cycle CO₂ emissions as the key evaluation metrics. The results show a clear economic advantage for solar PV, with an LCOE of \$0.14/kWh, compared to \$0.32/kWh for diesel generators and an estimated prevailing market price exceeding \$0.45/kWh. environmentally, replacing the city's 75 private diesel generators with solar PV systems would reduce an estimated of 25,000 tons of CO₂ annually. The findings establish Solar PV as the superior techno-economic solution for Anah. Thus, it supports a policy shift toward reallocating fossil fuel subsidies toward financial mechanisms designed to overcome the high upfront capital cost of renewable energy systems.

Keywords: sustainable development, post-conflict recovery, energy security, energy economics, levelized cost of energy, solar PV, diesel generator

INTRODUCTION

Reliable and affordable Access to electricity is a cornerstone of socio economic development, as it enables essential services such as health, education, water and local enterprise (Riva et al., 2018; Wahid & Mushref, 2026; Zhang et al., 2019). Despite its importance, hundreds of millions of people around the world do not have this access, particularly in rural or hard to reach areas, and especially in developing countries where extending centralized power grids is often economically or physically feasible (Duran & Sahinyazan, 2020). In such context, decentralized fossil fuel based (typically diesel generators) solutions have served as the primary source of electricity that can be commercially practical in these communities, even though with challenges due to sustainability and cost (Al-Shammari et al., 2021).

Iraq continues to face an electricity crisis accompanied by a gap between supply and demand (in the national grid), high technical and administrative losses, and frequent daily outages. Recent studies have observed economic losses on an annual basis, sometimes beyond \$7–\$20 billion (Al-Fahdawi

& Satam, 2022; Istepanian, 2014; Kadhim, 2024). The effects of this failure are seen most starkly in eremite outposts like the ones serving the Al-Anbar Governorate in western Iraq. Towns like such as Anah, with a population of over 24,000 residents, is located at the 'end of the line' for grid supply and struggle to survive on an expensive network that is largely privately owned diesel generators (Mushref et al., 2022; Sharaa, 2021).

This issue gives rise to the so called "energy trilemma," which manifests as economic hardship in the form of high and volatile energy prices, that increase generator costs to more than \$5 per amp during summer months, consuming a substantial part of average household income. It also contributes to energy insecurity due to frequent mechanical breakdowns and the scarcity of diesel, while environmental and health problems are caused by higher greenhouse gas emissions, as well as noise from generators that run during power outages (Ahmed et al., 2020; Istepanian, 2014; Tahir et al., 2025).

In contrast to its reliance on fossil fuels, the capacity for solar energy in Iraq is not small; annual average solar

irradiation is one of the highest globally (Al-Kayiem & Mohammad, 2019; Keya et al., 2022). This potential resource offers a clear strategic alternative to unsustainable energy systems.

Although numerous global studies have confirmed the techno economic viability of solar PV, most of their models are based on general data and do not consider specific situation in post conflict territories. such areas are characterized by informal energy markets, weak local economies, security related constraints with associated logistical costs and ultra local meteorological characteristics (Hassan, 2025).

This paper addresses this gap by conducting a direct quantitative comparison of solar PV with battery storage and diesel generators based on the conditions of Anah District. The main purposes of this study are:

- (1) To obtain data on and compare annual and life cycle emissions due to the three sources;
- (2) To develop a methodology that can be repeated in another context and used as an input by policymakers in questions of energy independence for RPM-dependent areas, such as Iraq, and similar post conflict regions (Al-Sarraj, 2024; Jalil & Mohammed, 2022).

This study offers a strong rationale, based on clear and easily comparable metrics, for large scale strategic shift in favor of decentralized renewable energy as a core component of sustainable development and energy independence in isolated Iraqi communities.

LITERATURE REVIEW

The world of energy has changed with the steep fall in the price of all renewable technologies, not least among them solar photovoltaics (PV). In the past 10 years, utility scale PV cost has decreased over 85% to become the lowest-cost additional new electricity generation in numerous places around the world (Ghadim et al., 2025; International Renewable Energy Agency [IRENA], 2024; Rana & Jindal, 2025). This narrative is becoming increasingly relevant for off grid and weak grid environments, as decentralized solar emerges as a credible threat to the hegemony of its diesel based predecessor (Wang et al., 2024).

Many investigations have demonstrated the techno-economic superiority of solar based solutions when compared to diesel in different isolated situations. Studies in Sub-Saharan Africa and South Asia have consistently shown that the solar PV systems cost more in terms of CAPEX, but their low/no fuel costs and less O&M contribute to a much lower lifetime cost than the diesel units (Aeggegn et al., 2023; Mulenga et al., 2023; Yimen et al., 2020). Moreover, hybrid solar diesel systems have been successful in significantly reducing fuel use combined with high reliability, thus representing a pragmatic intermediate solution (Yimen et al., 2020).

The MENA region, where the world's best solar resource is to be found, provides a compelling economic proposition for PV. Nonetheless, local studies, including those that have evaluated residential PV systems in Saudi Arabia consistently point to institutional constraints as a key barrier to the spread

of solar energy technologies, especially legacy fossil fuel subsidy policies affecting markets directly— notions that have analogs in Iraq (Abdullayev et al., 2023; Farahat et al., 2024; Maftouh et al., 2022; Ryu & Kim, 2024).

Studies in Iraq have found that western governorates, which also includes Al-Anbar, have high levels of solar irradiance and are suitable for the deployment of solar PV systems. Recent literature has taken the step beyond resource mapping towards sophisticated techno economic analysis, using simulation platforms such as HOMER Pro 32 and MATLAB in order to simulate hybrid renewable systems – often incorporating solar PV, wind, batteries, and occasionally diesel or hydro fields – for rural and urban settings. These analysis show that hybrid systems, especially the combination of PV and battery storage, are financially feasible with either lower or comparative net present costs and levelized energy cost (LEC) as standard diesel based options (Aziz et al., 2019, 2022; Aljaberi et al., 2024).

However, most of the studies in Iraq, are technically robust but reliant on coarse grained climate models (such as satellite databases) and modelled economic parameters rather than observed, hyper local data. For instance, successful models also failed to include inputs from real life, low level market prices for fuel or electricity, which are critical in post conflict shadow economies. Furthermore, studies have either predominately been conducted at a very small scale or they were not located within the specific social economic setting of remote communities that are almost exclusively reliant on private generators. As a result, many studies rely on sweeping estimates that the effect of localized conditions (like varying tariffs from private generators, logistic premiums on capital costs and unique microclimatic trends) is subtracted out, to scope out a wide space for transformative policy relevant research. Developing contexts that have recently experienced civil war provide an especially stark version of this methodological weakness, where generalized models can be inappropriate due to informalized economies and other idiosyncratic barriers.

In developing countries, particularly those that have recently emerged from internal wars, it is evident that economic theories often fail. This is because these countries rely on random selling and bartering in their economies, in addition to the existence of obstacles and special circumstances that make the application of general rules difficult.

This article uses data from the Anah station spanning 30 years, in addition to the monthly prices charged by generator owners, to fill an important gap beyond theoretical expectations and assumptions. This study contributes to preparing an in-depth analysis for decision-makers in the region and officials in areas with similar conditions, enabling them to take clear steps that contribute to strengthening the community.

METHODOLOGY

This study employs a comparative techno economic analysis to evaluate the long term feasibility of a solar PV

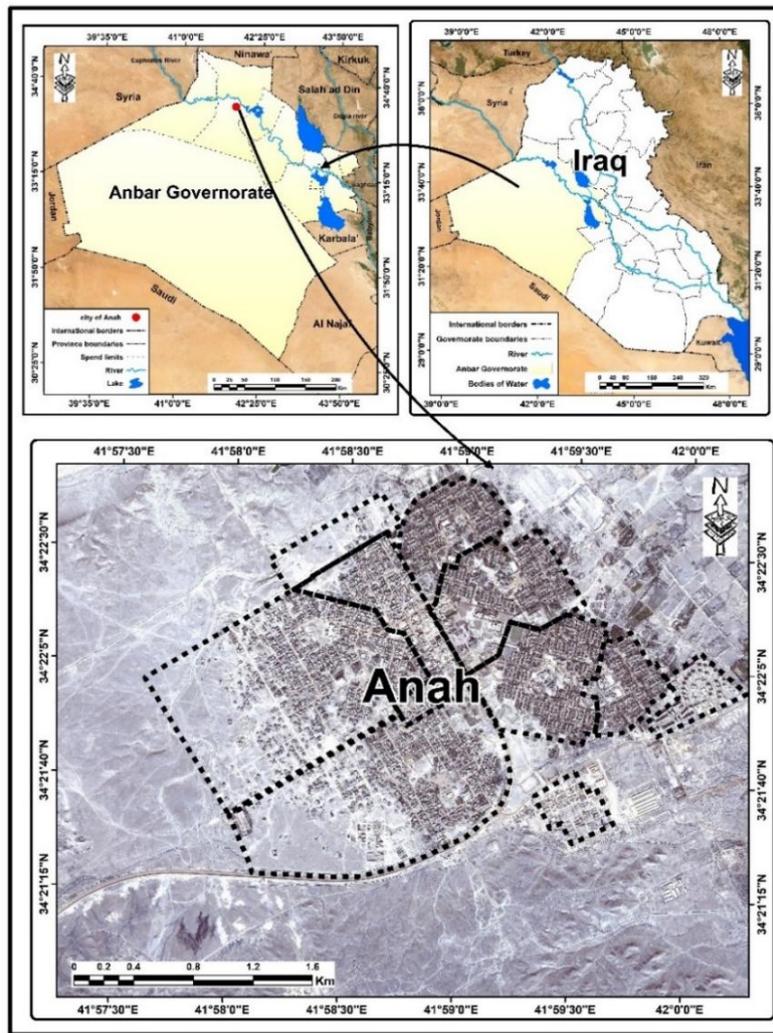


Figure 1. Location of the study area (Source: Authors' own elaboration)

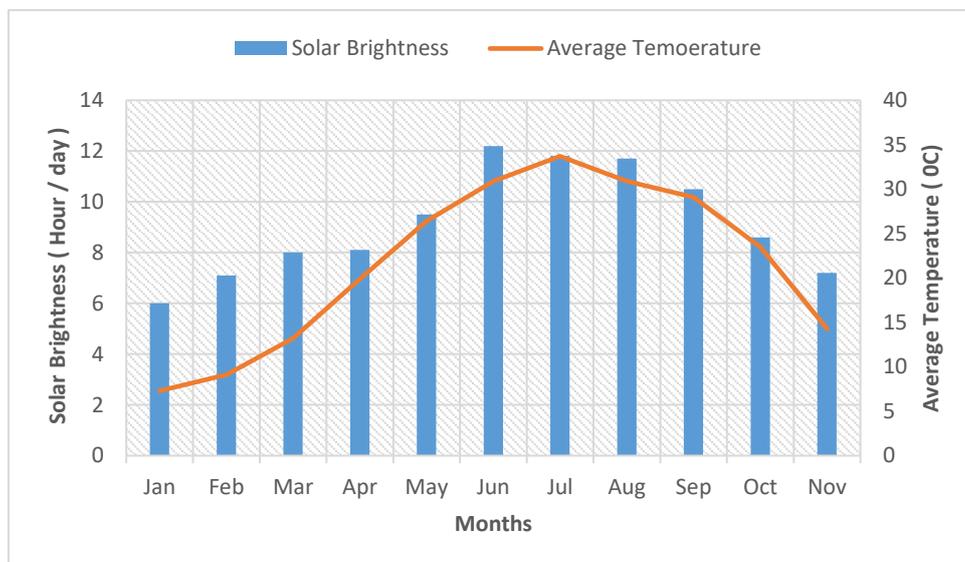


Figure 2. Climograph of Anah Station (1994-2024) (Source: Authors' own elaboration)

system with battery storage against a conventional diesel generator system for a representative load in Anah District.

Study Area and Climate Profile

The Anah District (approximately 34.37°N, 41.98°E), as shown in Figure 1, is characterized by an arid desert climate

(BWh, according to the Köppen classification). This study's analysis is grounded in a detailed, 30-year meteorological dataset (1994-2024) from the Anah climate station, as shown in Figure 2 and Table 1.

Table 1. Summary of key climatic characteristics for Anah station (1994-2024)

Climatic parameter	Annual average	Peak summer (Jun-Aug) avg.	Winter (Dec-Feb) avg.
Average temperature (°C)	20.5	31.8	8.3
Average max temperature (°C)	27.7	39.7	14.3
Actual sunshine hours (hr/day)	8.87	11.9	6.3
Dust storms (days/month)	0.2	0.4	0.1

Given the conditions that the region experienced during previous periods, satellite data (NASA POWER database), where the researchers used and compared with the records available at the study area station to ensure the accuracy of the information and data used during the periods when the station was out of service.

The data are evidence of the extraordinary solar resource for this area; its annual average 8.87 h/day of actual sunshine hours, reaching 12.2 July hours per day in June. Climate is characterized by very hot summers, where the average monthly temperature reaches as high as 33.7°C in July and the average maximum daily temperatures are above 40°C are important facts considered in performance modeling of PV system. Data also shows that the dust storms are a known environmental factor of relatively low frequency (monthly average 0.2 times).

System Configurations

To ensure a fair comparison, both systems are sized to meet the electricity demand of a typical rural household or small enterprise, estimated at an average of 20 kWh/day, assuming a typical residential load profile with consumption peaks in the morning and evening hours (Al-Mosawy et al., 2021; Al Sharaa, 2021; Aziz et al., 2019; Hafedh, 2021; IRENA, 2025; The World Bank Group, 2025). A 25-year project lifetime is used for the analysis.

System 1: Diesel generator (DG) system

- A standard 10 kW diesel generator is selected. This size is standard for powering a large home or small business, allowing for the handling of peak loads.
- The model assumes the generator is replaced every 10 years (i.e., two replacements over the project life) (Mohammed et al., 2021; Thango & Obokoh, 2024). This lifespan reflects a heavy duty operational cycle with regular major overhauls, which are financially accounted for in the model's conservative O&M allocation (set at 10% of CAPEX annually).

System 2: Solar PV with battery storage system

This is a standalone system designed for 24/7 reliability, consisting of:

- A 5 kWp solar PV array.
- A 25 kWh Lithium-ion (Li-ion) battery bank provides sufficient autonomy for night time use and overcast days.
- A hybrid inverter and other Balance of System (BOS) components.
- Assumptions include one battery replacement at year 12 and one inverter replacement at year 13 (Almadhhachi et al., 2022; Kassem et al., 2024). This schedule accounts for the accelerated degradation of

Li-ion batteries in high temperature arid climates typical of western Iraq (Jalil & Mohammed, 2022; Mohammed et al., 2021; Satam et al., 2025). The PV panels have a 25-year lifespan (IRENA, 2025).

The sizing of the components was determined based on a review of recent literature and best practices for similar off grid systems in Iraq and comparable regions (Aziz et al., 2022; Mohammed et al., 2021). This strategy makes sure that the selected sizes are matched with the existing standards of reliability and performance.

Note on Hybrid Systems: While hybrid PV diesel configurations are common in off grid literature, this study deliberately focuses on a standalone solar PV system to evaluate the feasibility of complete decoupling from the fossil fuel supply chain. In post conflict zones like Anah, dependency on fuel logistics regardless of the quantity remains a critical vulnerability due to security risks and market volatility. Therefore, the "Solar Only" scenario is selected to assess the viability of a fully resilient, fuel independent energy security model.

Economic Analysis: Levelized Cost of Energy (LCOE)

The economic comparison is done by LCOE. It represents the average revenue per unit of electricity, which required to recover the costs of building, operating, and generating plant during an financial life. It is calculated using the standard NREL formula (IRENA, 2025; Kosmadakis & Elmasides, 2021; Nahui-Ortiz et al., 2021; Salcido et al., 2024):

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (1)$$

where:

I_t = Investment expenditures in the year t

M_t = Operations and maintenance (O&M) expenditures in the year t

F_t = Fuel expenditures in the year t (zero for solar PV)

E_t = Electricity generation in the year t

r = Discount rate (assumed at 8%)

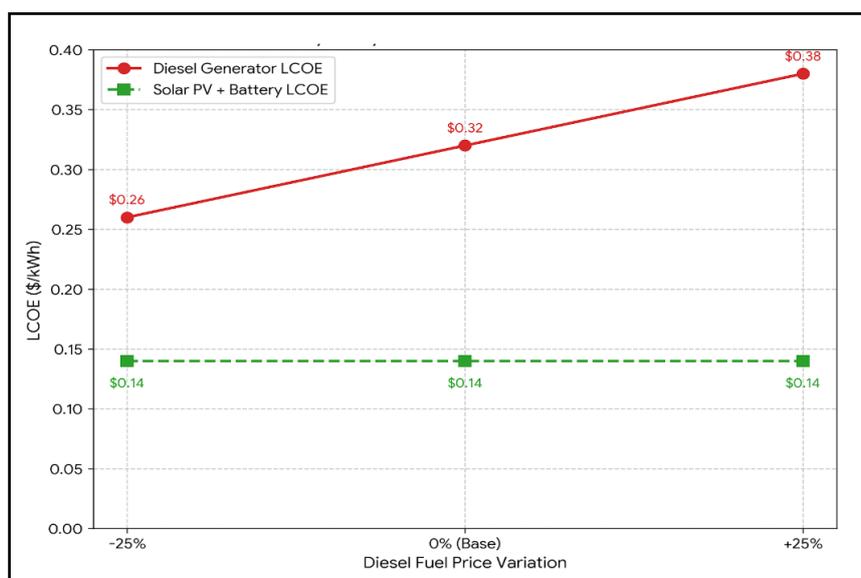
n = Life of the system (25 years)

The key financial and technical assumptions used for the LCOE calculation are detailed in **Table 2**. These figures are synthesized from recent IRENA reports (IRENA, 2025) regional market analysis, and local data where available, with a conservative approach to account for logistical costs in a remote area.

In addition to the typical LCOE comparison approach (which is a modelled lifecycle cost), this paper introduces an alternative, Direct Market Price Analysis. For Anah, an effective price per kWh is calculated here applying the actual

Table 2. Key assumptions for LCOE calculation

Parameter	Solar PV system	Diesel generator system	Source
Capital costs (CAPEX)			
PV array (5 kWp)	\$4,500 (\$900/kWp)	-	IRENA, 2025
Battery bank (25 kWh)	\$6,250 (\$250/kWh)	-	Salcido et al., 2024
Inverter & BOS	\$1,500	-	Philipps et al., 2025
Total initial CAPEX	\$12,250	\$4,000 (\$400/kW)	Lazard, 2025
Replacements			
Battery (at year 12)	\$4,500	-	Lazard, 2025
Inverter (at year 13)	\$1,200	-	Lazard, 2025
Generator (at years 10, 20)	-	\$4,000 x 2 = \$8,000	Lazard, 2025
Operational costs (O&M)			
Annual O&M	\$120 (1% of initial CAPEX)	\$400 (10% of initial CAPEX)	IRENA, 2025
Fuel costs			
Fuel price	-	\$0.75/liter	Global Petrol Prices, 2025
Fuel consumption	-	0.4 liters/kWh	Djelailia et al., 2019
System parameters			
Annual generation	7,300 kWh	7,300 kWh	International Energy Agency, 2022; IRENA, 2025
Project lifetime	25 years	25 years	International Energy Agency, 2022
Discount rate	8%	8%	International Energy Agency, 2022

**Figure 3.** Sensitivity analysis of LCOE regarding diesel price fluctuations compared to the stable cost of solar PV (Source: Authors' own elaboration)

monthly tariffs per ampere charged by 75 private generator owners in Anah's neighborhoods for the years 2024–2025 (as a secondary analysis).

This tariff information was captured in the field survey of generator operators cross referenced with informal household electricity receipts over the period. This indicator is a real-world benchmark of the actual economic burden in households and complements LCOE findings.

The key financial and technical assumptions used for the LCOE calculation for both systems are detailed in **Table 2**.

Sensitivity Analysis

The sensitivity test was performed to confirm the stability of the economic findings against fluctuation of market conditions. This study assesses the sensitivity of LCOE to variations in critical input factors for solar PV as well as for DG systems. Two important but highly uncertain parameters in the case of Iraq were chosen:

- **Price of Diesel:** The LCOE for the diesel system was recycled based on a $\pm 25\%$ deviation from the original fuel price of \$0.75 per liter.
- **Solar Battery Capital Cost (CAPEX):** For the LCOE estimation for the solar PV system, a $\pm 20\%$ change in the initial battery bank cost was considered to reflect global trends of decreasing price of batteries. The purpose of choosing varying percentages of 25% is to take into account the reality of the Iraqi market, which is experiencing a state of fluctuation influenced by market changes and government support (Istepanian, 2014). As for batteries, the decrease was taken into account in line with the global trend indicating that they become cheaper over time and with the development of the industry (IRENA, 2025).

As illustrated in **Figure 3**, the solar PV system remains the most economic option even if diesel prices drop significantly.

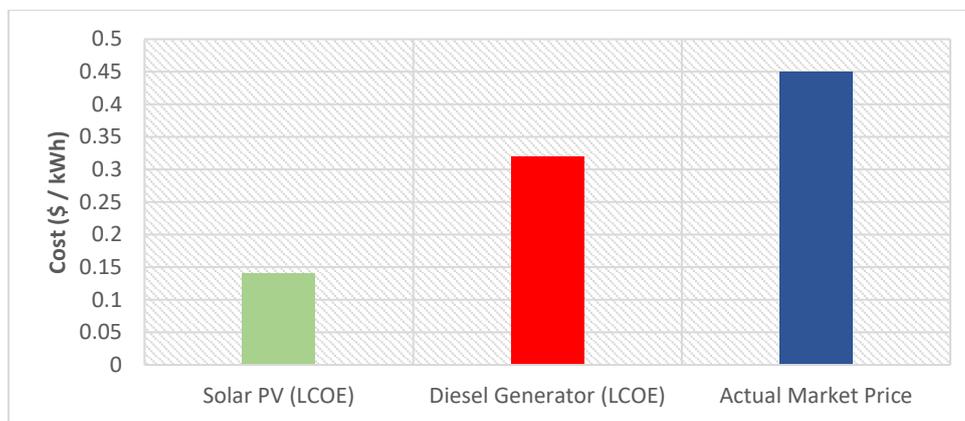


Figure 4. LCOE comparison of solar PV and diesel vs. actual market price of generator electricity in Anah (\$/kWh) (Source: Authors' own elaboration)

For the economic instability in post conflict Iraq, the sensitivity of the LCOE to the discount rate was also examined. Increasing the discount rate from 8% to 12%, to account for higher investment risk, raises the solar PV LCOE to approximately \$0.19/kWh. However, this remains well below the diesel LCOE (\$0.32/kWh), confirming that the project's feasibility is not compromised by higher financing costs.

Environmental Analysis

The environmental comparison focuses on CO₂ emissions, the primary greenhouse gas. The analysis calculates the annual emissions from each system.

- **Solar PV System:** Operational emissions are zero. Lifecycle emissions from manufacturing, transportation, and decommissioning are acknowledged but excluded from the direct operational comparison, as they are globally standardized (typically 40–60 gCO₂/kWh) and an order of magnitude lower than those from fossil fuels (Regional Environmental Center, Turkey, 2014).
- **Diesel Generator System:** Emissions are calculated based on fuel consumption. A standard emission factor for small scale diesel generators, sourced from the UNFCCC/CDM, of approximately 800 g CO₂/kWh is used. This aspect gives the less efficiency and less strict emission limits of smaller generators as opposed to large power plants (Esobinenwu, 2023; Ogunjuyigbe et al., 2016).

The environmental comparison analyses co2 emission in two dimensions:

- (1) A micro analysis at the household level where annual emission is analyzed in one exemplary system, and
- (2) A macro estimate on a city scale. The macro level analysis was designed to project the full year CO₂ emissions from all private generators (n = 75) in Anah, per the city's total energy demand approximated by its population (24,394).

Although this analysis estimates CO₂ emissions as the dominant greenhouse gas, it is important to emphasize that diesel burning in generators is associated with substantial local air pollution including nitrogen oxide (NO_x), sulfur oxide (SO_x) and particulate matter emission (PM2.5) (Esobinenwu,

Table 3. Summary of private generator electricity tariffs in Anah (2024-2025). Value (USD per Ampere)

Description	Period	Price (USD/Ampere)
Peak summer price	(Jun-Aug)	\$5.04
Lowest spring price	(Mar-Apr)	\$1.44
Annual average	Average cost over the year	\$3.02

Source: Calculated from local generator tariff data

2023; Shakya et al., 2022). The reduction of those pollutants caused by switching to solar PV would result in very large ancillary benefits on public health through improvement of local air quality an effect that was beyond the scope of this research but which has been widely highlighted by the World Health Organization.

RESULTS

The results of the techno economic and environmental analyses, based on the assumptions outlined in the methodology, are presented below.

Economic Feasibility: LCOE Comparison

The LCOE estimation based on the project's life time of 25 years demonstrates a strong economic leeway for the solar PV system. As shown in **Figure 4**, the LCOE of a solar PV system is estimated at \$0.14/kWh. Approximately double that of the solar option is the LCOE of \$0.32/kWh for diesel supplied electricity generation system.

To put these results into perspective in the local context, we performed a direct market price analysis applying prevailing 2024–2025 private generator owners' tariffs charged in Anah. As summarized in **Table 3**, there is a substantial financial impact on residents averaging more than \$5.00 per ampere during summer, and the cost burden is high. This would come to an effective electricity cost of more than \$0.45/kWh on high summer demand days. This comparison likens the actual cost of a solar system to approximately one half of what it would take for a diesel generator over its prolonged life expectancy, and also between 2 up to more than 3 times cheaper compared to those much higher real world

Table 4. Comparison of CO₂ emissions

Indicator	Solar PV system	Diesel generator system
Emission factor	0 g CO ₂ /kWh	800 g CO ₂ /kWh
Annual electricity generation	7,300 kWh	7,300 kWh
Annual CO ₂ emissions	0 kg	5,840 kg (5.84 tons)
Total lifetime CO ₂ emissions (25 years)	0 kg	146,000 kg (146 tons)

costs at which residents are currently purchasing unreliable grid substitutes.

Sensitivity Analysis

The sensitivity analysis confirms the robustness of the solar PV system's economic advantage against market volatility.

- **Impact of Diesel Fuel Price:** The economic viability of the diesel generator is highly sensitive to fuel costs. A 25% increase in the diesel price (to \$0.94/liter) would raise its LCOE to \$0.38/kWh, further widening the gap with solar PV. Conversely, a 25% decrease would lower the LCOE to \$0.26/kWh, which remains significantly higher than the solar LCOE.
- **Impact of Battery Capital Cost:** The solar PV system's LCOE shows resilience to fluctuations in battery prices. A 20% increase in the initial battery CAPEX would raise the system's LCOE modestly to \$0.16/kWh. More importantly, a projected 20% decrease in battery costs, in line with global trends, would lower the LCOE to an even more competitive \$0.12/kWh.

Environmental Feasibility: Emissions Comparison

For the purpose of comparing the two systems, **Table 4** highlights the key differences. Photovoltaic solar panels are characterized by the absence of visible emissions, while diesel generators, meeting a load of 7,300 kWh per year, produce 5.84 tons of CO₂ annually, or more precisely, 146 tons of CO₂ over 25 years. Thus, we find that converting 75 generators to solar power will contribute to reducing CO₂ emissions by about 25,000 tons per year.

DISCUSSION

The findings demonstrate that solar PV in Anah, outgrowing the issue of feasibility to become an economic and environmental necessity. The LCOE price of \$0.14/kWh for a solar PV plant isn't just a number; it is also compared to the total cost including lifecycle cost for diesel (\$0.32/kWh) and what people actually pay \$0.45/kWh is low priced on informal markets.

This led to that reliance on diesel generation is not just environmentally and physically unsustainable, it makes no financial sense for a community of 24,000 people. The study also provides insight into the risks associated with each energy technology. It is demonstrated that cost performance of diesel based power generation is quite sensitive to international fuel prices and at the same time, high initial investment for solar PV systems together with financial discount rate are major hurdles. The key difference is, diesel energy has this risky and uncertain long term cost, while solar power requires a one time upfront investment. Thus, with a

solar PV system made, installed and paid for the majority of consumers and local communities the cost becomes relatively fixed or predictable over time.

The environmental implications are also unequivocal, where City of Anah's 75 private generators would result in a total abatement of close to 25,000 tons CO₂ per year. The change also would remove a major cause of local air pollution including NO_x, SO_x and particulate matter and related noise that affects public health directly at home or in densely populated areas. This in turn links the local energy transition in Anah directly to global development and climate targets.

Sustainable Development Goal 7 (Affordable and Clean Energy) and SDG 13 (Climate Action)

The importance reason for the limited adoption of solar panels in post conflict areas, despite their advantages, is the high initial cost, which can exceed \$12,000 USD a significant sum for families in these regions. This is compounded by government subsidies for fossil fuels and a lack of support for renewable energy sources. Renewable energy can be supported through loans and financial facilities, as seen in some neighboring countries. For example, Jordan's implementation of a renewable energy law has strengthened these systems, while the gradual elimination of fuel subsidies has encouraged widespread adoption. Similarly, Egyptian financing mechanisms for small-scale solar energy projects have been successful in supporting this sector. These examples demonstrate that shifting financial support from fossil fuel consumption to renewable energy investment is a proven strategy for emerging economies.

CONCLUSIONS

This study confirms that solar photovoltaic energy is an economic for post conflict recovery in Anah specially, and Anbar Governorate in general. Also, reduction in cost and reduction of emissions indicators, the results show renewable energy offers to an energy security, entirely independent of volatile fossil fuel supply. The study uses accurate local data, which can applicable to different regions that have a similar off grid communities in western Iraq that currently rely on costly private power generation. This led to solar energy should be viewed not as an environmental choice but also as a key strategy for regional economic stability and sustainable development.

RECOMMENDATIONS

The study found that a number of practical steps would facilitate the shift to the clean energy in isolated regions of Iraq.

The government must create a national fund in the decentralization of renewable energy. This fund may offer low interest green loans or merely fund financial aid to help families and small enterprises cover the high initial cost of installing solar systems. Another solution is to reduce diesel fuel subsidy and use it towards renewable energy development so that people can gradually move off fossil fuels, and the transition can be economically feasible. Additionally, the removal of taxation on such quality solar equipment and a definite performance standard will go a long way in ensuring that the solar projects can be trusted and constructed to be durable.

The contribution of development agencies and other partner organizations can also be significant. They should open their doors with small pioneering initiatives of the local communities in Anah installing solar microgrids in areas of importance such as schools, clinics and water pumping stations. Such projects may be related to the data provided in this study and come up with locally modified systems. And it is vital to invest in job training programs that would prepare local workers to install and maintain solar systems; these investments are the most important to create a lasting green economy.

To carry out a more precise field work on the town of Anah in the future, real data regarding the consumption of electricity and the influence of dust and heat on the efficiency of solar panels should be collected and analyzed. Researchers might also desire to explore the hybrid systems of energy, whereby the facilities would be powered by solar as well as diesel, as they require continuous power, like hospitals. Lastly, it would be helpful to measure the social and economic payoff of spending on renewable energy it can reduce domestic bills, generate new employment, and raise education and healthcare quality in such areas.

Author contributions: ZJM: methodology, software, validation, visualization; MOA: conceptualization, investigation, writing - original draft; MJK: supervision, project administration, resources; ABAN: formal analysis, data curation; SOA: writing - review & editing. All authors agreed with the results and conclusions.

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AI statement: The authors stated that generative AI tools were not used during the study.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from corresponding author.

REFERENCES

- Abdullayev, V., Niu, Y., Ragimova, N., Alyar, A. V., & Kamran, A. T. (2023). Harnessing renewable energy for sustainable urban development: Case studies from the MENA region. *ESTIDAMAA*, 2023, 9-17. <https://doi.org/10.70470/ESTIDAMAA/2023/002>
- Aeggegn, D. B., Agajie, T. F., Workie, Y. G., Khan, B., & Fopah-Lele, A. (2023). Feasibility and techno-economic analysis of PV-battery priority grid tie system with diesel resilience: A case study. *Heliyon*, 9(9), Article e19387. <https://doi.org/10.1016/j.heliyon.2023.e19387>
- Ahmed, W. K., Abed, T. A., Salam, A. Q., Reza, K. S., Mahdiy, M. T., & Chaichan, M. T. (2020). Environmental impact of using generators in the university of technology in Baghdad, Iraq. *Journal of Thermal Engineering*, 6(6), 272-281. <https://doi.org/10.18186/thermal.822496>
- Al Sharaa, H. M. J. (2021). Assessment of electricity sector using geomatics techniques: (Ramadi city as a case study). *Engineering and Technology Journal*, 39(12), 1905-1910. 2021. <https://doi.org/10.30684/etj.v39i12.2035>
- Al-Fahdawi, A. H. A., & Satam, A. T. M. (2022). A study of the water reality of managing the Euphrates river in anbar governorate in light of the growing water demand for the period (2020-2040). *AIP Conference Proceedings*, 2400, Article 040004. <https://doi.org/10.1063/5.0125471>
- Aljaberi, A., Alwaeli, M. F., & Al-Anbagi, M. (2024). Technical, economic, and environmental analysis of solar system with management considering flexible energy sources in an educational building. In *The Fifth International Scientific Conference of Alkafeel University*, 97, Article 00065 <https://doi.org/10.1051/bioconf/20249700065>
- Al-Kayiem, H. H., & Mohammad, S. T. (2019). Potential of renewable energy resources with an emphasis on solar power in Iraq: An outlook. *Resources*, 8(1), Article 42. <https://doi.org/10.3390/resources8010042>
- Almadhhachi, M., Seres, I., & Farkas, I. (2022). Significance of solar trees: Configuration, operation, types and technology commercialization. *Energy Reports*, 8, 6729-6743. <https://doi.org/10.1016/j.egy.2022.05.015>
- Al-Mosawy, S. K., Al-Jawari, S. M., & Al-Yassri, I. J. (2021). Estimation of domestic urban electricity consumption: A case study of Baghdad, Iraq. *Periodicals of Engineering and Natural Sciences (PEN)*, 9(2), 678-683. <https://doi.org/10.21533/pen.v9.i2.773>
- Al-Sarraj, A. (2024). Hybrid PV-battery system evaluation in Baghdad: ICOE and NPV Analysis using SAM Software. *Al-Rafidain Journal of Engineering Sciences*, 2(2) 1-7. <https://doi.org/10.61268/t8cb2724>
- Al-Shammari, Z. W. J., Azizan, M. M., & Rahman, A. S. F. (2021). Feasibility of pv-wind-diesel hybrid renewable energy power system for off-grid rural electrification in Iraq: A case study. *Journal of Engineering Science and Technology*, 16(3), 2594-2609.

- Aziz, A. S., Tajuddin, M. F. N., Adzman, M. R., Azmi, A., & Ramli, M. A. M. (2019). Optimization and sensitivity analysis of standalone hybrid energy systems for rural electrification: A case study of Iraq. *Renewable Energy*, *138*, 775-792. <https://doi.org/10.1016/j.renene.2019.02.004>
- Aziz, A. S., Tajuddin, M. F. N., Zidane, T. E. K., Su, C.-L., Mas'ud, A. A., Alwazzan, M. J., & Alrubaie, A. J. K. (2022). Design and optimization of a grid-connected solar energy system: Study in Iraq. *Sustainability*, *14*(13), Article 8121. <https://doi.org/10.3390/su14138121>
- Regional Environmental Center, Turkey. (2014). *Mitigation of climate change. Promotion of Climate Change Policies in Turkey LIFE05/TCY/TR164*. <https://keneamazon.net/Documents/Publications/Virtual-Library/Impacto/157.pdf>
- Djelailia, O., Kelaiaia, M. S., Labar, H., Necaibia, S., & Merad, F. (2019). Energy hybridization photovoltaic/diesel generator/pump storage hydroelectric management based on online optimal fuel consumption per kWh. *Sustainable Cities and Society*, *44*, 1-15. <https://doi.org/10.1016/j.scs.2018.09.037>
- Duran, A. S., & Sahinyazan, F. G. (2021). An analysis of renewable mini-grid projects for rural electrification. *Socio-Economic Planning Sciences*, Article 100999. <https://doi.org/10.1016/j.seps.2020.100999>
- Esobinenwu, C. S. (2023). Optimization of hybrid solar PV and diesel generator system for an efficient electricity supply. *International Journal of Electrical and Electronics Engineering Studies*, *9*(1), 37-46. <https://doi.org/10.37745/ijeecs.13/vol9n13746>
- Farahat, A., Labban, A. H., Mashat, A.-W. S., Hasanean, H. M., & Kambezidis, H. D. (2024). Status of solar-energy adoption in GCC, Yemen, Iraq, and Jordan: Challenges and carbon-footprint analysis. *Clean Technologies*, *6*(2), 700-731, 2024. <https://doi.org/10.3390/cleantechnol6020036>
- Ghadim, H. V., Haas, J., Breyer, C., Gils, H. C., Read, E. G., Xiao, M., & Peer, R. (2025). Are we too pessimistic? Cost projections for solar photovoltaics, wind power, and batteries are over-estimating actual costs globally. *Applied Energy*, *390*, Article 125856. <https://doi.org/10.1016/j.apenergy.2025.125856>
- Global Petrol Prices. (2025). *Iraq gasoline prices per liter*. Global Petrol Prices. Retrieved September 27, 2025, from https://www.globalpetrolprices.com/Iraq/gasoline_prices/
- Hafedh, S. A. (2021). Feasibility study of hybrid energy system for off-grid electrification in rural areas. *Diyala Journal of Engineering Sciences*, *14*(1) 57-66. <https://doi.org/10.24237/djes.2021.14105>
- Hassan, Q. (2025). Assessment of renewable energy suitability and development constraints in Iraq. *Unconventional Resources*, *8*, Article 100248. <https://doi.org/10.1016/j.unres.2025.100248>
- International Energy Agency. (2022). *World energy outlook 2022*. <https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf>
- International Renewable Energy Agency (IRENA). (2024). *Renewable power generation costs in 2023*. <https://www.iea.org/reports/world-energy-outlook-2022>
- Istepanian, H. H. (2014). Iraq's electricity crisis. *The Electricity Journal*, *27*(4), 51-69. <https://doi.org/10.1016/j.tej.2014.04.006>
- Jalil, R. R., & Mohammed, H. J. (2022). The economic feasibility of using renewable energy in Iraqi oil fields. *Journal of Petroleum Research and Studies*, *12*(4), 137-156. <https://doi.org/10.52716/jprs.v12i4.727>
- Kadhim, A. M. (2024). The challenges faced by the Iraqi electricity sector: Reform program and proposed solutions. *Al-Rafidain Journal of Engineering Sciences*, *2*(1), 185-203. <https://doi.org/10.61268/gfpcsx76>
- Kassem, R., Mahmoud, M. M., Ibrahim, N. F., Alkuhayli, A., Khaled, U., Beroual, A., & Saleeb, H. (2024). A techno-economic-environmental feasibility study of residential solar photovoltaic/biomass power generation for rural electrification: A real case study. *Sustainability*, *16*(5), Article 2036. <https://doi.org/10.3390/su16052036>
- Keya, D. R., Farangis, B., Sirwan, R., & Behler, K. (2022). GIS based analysis of the solar radiation mapping and potential assessment for the North Iraq-Kurdistan Region. *Journal of Engineering Science and Technology*, *18*(5), 2269-2280. <https://doi.org/10.21203/rs.3.rs-1914165/v1>
- Kosmadakis, I. E., & Elmasides, C. (2021). A sizing method for PV-battery-generator systems for off-grid applications based on the LCOE. *Energies*, *14*(7), Article 1988. <https://doi.org/10.3390/en14071988>
- Lazard. (2025). *Levelized cost of energy analysis (Version 18.0)*. <https://www.lazard.com/research-insights/levelized-cost-of-energyplus-lcoeplus/>
- Maftouh, A., Fatni, O. E., Fayiah, M., Liew, R. K., Lam, S. S., Bahaj, T., & Butt, M. H. (2022). The application of water-energy nexus in the Middle East and North Africa (MENA) region: A structured review. *Applied Water Science*, *12*(5), Article 83. <https://doi.org/10.1007/s13201-022-01613-7>
- Mohammed, A. Q., Al-Anbari, K. A., & Hannun, R. M. (2021). Using particle swarm optimization to find optimal sizing of PV-BS and diesel generator. *Journal of Engineering and Sustainable Development*, *25*(3), 51-59. <https://doi.org/10.31272/jeasd.25.3.6>
- Mulenga, E., Kabanshi, A., Mupeta, H., Ndiaye, M., Nyirenda, E., & Mulenga, K. (2023). Techno-economic analysis of off-grid PV-Diesel power generation system for rural electrification: A case study of Chilubi district in Zambia. *Renewable Energy*, *203*, 601-611. <https://doi.org/10.1016/j.renene.2022.12.112>
- Mushref, Z. J., Wally abd, A. H., Mikhlif, A. M., & Abed, S. O. (2022). A cartographic representation of the characteristics of Al-Rutba district population. *International Journal of Design & Nature and Ecodynamics*, *17*(4), 621-626. <https://doi.org/10.18280/ijdne.170418>
- Nahui-Ortiz, J., Quillos-Ruiz, S., Escalante-Espinoza, N., & Sotelo-Valer, F. (2021). A comparative cost analysis of electricity produced by a diesel and a solar-PV generation system for an energy load located in Chimbote, Ancash-Perú. In *Proceedings of the 19th LACCEI International Multi-Conference for Engineering, Education and Technology* (Article 377). <https://doi.org/10.18687/LACCEI2021.1.1.377>

- Ogunjuyigbe, A. S. O., Ayodele, T. R., & Akinola, O. A. (2016). Optimal allocation and sizing of PV/wind/split-diesel/battery hybrid energy system for minimizing life cycle cost, carbon emission and dump energy of remote residential building. *Applied Energy*, *171*, 153-171. <https://doi.org/10.1016/j.apenergy.2016.03.051>
- Philipps, S., ISE, F., & Warmuth, W. (2025). *Photovoltaics report*. Fraunhofer. <https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html>
- Rana, G. S., & Jindal, R. (2025). Factors affecting solar levelized cost of electricity in India & policy recommendations. *Energy and Climate Change*, *6*, Article 100207. <https://doi.org/10.1016/j.egycc.2025.100207>
- Riva, F., Ahlborg, H., Hartvigsson, E., Pachauri, S., & Colombo, E. (2018). Electricity access and rural development: Review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling. *Energy for Sustainable Development*, *43*, 203-223. <https://doi.org/10.1016/j.esd.2018.02.003>
- Ryu, D.-H., & Kim, K.-J. (2024). The influence of information privacy concerns and perceived electricity usage habits on the usage intention of advanced metering infrastructure. *Renewable and Sustainable Energy Reviews*, *189*, Article 113851. <https://doi.org/10.1016/j.rser.2023.113851>
- Salcido, R. D., Lockwood, G. W., Rebullar, C. I., Anderson, K. R., & Shafahi, M. (2024). Modeling of small-scale hybrid biogas renewable energy facility. In *Proceedings of the ASME 2024 18th International Conference on Energy Sustainability collocated with the ASME 2024 Heat Transfer Summer Conference and the ASME 2024 Fluids Engineering Division Summer Meeting. ASME 2024 18th International Conference on Energy Sustainability*. American Society of Mechanical Engineers. <https://doi.org/10.1115/ES2024-130609>
- Satam, A. T. M., Mukhleif, W. H., Razzaq, A. S. A. A., Mushref, Z. J., & Sulaiman, S. O. (2025). Spatial and temporal variations in water quality of the Euphrates river: A sustainable water management approach for Anbar Governorate, Iraq. *International Journal of Design & Nature and Ecodynamics*, *20*(1), 99-106. <https://doi.org/10.18280/ijdne.200111>
- Shakya, S. R., Bajracharya, I., Vaidya, R. A., Bhawe, P., Sharma, A., Rupakheti, M., & Bajracharya, T. R. (2022). Estimation of air pollutant emissions from captive diesel generators and its mitigation potential through microgrid and solar energy. *Energy Reports*, *8*, 3251-3262. <https://doi.org/10.1016/j.egy.2022.02.084>
- Tahir, K. A., Nieto, J., Díaz-López, C., & Ordóñez, J. (2025). From diesel reliance to sustainable power in Iraq: Optimized hybrid microgrid solutions. *Renewable Energy*, *238*, Article 121905. <https://doi.org/10.1016/j.renene.2024.121905>
- Thango, B. A., & Obokoh, L. (2024). Techno-economic analysis of hybrid renewable energy systems for power interruptions: A systematic review. *Eng*, *5*(3), 2108-2156. <https://doi.org/10.3390/eng5030112>
- The World Bank Group. (2025). *Iraq country climate and development report*. The World Bank.
- Wahid, T. B., & Mushref, Z. J. (2026). Geospatial analysis of urban expansion using the NDBI spectral index and Landsat-8 data. *European Journal of Sustainable Development Research*, *10*(1), Article em0362. <https://doi.org/10.29333/ejosdr/17556>
- Wang, G., Sbai, E., Wen, L., & Sheng, M. S. (2024). The impact of renewable energy on extreme volatility in wholesale electricity prices: Evidence from organisation for economic co-operation and development countries. *Journal of Cleaner Production*, *484*, Article 144343. <https://doi.org/10.1016/j.jclepro.2024.144343>
- Yimen, N., Tchotang, T., Kanmogne, A., Idriss, I. A., Musa, B., Aliyu, A., Okonkwo, E. C., Abba S. I., Tata, D., Meva'a, L., Hamandjoda, O., & Dagbasi, M. (2020). Optimal sizing and techno-economic analysis of hybrid renewable energy systems—A case study of a photovoltaic/wind/battery/diesel system in Fanisau, Northern Nigeria. *Processes*, *8*(11), Article 1381. <https://doi.org/10.3390/pr8111381>
- Zhang, T., Shi, X., Zhang, D., & Xiao, J. (2019). Socio-economic development and electricity access in developing economies: A long-run model averaging approach. *Energy Policy*, *132*, 223-231. <https://doi.org/10.1016/j.enpol.2019.05.031>