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Sustainable Solar Energy Development in Zakho, Iraq: A Techno-Economic And Environmental Assessment

Ahmed Mohammed Ahmed[1*], Idrees Majeed Kareem[2], Lana Ayad Abdulateef[3]

[1*, 2]*Department of Civil and Environmental Engineering, University of Zakho, Zakho, KRG, Iraq,*
[3]*Civil Engineering Department, Nawroz University, Duhok, KRG, Iraq*

***Corresponding Author:** Ahmed Mohammed Ahmed*
Email: eng.ahmedahmed1998@gmail.com

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ABSTRACT

This study presents a solar energy roadmap aimed at attracting investors to capitalize on the abundant solar resources in Zakho, Iraq, for clean energy technology. The objective is to mitigate global warming effects caused by fossil fuel combustion and promote sustainable technological development. To end this, the study employs RETScreen Expert software to validate the techno-economic and environmental viability of a grid-connected solar photovoltaic system utilizing climatic data from the Astronaut Office Information System (NASA) Database. Additionally, the Photovoltaic Geographical Information System (PVGIS) modeling method determines optimal angles for installing residential rooftop Photovoltaic (PV) systems across selected locations. Results indicate that all selected locations are suitable for solar photovoltaic projects, with Rezgari identified as the optimal district due to its highest annual solar radiation of 1863.117 kWh/m2 and the highest annual electricity production at 7905.38 kWh. The capacity factor (CF) values fall within the range of 17.395-17.574%. The study reveals an annual greenhouse gas (GHG) emissions reduction ranging from 6.9876 to 7.1123 (tCO2) across four districts. Considering the financial and environmental indicators, Rooftop Photovoltaic Systems emerge as a sustainable and efficient solution to enhance the environment and prove economically viable in Zakho City.

Keywords: Solar energy, Rooftop Photovoltaic Systems, Solar potential, Sustainability development, RETScreen Expert, NASA Database, PVGIS

1. Introduction

The simultaneous rise in population and technological progress has resulted in a notable upswing in energy usage, especially within the electricity sector, in recent years [1]. This increased demand is exacerbated by the absence of electricity access in numerous rural and remote areas, particularly in developing nations [2,3]. Tackling these issues necessitates a substantial increase in electricity generation [4]. Despite the pivotal role played by fossil fuels in meeting global electricity requirements, it is imperative to acknowledge their constraints. Conventional energy sources are finite and depleting rapidly, posing a risk to the equilibrium of global energy demand and supply [5].

Furthermore, the heavy dependence on fossil fuels plays a substantial role in the release of greenhouse gases, intensifying the issues of global warming and climate change [6]. These environmental challenges are closely intertwined with economic problems, underscoring the urgency of transitioning towards more sustainable and renewable energy sources for a cleaner and more resilient energy future [7,8]. The adverse environmental effects linked to the use of fossil fuels have spurred scientific exploration into viable alternative energy sources [9]. Various studies emphasize the dependability of renewable energy as a promising solution to address the current issues associated with energy production [10]. Solar energy emerges as a renewable resource with boundless potential. The direct harnessing of sunlight's energy through photovoltaic (PV) tools is increasingly acknowledged as a fundamental factor in shaping the future of the world's energy supply [11, 12].

Iraq faces a persistent electricity shortage crisis despite having abundant renewable energy resources [12]. The current reliance on large-scale thermal energy from flared gases contributes to the challenge of reducing dependence on fossil fuels. Initiatives to capture natural gas and embrace renewable energy are underway, but billions of cubic meters are still flared annually [13]. In high-temperature countries like Iraq, establishing advanced, long-term electrical stations is crucial [14]. The existing stations, strained by rapid population growth and reaching the end of their operational life, see a yearly increase in electricity demand by 7-10%. The adoption of renewable energy has the potential to achieve self-sufficiency, reducing the need for costly electricity and gas imports, currently totaling 2.5 to 2.8 billion dollars annually [15,16]. Globally, renewable energy projects play a vital role in reducing carbon dioxide levels and addressing economic challenges [17].

Both the Kurdistan Region and Iraq contend with persistent electricity shortages and deteriorating infrastructure [18]. On average, national electricity is accessible for only around 10-12 hours per day, with the remaining hours relying on commercial power plants. Electricity is primarily generated through fossil fuel-based thermal power plants, leading to economic challenges (high costs), environmental issues (CO2 emissions), and a decline in urban livability (noise pollution, fire risks from disorganized wiring). This underscores the urgent requirement for infrastructure upgrades and efficient energy solutions to mitigate the persistent electricity deficit in the region. This study aims to delve into the environmental sustainability of PV systems, assess their economic viability in Zakho City, and formulate policies to promote the growth of the PV market in the country.

2. Literature Review

Various studies have explored the potential of renewable energy sources in Iraq to address the country's electricity challenges. Abed et al. (2014) emphasized the potential of solar and hydropower systems as alternative energy sources to address electricity-related issues in the country. They also underscored the environmental benefits, particularly in reducing CO2 emissions [19]. Similarly, Kayim and Mohamed (2019) highlighted the substantial energy production capability of solar energy, ranging from 1800 to 23900 kWh/m^2, available for 10 hours daily. Their study proposed that this level of energy generation could effectively mitigate the electricity crisis, emphasizing the importance of renewable energy in achieving sustainable solutions [20]. Ibrahim et al. (2020) searched for the ideal spot to establish a solar energy system in Dohuk, Iraq, using Boolean logical-AHP technology. The results showed that 68.5% of the land in the city might be utilized for solar energy plants [21]. Aziz et al. (2019) assessed hybrid energy options using HOMER software for an Iraqi rural village. The study found the PV/hydro/diesel/battery system to be the most economical, with low cost and high environmental efficiency, minimizing uncertainties in rural electrification [22]. Ahmed et al. (2018) determined that solar energy offers a sustainable and effective solution to address challenges in Iraq. They highlighted its suitability for alleviating electricity shortages and mitigating environmental issues, emphasizing its potential to tackle pollution in the country [23]. Al-Waeli and Al-Asadi (2018) affirmed that Iraq's increasing energy demand, projected at 20,000 megawatts, necessitates strategic solutions. The study highlighted the government's commitment to addressing the electricity crisis by considering solar energy. This approach is viewed as a sustainable, environmentally friendly solution that is cost-effective and aligns with economic conservation objectives [24]. Ibrahim et al. (2021) employed Boolean AHP and GIS techniques to determine an optimal site for solar energy in Erbil, Iraq, considering economic, environmental, and equally weighted scenarios. The study identified 369 potential sites for solar energy installation, revealing that approximately 85% of these sites, particularly in the southern and central regions, were deemed suitable for solar energy systems [25]. Khaled and Ali (2020) conducted a seven-month experimental and digital survey on a hybrid solar PV thermal energy system in Dohuk. The study gathered data on total temperature, water mass flow, sun density, and average wind speed. Results, comparing experimental and numerical findings, revealed a 2.36% error between the two thermal assessments. Notably, the PV/T complex exhibited its highest density (72.1%), while the lowest percentage (63.1%) occurred in January [26].

3. Methodology

The objective of the proposed methodology is to assess the solar energy potential in four districts within Zakho city, to identify optimal locations for future installations of solar PV systems. The economic feasibility of these PV systems is also assessed. Fig.1 provides a visual representation of the methodology employed in this study.

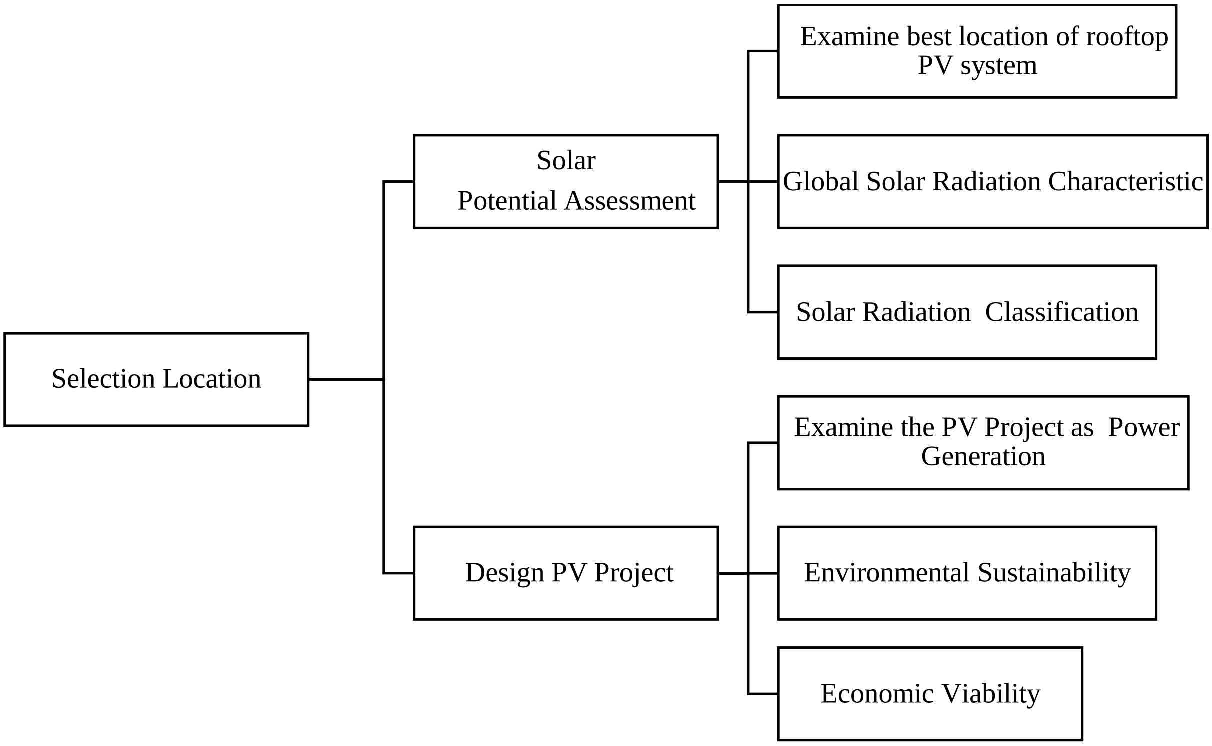

Fig.1 The proposed methodology diagram

3.1 Study Area

Zakho positioned approximately 55 km northwest of Dohuk in northern Iraq at coordinates 37°08′37.00″N 42°40′54.88″E, functions as a crucial commercial hub. Its strategic location, just 8 km from the Turkish-Iraqi border, underscores its importance as a key customs checkpoint. With a population of around 260 thousand inhabitants, the city stands as a significant economic center in the region, playing a vital role in various economic activities.

Zakho district experiences diverse weather conditions with an average annual precipitation of 66.5 mm. Summers are hot and dry, reaching 40.4°C in July, while winters are moderate at 1.9°C in January. The westward wind at 5.2 km/h and 44.9% humidity provide balance [27]. In Zakho, the Global Solar Radiation levels peak during June and July, registering the highest monthly averages, while December and January recorded the lowest values. The mean monthly sunshine hours range from 7.42 in winter to 14.11 in summer [28].

Four districts of Zakho city are chosen in this study which are Zakho, Rezgari, Darkar, and Batofa as shown in Fig.2.

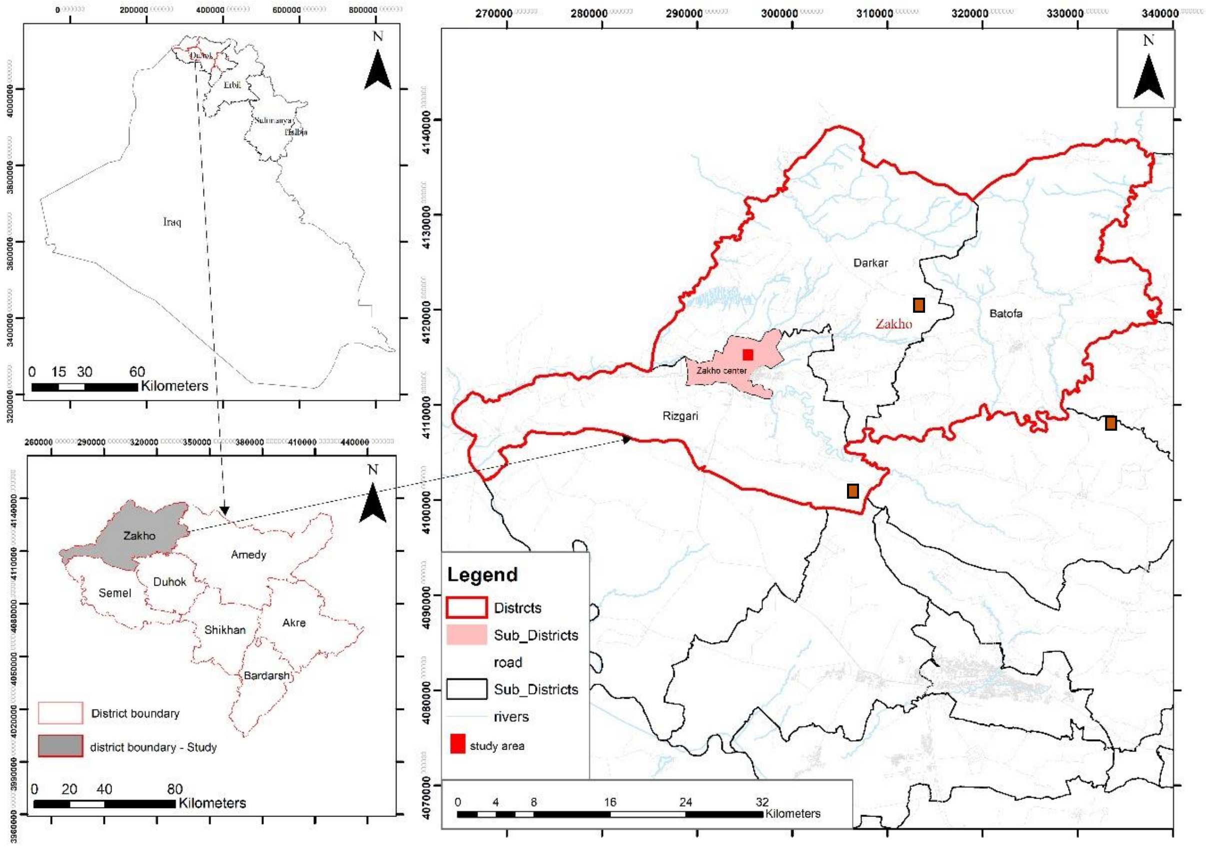

Fig.2 Selected locations of the study

3.2 Classification of Solar Potential

Various methods are employed to estimate global solar radiation using satellite data, wherein the satellite measures the light emitted from the Earth. An assessment of solar energy potential was conducted in four regions in Zakho, Iraq, utilizing National Aeronautics and Space Administration (NASA) data. This analysis aims to fulfill the requirement of understanding and unlocking the solar energy potential in the chosen area. The discussion encompasses photovoltaic (PV) systems and strategies for optimizing their usage and efficiency.

Global horizontal irradiation (GHI) holds significant importance in the assessment of flat-plate photovoltaic energy generation, solar power concentration, and photovoltaic concentration systems. Global solar radiation is deemed applicable for assessing the energy generation potential of flat photovoltaic (PV) systems [30, 31]. Table 1 presents the classification of solar potential based on (GHI).

Table 1 Description of solar potential classification

Class	Description	GHI (kWh/m^2)
1	Poor	<1191.8
2	Marginal	1191.8–1419.7
3	Fair	1419.7–1641.8
4	Good	1641.8–1843.8
5	Excellent	1641.8–2035.9
6	Outstanding	2035.9–2221.8
7	Superb	>2221.8

3.3 Design of PV System

The key factors taken into account in the planning of a photovoltaic (PV) power facility include:

Power generating factor, [30]:

$$PGE = \frac{Solar\ irradiance\ \times\ Sunshine\ hours}{Standard\ test\ condition\ irradiance} \qquad Eq, 1$$

Solar PV energy required:

$$The\ energy\ required\ from\ PV\ modules = Peak\ energy\ requirement \times Energy\ lost\ in\ the\ system \quad Eq, 2$$

PV module sizing:

$$\text{Total Watt peak rating} = \frac{Solar\ PV\ energy\ required}{panel\ generation\ factor} \quad Eq, 3$$

$$\text{PV module size} = \frac{Total\ Watt\ peak\ rating}{PV\ output\ power\ rating} \quad Eq, 4$$

Inverter sizing:

$$Inverter\ size = Peak\ energy\ requirement \times Factor\ of\ safety. \quad Eq, 5$$

3.4 Residential rooftop PV system

The proposed 5 kW grid-connected rooftop photovoltaic (PV) system utilizes mono-crystalline silicon (mono-Si) technology, specifically the mono-Si-CS6X-300M modules. Seventeen modules are required for the residential rooftop installation in selected locations [32]. The chosen inverter is the Growatt 5500MTL-S Dual MPPT 6000 W Solar Inverter, and its specifications are detailed in Table 2. This careful selection of PV technologies and components aims to optimize system efficiency and performance.
Furthermore, utilizing the PVGIS modeling method, the optimal slope angle and azimuth angle were identified for all chosen locations, ensuring the ideal orientation for the future installation of the PV devices.

Table 2 Specifications of the Photovoltaic (PV) modules

PV Module Technology	Mono-si
Manufacture	Canadian Solar
Model	mono-Si-CS6X-300M
The voltage points of maximum power (V)	36.5
Nominal power (W)	300
Current at point of maximum power (A)	8.22
Module area (m2)	1.919
Efficiency (%)	15.63
Warranty (Year)	25
Cost (USD/Wdc)	0.83

3.5 Economic Analysis and Emission Reduction

Researchers employ diverse modeling approaches to estimate the annual and monthly energy output, as well as the power factor, of installed solar PV systems. Using tools like RETScreen and related software such as HOMER, scientists assess the technological and environmental feasibility of solar PV technologies on a global scale [32].
To assess the economic and environmental aspects of a 5kW grid-connected rooftop solar PV system, RETScreen Expert software is utilized for power comparisons across selected regions. RETScreen serves as a valuable tool for evaluating the viability of grid-connected clean energy devices. For the assessment of the project's economic feasibility parameters, the RETScreen Specialist application was used [33]. The indications listed below, represented as an equation, are as follows:
Net present value (NPV):

$$(NPV) = \sum_{N=0}^{N} \frac{C_n}{(1+r)^n} \quad Eq, 6$$

Simple payback (SP):

$$SP = \frac{C - C1}{\left(C_{ener} + C_{capa} + C_{RE} + C_{GHG}\right) - \left(C_{0\&M} + C_{fuel}\right)} \quad Eq, 7$$

Equity payback (EP):

$$(EP) = \sum_{N=0}^{N} C_n \quad Eq, 8$$

The annual life cycle savings (ALCS):

$$(ALCS) = \frac{NVP}{\frac{2}{r}\left(\frac{1}{(1+r)^N}\right)} \quad Eq, 9$$

The internal rate of return (IRR):

$$(IRR) = \sum_{N=0}^{N} \frac{C_n}{(1+IRR)^n} \qquad Eq, 10$$

Benefit-Cost ratio (B-C):

$$B - C = \frac{(NPV) + (1 - f_d)}{(1 - f_d)^C} \qquad Eq, 11$$

Capacity factor (CF):

$$CF = \frac{P_{out}}{9 \times 8760} \qquad Eq, 12$$

Pout is the primary annual energy output, p is the installed capacity, N is the project life, Cn is the after-tax cash flow in the nth year, r is the full deduction rate, C is the initial project cost, fd is the debt ratio, B is the total interest, Cener is annual income, Ccapa is annual income, CRE is renewable energy produced annually, CGHG is thermal gas reduction, and, and DGHG is the annual reduction in GHG emissions.

4. Result and Discussion

4.1 Classified Solar Potential

Table 3 displays the average Annual Mean Global Horizontal Irradiation (GHI) for districts Zakho, Rezgari, Darkar, and Batofa, providing a Description of the global solar characteristic classification of solar energy potential according to annual GHI values as shown ranging from 1794.653 to 1863.117 kWh/m2. It is important to highlight that these areas exhibit a substantial solar capacity and have received ratings of either good or excellent for future prospects. It is worth noting that all the selected locations are deemed suitable for the installation of photovoltaic (PV) projects.

Table 3 Result and Classification of (HGI)

Location	GHI (kWh/m2)	Class	Description
Zakho	1849.563	5	Excellent
Rezgari	1863.117	5	Excellent
Darkar	1794.65	4	Good
Batofa	1856.173	5	Excellent

4.2 Installing residential rooftop PV system

The PVGIS modeling method determines the optimal slope and azimuth angles for all selected locations. Table 4 provides a list of the optimal angles for the prospective installation of PV devices at these selected locations.

Table 4 Optimum angles for the PV system

Location	Slope angle (°)	Azimuth angle (°)
Zakho	-3	32
Rezgari	-6	31
Darkar	-2	33
Batofa	-4	33

4.3 Assessment of PV System Efficiency

The annual electricity generation and capacity factor from the proposed PV technology system are illustrated in Fig. 3 and Fig. 4, respectively. Notably, Rezgari reported the highest annual electricity production at 7905.38 kWh, while Darkar recorded the lowest at 7791.98 kWh. Additionally, the capacity factor (CF) values fall within the range of (17.395-17.574%), these values indicate that the selected locations provide favorable conditions for the development of PV projects. The consistency in capacity factor percentages underscores the suitability of these locations for efficient and sustained photovoltaic energy generation.

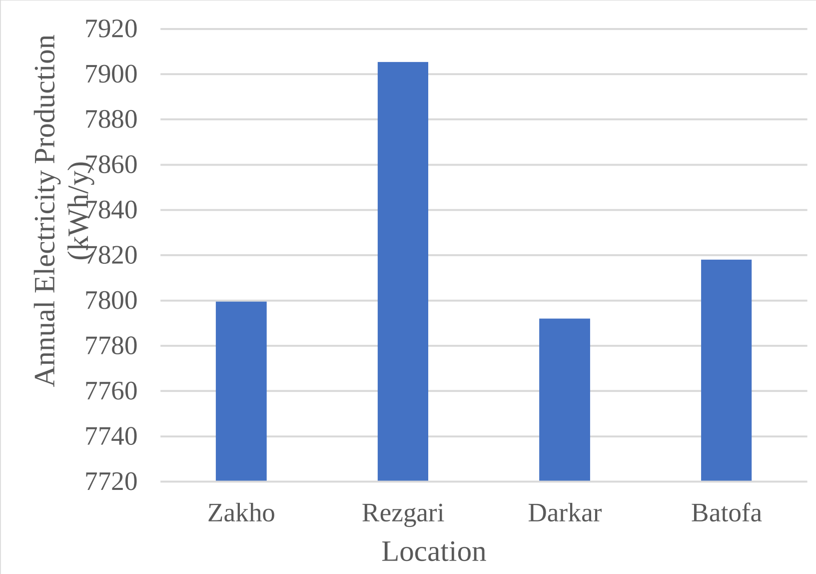

Fig.3 Annual electricity generation

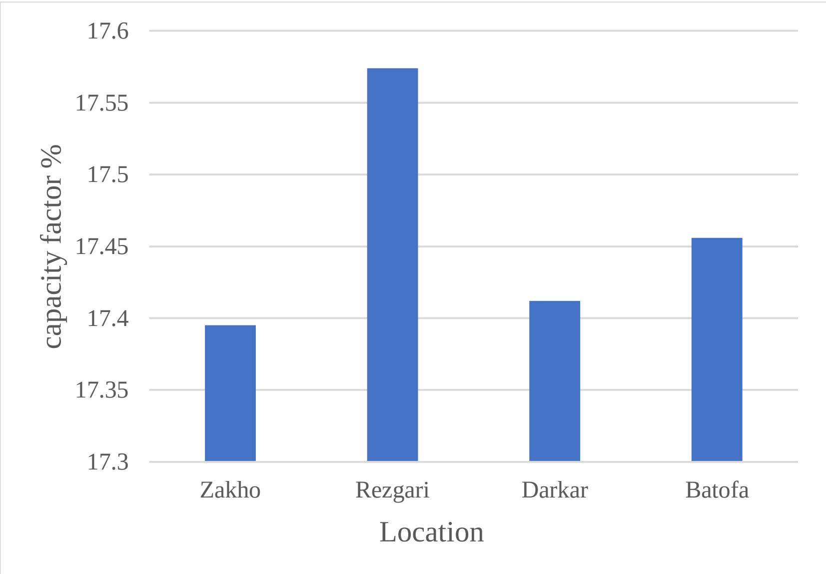

Fig. 4 Capacity factor

4.4 Economic viability

Economic analysis assesses the commercial viability of PV power plants. Key criteria NPV and payback period determine project feasibility. Study results show in Table 5 NPV, payback period and other criteria values across location, informing consumers and policymakers.

Table 5 Financial and Emission Reduction Analysis Results

Parameter	Zakho	Rezgari	Darkar	Batofa
Simple payback (Year)	6.8027	6.7879	6.7791	6.7751
Equity payback (Year)	3.5789	3.5738	3.5787	3.5711
Pre-tax Internal Rate of Return - equity [%]	31.44	31.23	32.09	31.52
Pre-tax Internal Rate of Return - assets [%]	17.79	17.86	18.01	17.56
Net Present Value ($)	33,971.60	32198.8	31724.4	33127.1
Annual life cycle savings ($/year)	1224.76	1321.17	1384.25	1279.11
Annual GHG emission reduction (tCO2)	6.9984	7.1123	7.0642	6.9876
Energy production cost ($/kWh)	0.0218	0.0254	0.0286	0.0269

The proposed photovoltaic project exhibits varying payback periods across locations. Zakho records the longest at 6.8027 years, whereas Batofa boasts the shortest at 6.7951 years. Additionally, Zakho presents the

highest equity payback 3.5789 years, while Batofa showcases the lowest 3.5057 years. Furthermore, Zakho features the lowest electricity cost at 0.0218$/kWh, contrasting with Darkar, which experiences the highest average electricity cost of 0.0236$/kWh.
The results of the analysis highlight significant results in the annual life cycle savings and Net Present Value (NPV) between Darkar and Zakho. Darkar demonstrates the highest annual life cycle savings, reaching an impressive 1384.25 (year/$), indicating substantial economic benefits over lifespan of projects. In contrast, Zakho records the lowest annual life cycle savings, amounting to 1224.76 (year/$), suggesting a comparatively lower financial advantage. Moreover, the highest NPV stands at a notable 33,971.6 ($) in Zakho indicating a robust positive financial outcome.
RETScreen software estimated the annual GHG emissions reduction for the four districts, revealing a range of 6.9876 to 7.1123 (tCO_2). This data highlights the potential environmental impact of the photovoltaic project in each district.
The highlighted findings not only stress the economic feasibility of the PV project but also underscore the vital role of location-specific factors in effectively handling its financial implications. This knowledge empowers managers and stakeholders to make informed decisions, optimizing resource allocation for maximum returns. Additionally, it contributes to a sustainable resolution of the electricity crisis by promoting clean energy initiatives, ensuring both economic viability and environmental responsibility in addressing the country's energy challenges.

5. Conclusion

This study comprehensively examined the feasibility of implementing a 5kW grid-connected solar photovoltaic project in the Four district of Zakho, Iraq. Moreover, this study shed light on promising outcomes revealed through meticulous monthly solar radiation assessments using NASA data. The economic scrutiny of a 5kW grid-connected rooftop PV project across four carefully selected areas not only validated their suitability but also revealed a promising avenue for photovoltaic system implementations. The estimations provided by RETScreen software, projecting an annual reduction of greenhouse gas emissions ranging from 6.9876 to 7.1123 (tCO_2), serve as a beacon, signaling the positive environmental impact these proposed photovoltaic projects can bring to each district. Altogether, the adoption of grid-connected solar PV systems emerges as a beacon of hope, offering a sustainable solution to energy production crises while bestowing substantial benefits such as heightened energy provision, diminished emissions, and noteworthy cost savings. This study underscores the critical importance of harnessing solar energy potential, embracing technological advancements, and cultivating supportive policies to illuminate a greener and economically efficient energy landscape specifically tailored for Zakho city.

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Declaration of Competing Interest

The authors state that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study

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