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SIMULATION DESIGN OF HYBRID RENEWABLE ENERGY SYSTEMS AT THE COLLEGE OF SCIENCE IN THE UNIVERSITY OF ZAKHO, IRAQ.

Bilind Shukri Sadiq [1], and Kamil M. Yousif [1,*]

[1] Department of Environment, College of Science, University of Zakho, Zakho, Kurdistan Region, Iraq.

*Corresponding author email: kamil.yousif@uoz.edu.krd

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ABSTRACT:

Utilising renewable energy sources (RESs) instead of conventional power generation methods is crucial for mitigating climate change and global warming. As in other cities of the Kurdistan Region and Iraq, the national electricity outage crisis persists in Zakho, and power production via various sources remains necessary. In this study, the optimisation program 'Hybrid Optimisation Model for Electric Renewables' HOMER Pro has been utilised to simulate two solar energy systems: grid-connected and off-grid. The systems are modelled for installation on the roof of the College of Science building at Zakho University, Iraq, which operates for 6 hours daily, from 9:00 a.m. to 3:00 p.m., Sunday to Thursday, while electricity consumption is extremely low during the summer weekends. Our findings confirm that the on-grid system is the more favourable option, with a cost of energy (COE) of $0.0194/kWh and a net present cost (NPC) of $295,544. On the other hand, the stand-alone design has a COE of $0.159/kWh and an NPC of $699,14. Moreover, the on-grid model derives 96% of its energy from renewable sources; whereas, the grid-independent design achieves 91.2%.

KEYWORDS: Emissions from fossil fuels, Hybrid Renewable Energy Systems, Photovoltaic System, solar energy, cost of energy, HOMER Pro Software

1. INTRODUCTION

The Kurdistan Regional Government (KRG) recently emphasized its commitment to clean energy. The region has signed three contracts to build solar power plants in Erbil, Sulaymaniyah, and Duhok, targeting a total capacity of 350 MW to extend electricity supply hours (Shafaq-News, 2025). Moreover, the Ministry of Education announced that 81 regional schools are now supplied with 24-hour solar-generated electricity (KRG, 2025).

It is well established that the global energy supply is still largely dependent on fossil fuels, such as petroleum, natural gas, and oil. Fuel combustion or power generation from these fuels constitutes the primary source of greenhouse gas (GHG) emissions. These fuels are the main contributors to climate change due to the release of GHGs (Akram *et al.*, 2018; Shahveran & Yousefi, 2025). To ensure a secure planet and enhance the quality of life for all organisms, innovative, clean, and renewable energy sources (RESs) and associated technologies are being researched, developed, and deployed globally *(*Mawlood *&* Hamarash, 2023*)*.

Renewable energy sources encompass solar energy (SE), wind, hydro, geothermal, and biomass. Solar radiation refers to the total radiant energy emitted by the sun; whereas, solar irradiation denotes the quantity of solar radiation received per unit area, expressed in kW/m^2 (Mawlood & Hamarash, 2023). In addition to economic factors, usability and logistical practicality of fuel-less generation methods make renewable hybrid systems (HSs) a practical solution for meeting energy needs in rural areas, especially in developing countries. Integrating renewable energy (RE) generation methods, like a hybrid solar-wind power generation system, may enhance the reliability of RESs, cost-effectiveness, and efficiency (Karimi, 2014). Photovoltaic (PV) systems are classified into two categories: grid-connected (on-grid) and standalone (off-grid) systems (Ramoliya, 2015).

On-grid PV systems provide power straight to the utility grid, functioning simultaneously with traditional energy sources. These models generate clean electricity near the point of consumption, eliminating the necessity for batteries and mitigating transmission and distribution losses. Due to the electricity constraints in Kurdistan Region, battery backups have been used in both off-grid and grid-connected PV systems in this research. Some studies have concentrated on the planning and designing grid-connected PV systems, with some exclusively addressing On-grid systems that integrate PV designs with no energy storage options.

Qasim *et al*. (2025) developed a hybrid power model integrating PV panels, wind turbines (WTs), battery energy storage, and a diesel generator (DG) to provide sustainable and economical electricity to isolated areas in Iraq. The design generated approximately 90.1 MWh annually, diminishing reliance on traditional energy sources. Aktacir and Sadiq (2025) performed a case study in Dohuk, Iraq, where the national grid suffers from recurrent outages attributed to insufficient infrastructure. Incorporating an on-grid PV system with energy storage decreased the electricity cost from $0.022 to $0.010 per kWh. The system achieves a payback period of 4.5 years,

* Corresponding author

underscoring significant economic benefits compared to traditional energy sources.

Salim and Rashed (2025) designed a hybrid off-grid power system for the Al-Taib region in eastern Iraq, including PV panels, WTs, DG, and battery storage. The system was engineered to deliver a sustainable and economical power supply to the city while diminishing dependence on fossil fuels. Ren *et al*. (2016) investigated a grid-connected hybrid PV/DG/battery system for the electricity of houses. Their findings indicated that electricity buy-back mechanisms significantly influenced the system's performance. Mohamed *et al.* (2017) optimised a grid-connected PV/wind configuration using the particle swarm optimisation (PSO) algorithm and concluded that the proposed model was economically feasible.

Ndwali *et al.* (2020) employed mixed integer linear programming (MILP) to optimise a grid-integrated PV design, reporting an energy saving of approximately 64.16%. Kim *et al.* (2014) studied grid-connected and stand-alone HS designs. The most suitable HS was identified as an on-grid configuration consisting of a wind turbine, PV panels, and a battery. Based on financial, environmental, and technical criteria, this assessment was conducted for a hybrid energy model installed on a South Korean island. Usman *et al.* (2024) developed a grid-connected hybrid microgrid comprising solar PV panels, WTs, and grid integration for the village of Chittorgarh in India. The system was engineered to provide dependable, sustainable, and economical energy, generating approximately 58,772,300 kWh per year to mitigate the issues of inconsistent power supply in the area. Alghamdi *et al.* (2018) presented an optimisation approach for energy cost reduction in grid-connected PV/battery systems, applying the methodology to a case study in the Brazilian Amazon region. Aziz *et al.* (2022) evaluated the optimal design of a Grid-connected PV/battery system capable of fulfilling the load requirements of homes in Iraq. Al-Shammari *et al.* (2021) assessed the feasibility of employing diesel, battery packs, wind, and SE for Al-Faw, a city in southern Iraq near Kuwait. Their study involved seven hybrid energy model scenarios, among which the configuration incorporating wind, diesel, battery, and converters demonstrated the lowest cost of energy (COE) and net present cost (NPC).

Hussain *et al.* (2021) evaluated the design of an on-grid PV system implemented at the Diyala Police Directorate, Iraq. The study concentrated on the economic assessment by providing the requisite electricity for local demand and sending extra energy to the national power grid with enhanced efficiency and reduced losses. Omar (2025) proposed the (solar/Battery/DG) HS as the most effective power option for rural electrification across the Northern West Bank, balance between cost-efficiency, dependability, and environmental sustainability.

Al-Sarraj *et al.* (2020) conducted a study on HS consisting of wind, solar, DG, and grid components for a station at the University of Nahra, Baghdad, Iraq. Two designs were created, one incorporating a sellback price and the other excluding it. The results indicated that the HS with the sellback option was the most suitable design. Kazem *et al.* (2017) proposed the design and evaluated a hybrid wind/solar/ DG /battery system in terms of emissions and cost for the remote island of Masirah in Oman. HOMER software calculates the system size and lifetime cost of all the studies above. Meanwhile, Mahmood (2019) proposed an independent PV design to ensure uninterrupted power supply for electrical loads throughout the operational hours of three labs at Al-Nahrain University, Baghdad. The simulation was carried out utilizing the Pvsyst6 tool suite.

Previous literature reviews indicate that numerous studies have been conducted to identify the optimal hybrid energy system designs. These studies assess techno-economic feasibility and environmental benefits through various design scenarios and comparative analyses. HOMER Pro has proven to be a valuable tool in achieving these objectives. HOMER was employed in this study as one of the most widely used, open-source, and user-friendly platforms for hybrid energy system design**.** The present energy provision at the College of Science in Zakho University is wholly dependent on DGs and grid electricity, yielding a renewable proportion of 0%. This study aims to evaluate the effects of incorporating wind and solar PV panels into the power supply for the College of Science building at Zakho University. To reduce diesel consumption, mitigate environmental pollution, and enhance economic viability. The strategy provides substantial financial benefits, realising cost reductions and recouping its initial investment over time. The project improves dependence on RES, offering a more environmentally friendly and economically feasible energy option for the building.

Study Area:

The College of Science of the University of Zakho is located in Zakho city, a short distance from the Iraqi-Turkish border. It is at coordinates 37°6’48.00” N, 42°40’9.01” E. Figure 1 shows the location of the study. The Zakho district has varied weather patterns, with a median annual rainfall of 66.5 mm. Summers are arid and sweltering, occasionally attaining temperatures of 40 °C in July, and winters are temperate at 1.9°C in January.

The average wind velocity is around 5.2 km/h, with a relative humidity of 44.9 % (Ali, 2018). In Zakho, Global SRD levels reach their zenith in June and July, demonstrating the highest monthly averages, while December and January exhibit the smallest levels. The average monthly sunlight hours vary from 7.42 throughout winter to 14.11 during summer (Keya *et al*., 2023). Global Horizontal Irradiance (GHI) is a critical parameter for evaluating solar energy potential in flat-plate PV systems and concentrating technologies. The annual GHI in the study area is 1867.2 kWh/m², which falls within the optimal range for SE generation.

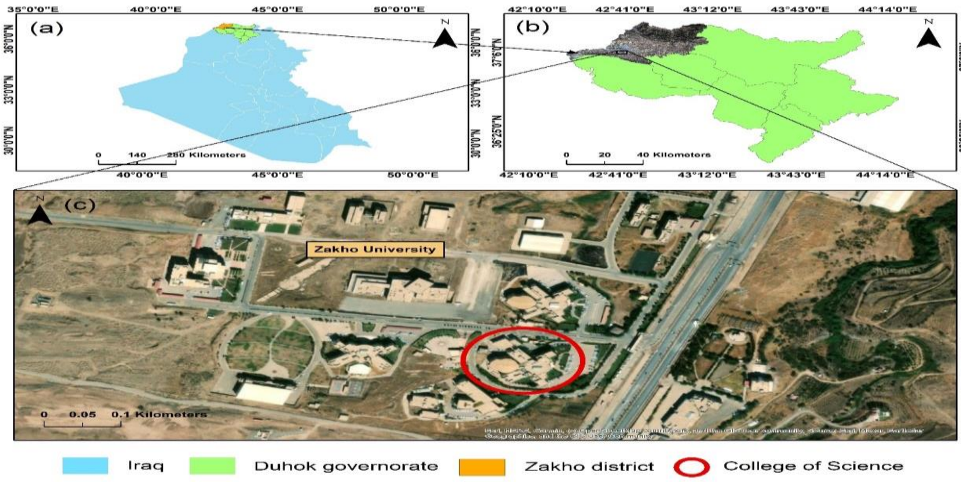

Figure 1: Location of the study area.

Estimation of Electrical Load Profile:

The College of Science building operates for 6 hours each day, from 9:00 a.m. to 3:00 p.m., Sunday to Thursday. Power demand is markedly reduced over the summer months of June, July, and August. The building contains a variety of electrical appliances, including laboratory equipment, laptops, cooling and heating systems, data projectors, heaters, TVs, printing devices, and several other items typically used in educational settings. The daily operating hours for each device were determined based on actual usage patterns. A clamp meter was used to measure the power consumption of each device in real time, recording values in amperes (A) and Volts (V). These measurements were then converted to kilowatts (kW).

Energy consumption was assessed individually for each season to examine fluctuations in load demand. Table 1 presents the key energy consumption parameters for the College of Science building.

Table 1: Energy consumption parameters for the College of Science building in Zakho University.

parameter	Value	Unit
Maximum power requirement	557	kW
Peak daily energy consumption	934	kWh/day
Annual energy consumption	211,586	kWh/year

Figure 2 displays the daily, seasonal, and annual load profiles. The load varies during the day, as indicated by the load profile. Peak power demand occurs throughout the daytime, specifically during operational hours. The following equation has been used to evaluate the electric load:

Yearly energy consumption $=\Sigma_i^n =1$ [m (appliance (i) * p $_{appliance}$ (i) * operation hour of appliance (i)) / 1000] (Mawlood & Hamarash, 2023) (1)

Where:

n: type of equipment.

m: number of equipment (i)

P: power rating (watts)

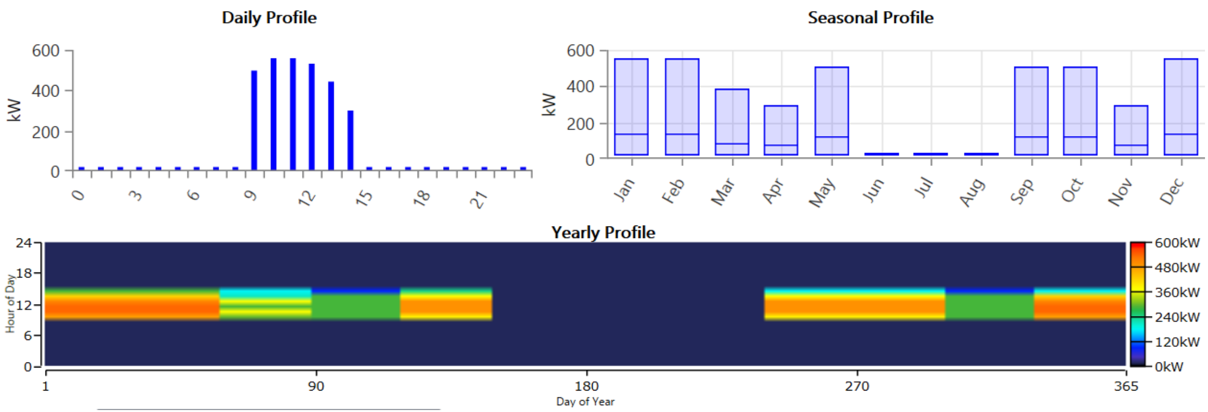

Figure 2: Load demand profile at the College of Science building in Zakho University.

HOMER Pro Software:

The HOMER pro software is a computational model created by the U.S. National Renewable Energy Laboratory (NREL). This tool has been employed to optimise hybrid designs. It assists in designing, planning, and figuring out how to build reliable and cost-effective microgrids that integrate conventional and RES, storage, and load control (HOMER-PRO SOFTWARE, 2024). The software evaluates the viability of the modelled system, providing the Levelized Cost of Energy (LCOE) and NPC as evaluation metrics. NPC and COE are utilised to assess the optimal design of HESs. NPC represents the life-cycle cost of the system, computed using equation (2):

$$NPC = C_{annual.tot} / CRF\ (i, L_{protect}) \qquad (2)$$

Where ($C_{annual.tot}$) represents the entire yearly cost, (i, $L_{protect}$) denotes the capital recovery factor, (i) signifies the interest rates (%), and ($L_{protect}$) indicates the project's lifespan. The COE represents the mean expense of producing usable energy, determined by the equation (3):

$$COE = C_{annual.tot} / E_{used} \qquad (3)$$

(E_{used}) denotes the energy utilised to meet the load (kWh/year). NREL periodically improves HOMER to rectify bugs and enhance the previous version to a superior iteration. This study mainly used the latest version of HOMER Pro (HOMER Pro X64) for system feasibility analysis. HOMER Pro necessitates many inputs to simulate the represented system. The key input categories are summarized in Table 2. The software performs three fundamental tasks: simulation, optimization, and sensitivity analysis.

Table 2: Essential input parameters required by HOMER Pro for system simulation.

Input	Condition
Meteorological Data	Natural assets, namely solar radiation, wind velocity, and temperature.
Load Profile	Electricity demand that the energy system must fulfil within a designated period. Specifically, loads from villages, hospitals, schools, and colleges.
Component Characteristics	Any design component that produces, transmits, transforms, or retains electricity, namely, PV modules, a DG, an inverter, and batteries.
Economic Data	optimisation and simulation phases encompass specific costs linked to each piece of equipment, including capital, replacement, maintenance, and overall project costs such as fixed capital, maintenance, and fines associated with emissions. The NPC for each configuration is calculated based on these expenditures.
Search Space	Diversity in the size of each component for optimisation.
Controller	Technical information encompassing the dispatch plan and operational reserve.

Meteorological Data:

The meteorological data used for this study were partially acquired through the Duhok Meteorological Directorate, covering a ten-year period (Directorate-of-Meteorology- duhok, 2024). Due to the lack of specific data, the supplementary data were acquired via HOMER Pro Software, which utilises NASA as its data source. The gathered data encompass temperature, wind speed, daily radiation, and clearness index. Clearness index and Daily radiation are key indicators of atmospheric transparency. The clearness index indicates the proportion of solar radiation penetrating the atmosphere and arriving at the Earth's surface. This is calculated by dividing surface radiation by extraterrestrial radiation, yielding a single-dimensional number between 0 and 1. During clear and sunny conditions, the clearness index exhibits a high value. On the other hand, during cloudy days, the clearness index demonstrates a diminished value. Figure 3 illustrates the study location's monthly average daily solar radiation (kWh/m²/day) and clearness index. Figures 4 and 5 present the location's average monthly temperature and wind velocity.

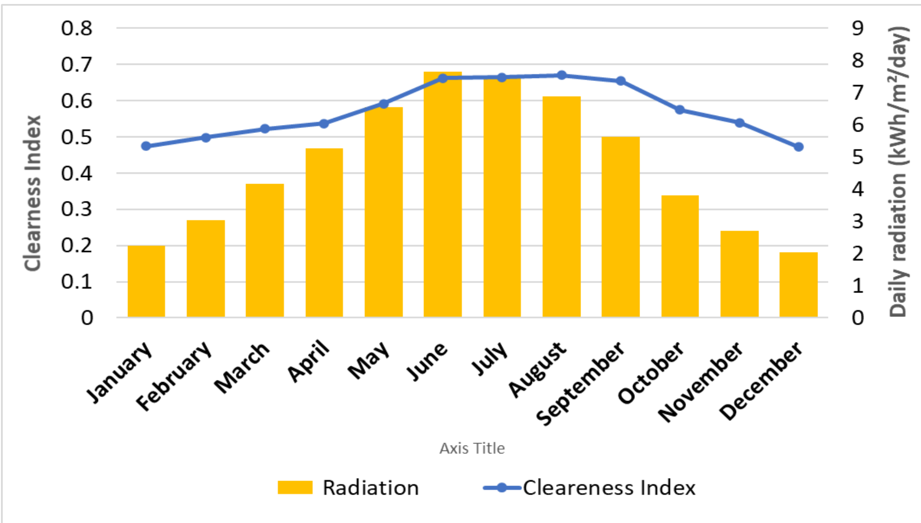

Figure 3: Solar monthly radiation and clearness index at the location.

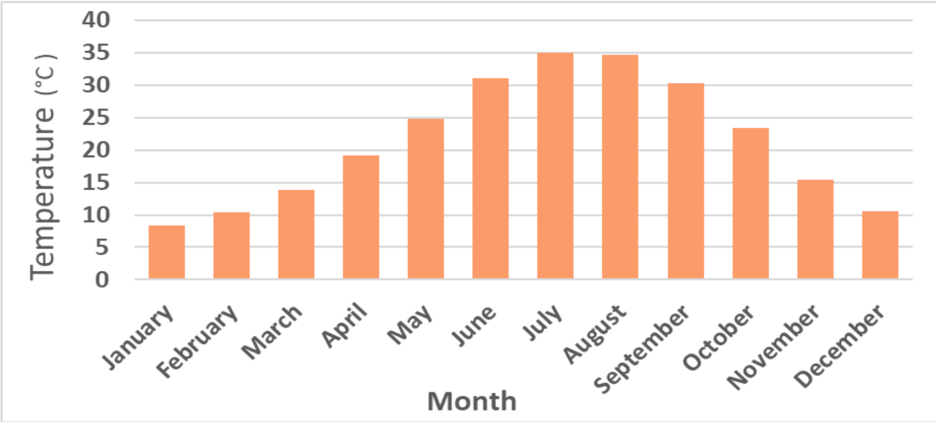

Figure 4: The monthly average temperature at the location.

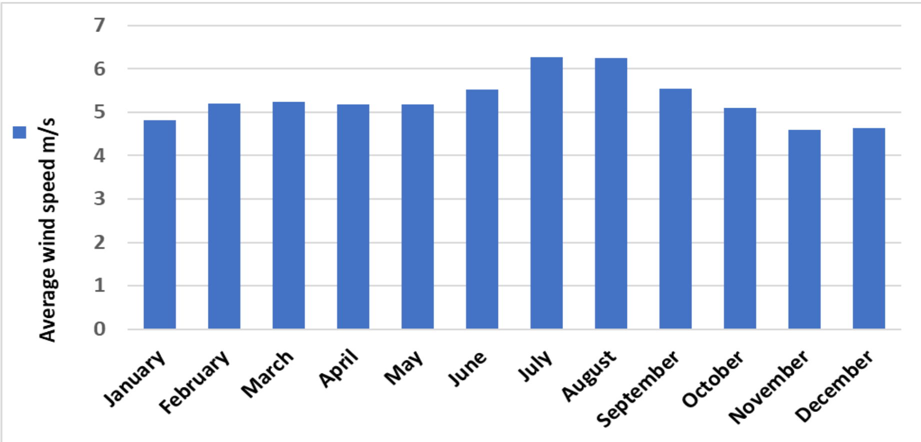

Figure 5: The monthly average wind velocity (m/s) at the location.

Grid Electricity:

Based on available data, the electricity supply in the Kurdistan Region is currently irregular. Due to high demand, the system provides energy for 10 to 12 hours daily, averaging three hours every interval. Electricity prices in the region vary according to consumption. The current cost for residential use ranges from \$0.013 to \$0.183 /kWh, based on consumption levels, while the rate for government facilities is \$0.061/kWh. This pricing mechanism is anticipated to change soon. According to the Project-Runaki (2025)The project, planned for completion by the end of 2026, aims to provide 24/7 electricity to the entire region. New rates will be applied across the region. According to this plan, the cost of residential electricity will range from \$0.054 to \$0.267 /kWh, whereas the government facilities will be charged \$0.091 /kWh (Project-Runaki, 2025).

System Design Specification and Cost Estimation

Solar PV Module:

The Jinko solar panel PV system is selected with an annual average of 5.11 kWh/m²/day. The ideal angle of azimuth for Zakho is 32 degrees (Ahmed *et al*., 2024). Each PV module delivers 720 watts; however, the energy supply is contingent upon sun availability. The price of the PV panel is around \$150 (based on the local market in Duhok, Kurdistan Region). The annual operating and maintenance (O&M) cost is estimated at \$10, with a derating factor of 88%. The manufacturer specifies a lifespan of 30 years for this PV panel system. Table 3 presents the cost inputs for the solar panel.

Table 3: Cost inputs for PV modules.

Type	Jinko flat plate PV
Lifetime	30 years
Derating factor	88 %
Efficiency	17.8%
Capital cost	\$150
Installation cost	\$100
O & M	\$ 10 /year

Wind Turbine:

The XANT M-24 Wind Turbine is selected based on the average wind speed of 5.29 m/s at an elevation of 38 m. It generates 95 kW of alternating power. The amount of electricity produced is contingent upon wind speed variations and availability. The annual set-up and O&M costs are estimated at \$32,000 and \$300, respectively. The operational lifespan of this turbine is 20 years (Akhtari & Karlström, 2019)). Table 4 displays the cost inputs for the WT.

Table 4: Wind turbine cost inputs.

Type	XANT M-24 [95kw]
Lifetime	20 years
Hub height	38 m
Capital cost	$ 32000
Installation cost	$ 32000
O & M	$ 300/year

Battery:

A battery bank is recommended as a backup device and energy storage solution. The chosen battery for this design is a Lithium Iron Phosphate (LIP) with a nominal voltage of 48 V, a maximum capacity of 2100 Ampere-hours (Ah), and a nominal capacity of 101 kWh. The capital and installation costs for a single unit of this battery have been estimated at around $18,180. (Akhtari & Karlström, 2019). The cost inputs for the storage battery are shown in Table 5.

Table 5: Storage battery cost inputs.

Type	Lithium Iron Phosphate
Lifetime	Lifetime 10 years
Nominal Capacity	101 kWh
initial cost	$ 18,180
replacement cost	$ 18,180.
O & M	$ 0

onverter Arrangement:

The converter can convert direct current (DC) to alternating current (AC), and vice versa, indicating that the converter operates as a rectifier or an inverter. In the design model, changing the DC voltage supplied by the PV modules and batteries is necessary, as AC loads utilize the energy. So, in this research, a 100-kW converter was used for conversion purposes. The capital cost and Replacement cost are estimated at $171/ kW, with O&M cost of $4/ kW/ year. The lifespan is 15 years. Table 6 displays the cost inputs for the converter.

Table 6: Converter cost inputs.

Type	System converter (100 kW)
Lifetime	15 years
Efficiency	95%
Capital cost	$171/ kw
Replacement cost	$171/ kw
O & M	$ 4/ kw/ year

Diesel Generator (DG)

The Generic 500 kW Fixed Capacity Generator Set DG has been chosen for this model in the HOMER program. This generator's initial and replacement costs are estimated at $150,000 and $100,000, respectively, while the annual O&M is $5,000. The fuel price in Iraq is approximately $0.50 per litre. The generator emits carbon dioxide at a rate of 13.566 g/L of fuel and has a lifespan of 15,000 hours. Table 7 displays the cost inputs for the DG.

Table 7: Diesel generator cost inputs.

Type	Generic 500 kW Fixed Capacity Genset
Lifetime	15000 hours
Capital cost	$ 150,000
Replacement cost	$ 100,000
O & M	$ 5,000 (per op. Hour)

Analysed Cases:

Two cases were examined to provide energy to the Faculty of Science at the University of Zakho, utilising various energy sources.

a) Case 1:

In this case, PV, WT, and the grid provided power to the load. This instance included grid-tied PV, WT, battery storage, and a converter, as shown in Figure 6.

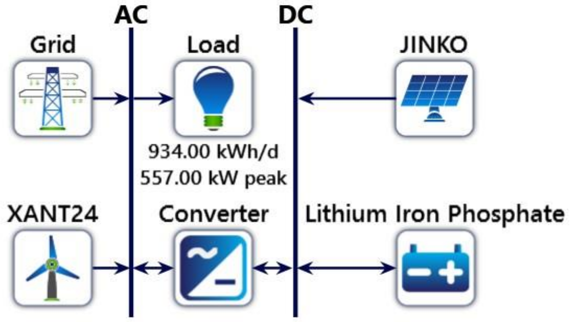

Figure 6: Schematic diagram of the grid-connected PV system.

b) Case 2

In this case, PV, WT, and DG supplied power to the load independently of the grid. This scenario featured PV, WT, DG, battery storage, and converters, as shown in Figure 7.

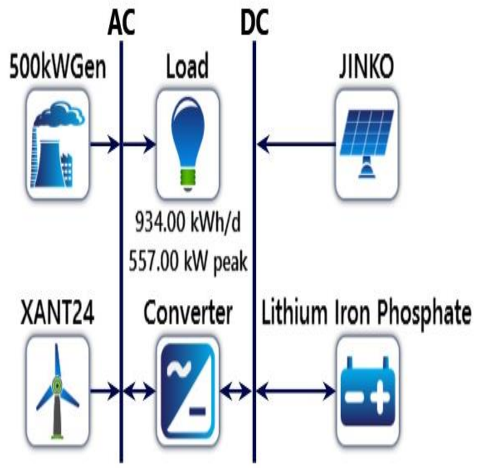

Figure 7: Schematic diagram of a stand-alone PV system.

2. RESULTS AND DISCUSSION

Optimisation Results:

College of Science building at Zakho University. Figure 8 illustrates the overall expenditures for both cases. Consequently, case (1), including PV, wind, grid power, battery storage, and converters, represents the most economically viable design among both scenarios. The NPC for the on-grid model is $295,544; whereas, for the stand-alone design it is $699,146.20. The off-grid power architecture for the identical load is more costly ($403,602) than the on-grid system. For the on-grid design, the simulated COE in this study is $0.0194/kWh, which is lower than the $0.0435/kWh COE of the most economical among the four systems assessed in the study done at the College of Engineering, University of Baghdad by (Abdullah & Habbi, 2024).

It is also more cost-effective than the $0.0890/kWh COE, which signifies the most inexpensive COE among the systems optimised by KABAO and Omar (2023) for the schools in the eight regions of Duhok province.

An optimal number of RES is activated for the off-grid model to provide power to meet the load. The LCOE of stand-alone design is $0.159 /kWh, which is lower than the best scenario for the Electrical Engineering Technical College (EETC) in Baghdad, Iraq, where the LCOE is $0.372/kWh, as stated by Ibrahim *et al.,* (2023). It is also less expensive than the COE of $0.236/kWh for the College of Engineering at Al-Nahrain University in Baghdad, Iraq, as reported by Mahmood *et al.* (2020).

Tables 8 and 9 contain the cost summary for both designs, detailing the economic performance of the essential components of the on-grid configuration, including capital cost (C. Cap.), operating and maintenance cost (C. O&M), replacement Cost (C. Rep.), and salvage costs (C. Sal.) for each component in the two arrangements.

The total capital cost of the on-grid design is $451,508, whereas for the standalone model, it is $553,479. Furthermore, based on HOMER, the simple payback period for the grid-tied design is 7.9 years, whereas for the stand-alone configuration, it is 5.7 years. Additionally, both designs are designed to minimize reliance on fossil fuels. The first case presents a more economical alternative owing to the lack of construction expenditures for the grid infrastructure. Moreover, it facilitates selling more energy to the grid than is purchased.

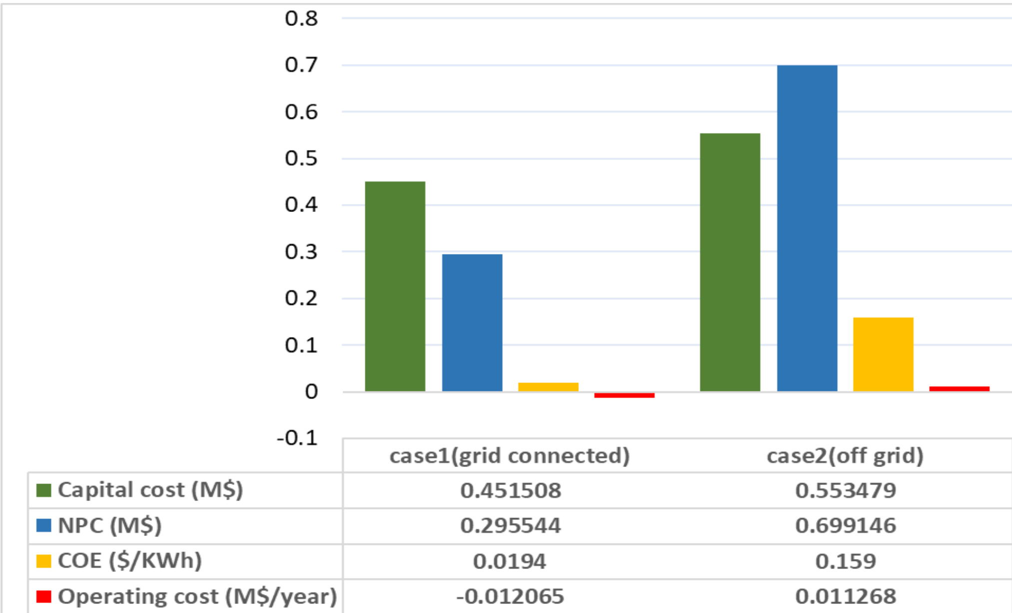

Figure 8: Costs related to the system for each case.

Table 8: Cost Summary of the Model (for On-Grid System).

COMPONENT	C. Cap. ($)	C. O&M ($)	C. Rep. ($)	C. Sal. ($)	Total ($)
Grid	0.00	-268,573	$0.00	0.00	-268,573
JINKO PV	132,510	114,202	$0.00	-3,527	243,185
LIP Battery	218,160	33.04	$0.00	-50,955	167,238
Converter	68,838	20,817	$29,206	-5,497	113,364
WT [95kw]	32,000	3,878	$10,202	-5,749	40,331
Total	451,508	-129,643	$39,408	-65,729	295,544

Table 9: Cost Summary of the Model (for stand-alone design).

COMPONENT	C. Cap. ($)	C. O&M ($)	C. Rep. ($)	C. Sal. ($)	C. Fuel ($)	Total ($)
DG (500kw)	150,000	14,220	0.00	-15,172	57,486	206,535
JINKO PV	88,542	76,308	0.00	-2,357	0.00	162,493
LIP Battery	218,160	33.04	0.00	-35,081	0.00	183,112
Converter	64,777	19,588	27,483	-5,173	0.00	106,676
WT (95kw)	32,000	3,878	10,202	-5,749	0.00	40,331
Total	553,479	114,028	37,685	-63,532	57,486	699,146

Electrical Results and System Performance:

The proposed system was modelled using HOMER Pro software. The optimal configuration scenario involves an HS combining solar PV/wind/grid electricity/ battery system. Having an output energy of 636 kW from solar PV, 95 kW from the WT, and 12 strings of LIP batteries, each possessing a capacity of 2100 Ah, alongside a converter capacity of 403 kW. The PV array produces the highest power production at 80.6%, 1,027,700 kWh/year, followed by WT generation at 15.7%, (200,673 kWh/year), while grid purchases constitute 3.69%, (47,104 kWh/year) of the overall power produced by the HS. The entire electric power generation of this system design was 1,275,476 kWh/ year, 100%, whereas the overall power consumption of the AC load was approximately 211,586 kWh/year. The design could sell 836,182 kWh of electricity to the grid annually, resulting in an estimated financial benefit of $20,775.28 /year. Figure 9 presents the overall energy acquired from and sent to the grid in kWh each month. Figure 10 illustrates the system's total generated electricity (kWh/year) attributed to each component: PV, WT, and grid purchase.

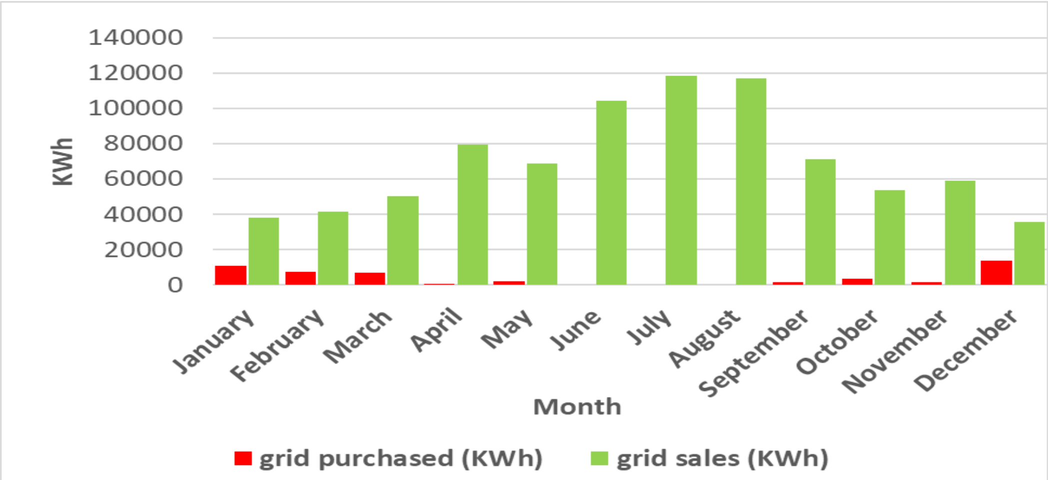

Figure 9: Monthly total energy purchased from and sold to the grid (kWh).

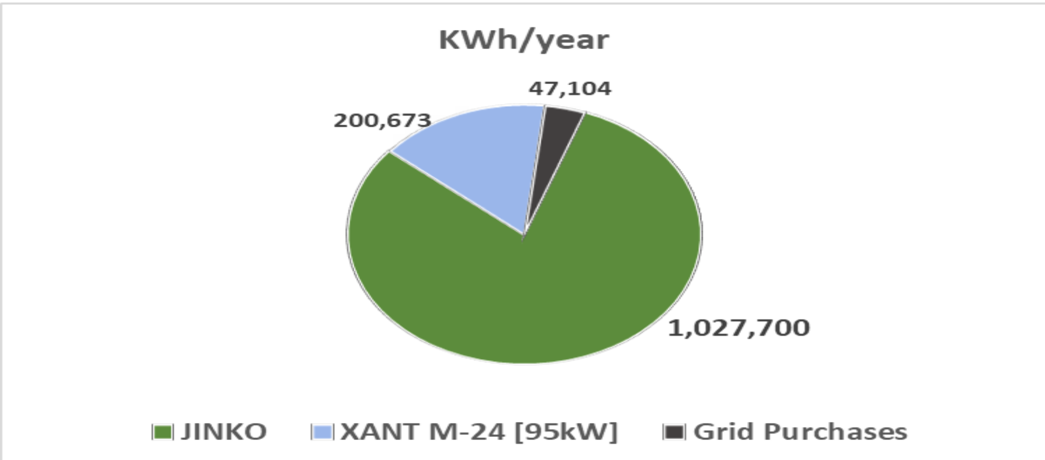

Figure 10: Yearly total electricity generation of the on-grid system (kWh).

Emissions:

The emissions data were obtained using the simulated results of the HOMER Pro software to determine the annual quantity of each pollutant produced by the power system, quantified in kilograms per year (Kg/year). The current power system at the university relies exclusively on non-renewable sources, specifically from the national grid and DGs, resulting in a renewable fraction of 0%. The off-grid configuration employs 91.2% RE and relies on the diesel generator for only 3.2% of its total energy production. On the other hand, the on-grid model is marginally superior, depending on 96% renewable sources. These results closely align with the KABAO and Omar (2023) study on schools across six sites: Akre, Mangesh, Semel, Amedi, Bamarni, and Kanimasi. with RE contributions of 90.1%, 92.7%, 94.7%, 96.2%, 96.8%, and 97.7%, respectively.

In this study, the CO_2 emissions generated by the stand-alone configuration were 23,321 kg/year, compared to 29,769 kg/year for the grid-connected design. As shown in Table 10, the emissions associated with each energy system are presented. Furthermore, both designs substantially minimize air pollution. Thus, increasing the share of RE in the power system helps the environment, facilitates a swifter financial return, and reduces operational costs (Adaramola *et al.*, 2014; Wang *et al.*, 2020). The grid-connected model is the most environmentally beneficial alternative in this study, since it efficiently reduces carbon monoxide (CO), particulate matter (PM), and unburned hydrocarbons (UHC). Figure 11 illustrates the overall monthly average RE generation for the grid-connected design. The system produces hundreds of kilowatts monthly via RESs.

The emission results of this study indicate a significant reduction in CO_2 and other harmful gases across the hybrid energy designs, representing a major advancement toward environmental sustainability. Iraq's current electricity system depends on fossil fuels for over 98% of its generation, with per capita CO_2 emissions reaching 2.3 tCO_2, above the global average of 1.8 tCO_2. However, Iraq has not yet established a clear RE generation target for 2030 (Ember-energy.org, 2025). The findings of this research offer a practical contribution toward achieving that national goal.

Table 10: Emissions Comparison of Energy Systems.

Pollutant	Off-grid design (kg/y)	On-grid design (kg/y)
Carbon dioxide (CO2)	23,321	29,769
Carbon monoxide (CO)	121	0
UHC	6.40	0
Particulate matter (PM)	1.03	0
Sulphur dioxide (SO2)	57	129
Nitrogen Oxides (NOx)	23.1	63.1

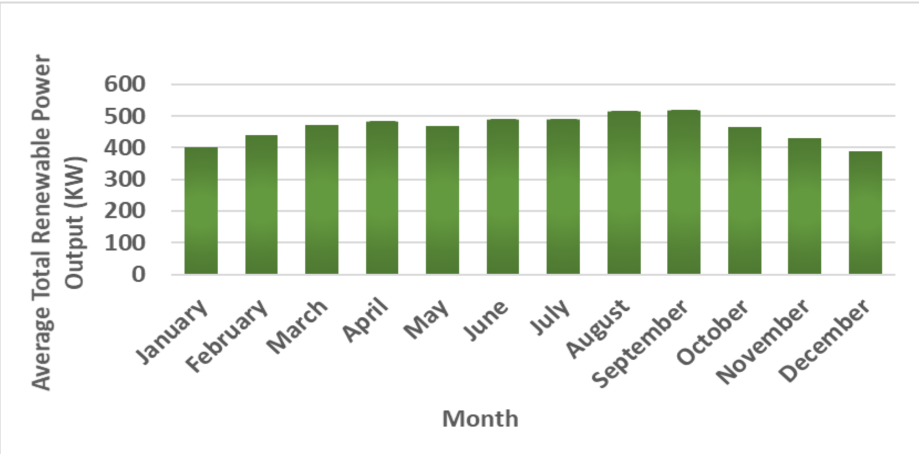

Figure 11: Total monthly average renewable power output for the grid-connected system.

CONCLUSION

This study modelled both grid-connected and standalone PV systems for the College of Science at the University of Zakho, Iraq, utilizing HOMER Pro software. The findings demonstrate that the grid-dependent HS including PV panels, wind turbines, and battery storage is more suitable than the off-grid configuration (PV, DG, wind turbine, and battery) for identical load requirements, owing to its markedly reduced COE of $0.0194/ kWh, in contrast to $0.159/ kWh for the off-grid system. Alongside its lower COE, the grid-tied model demonstrates a reduced NPC compared to the off-grid design. Moreover, the study indicates that the on-grid system comprises 96% renewable energy, and the stand-alone model has 91.2%, illustrating high reliance on clean energy in both scenarios. Concerning the environment, both models possess beneficial attributes for ecosystem preservation.

Finally, a hybrid energy system is strongly recommended to enhance energy stability and reduce the reliance on harmful gases. This would facilitate clean energy planning for university campuses in a country that relies heavily on conventional energy sources. Hopefully, this study will motivate authorities to prioritize renewable energy development in KRG /Iraq, which possesses substantial solar and wind resources suitable for primary electricity generation.

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Authors Contribution Details:

B. S. S, as the primary author, conducted data collection, designed the system, performed data analysis, and carried out optimisation processes. K. M. Y., as the supervisor, conceptualised the study, designed the methodology, contributed to data interpretation, and critically reviewed and edited the manuscript.

Ethical Statement:

The Ethical Committee of the College of Science at the University of Zakho, Kurdistan Region, approved the current experiment.

REFERENCES

Abdullah, A. K., & Habbi, H. M. D. (2024). Enhancing Sustainable Energy Integration with a Techno-Economic Evaluation of Hybrid Renewable Energy Systems at the College of Engineering in the University of Baghdad. *Journal of Engineering*, *30*(11), 71-89. https://doi.org/10.31026/j.eng.2024.11.05

Adaramola, M. S., Paul, S. S., & Oyewola, O. M. (2014). Assessment of decentralized hybrid PV solar-diesel power system for applications in Northern part of Nigeria. *Energy for Sustainable Development*, *19*, 72-82. https://doi.org/10.1016/j.esd.2013.12.007

Ahmed, A. M., Kareem, I. M., & Abdulateef, L. A. (2024). Sustainable Solar Energy Development in Zakho, Iraq: A Techno-Economic And Environmental Assessment. *Journal of Advanced Zoology*, *45*(3). 88-91. https://doi.org/Journal

Akhtari, M. R., & Karlström, O. (2019). Techno-Economic Assessment Ofhybrid Renewable Energy System (Hres) in Northern Europe. *Available at SSRN 4743194*. doi: 10.1016/j.renene.2019.10.169

Akram, U., Khalid, M., & Shafiq, S. (2018). Optimal sizing of a wind/solar/battery hybrid grid-connected microgrid system. *IET Renewable Power Generation*, *12*(1), 72- https://doi.org/10.1049/iet-rpg.2017.0010

Aktacir, M. A., & Sadiq, H. Z. (2025). A Small-Scale Hybrid Power System Consisting of On-Grid Photovoltaic System and Energy Storage Unit: A Case Study. *Energy Storage*, *7*(2), e70152. https://doi.org/ https://doi.org/10.1002/est2.70152

Al-Sarraj, A., Salloom, H., Mohammad, K., & Ghareeb, M. (2020). Simulation design of hybrid system (grid/PV/wind turbine/battery/diesel) with applying HOMER: A case study in Baghdad, Iraq. *Int J Electron Commun Eng*, *7*, 10-18 http://www.internationaljournalssrg.org/

Al-Shammari, Z. W., Azizan, M., & Rahman, A. (2021). Grid-independent pv-wind-diesel generator hybrid renewable energy system for a medium population: A case study. *Journal of Engineering Science and Technology*, *16*(1), 92-106. https://jestec.taylors.edu.my/V

Alghamdi, A. H. S., Castro, C. H. M. R., & Zamora, R. (2018). Review of cost optimization of electricity supply by using homer and a case study for a big commercial customer in brazilian amazon area. Smart Grid and Innovative Frontiers in Telecommunications: Third International Conference, SmartGIFT 2018, Auckland, New Zealand, April 23-24, 2018, Proceedings, https://doi.org/10.1007/978-3-319-94965-9_22

Ali, F. A. (2018). Optimum tilt angle of photovoltaic panels for some Iraq cities. *Journal of University of Babylon for Engineering Sciences*, *26*(1), 155-163. https://www.journalofbabylon.com/index.php/JUBES/article/download/1191/939

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), 8121. https://doi.org/10.3390/su14138121

Directorate-of-Meteorology- duhok. (2024). Retrieved september 9, 2024 from http://duhokprovince.com/directorate-of-meteorology-seismology-duhok/

Ember-energy.org. (2025). Retrieved JUNE 12, 2025 from https://ember-energy.org/

HOMER-PRO SOFTWARE. (2024). Retrieved 2 APRIL 2025 from https://www.homerenergy.com/products/pro/index.html

Hussain, A. N., Al-Tamimi, M. K. A., & Abid, M. (2021). On-grid Photovoltaic Power System for Governmental Office Electrification. *Journal of Techniques*, *3*(2), 45-52. https://doi.org/10.51173/jt.v3i2.325

Ibrahim, L. Q., Abid, A. J., Obed, A. A., Saleh, A. L., & Hassoon, R. J. (2023). A HOMER-Aided Study for PV System Design and Cost Analysis for a College Campus in Baghdad. *Journal of Techniques*, *5*(2), 95-107. https://doi.org/10.51173/jt.v5i2.722

KABAO, F. K., & Omar, O. S. (2023). Sizing Photovoltaic System In Duhok Province, Kurdistan Region Of Iraq. *Science Journal of University of Zakho*, *11*(3), 346–354-346–354. https://doi.org/10.25271/sjuoz.2023.11.3.1098

Karimi, Z. M. (2014). *Modelling, implementation and performance analysis of a hybrid wind solar power generator with battery storage* Universidade de Coimbra (Portugal)]https://estudogeral.uc.pt/bitstream/10316/39033/1/.

Kazem, H. A., Al-Badi, H. A., Al Busaidi, A. S., & Chaichan, M. T. (2017). Optimum design and evaluation of hybrid solar/wind/diesel power system for Masirah Island.

Environment, Development and Sustainability, *19*, 1761-1778. https://wayf.springernature.com/?redirect_uri
KEYA, D. R., Farangis, B., Sirwan, R., & Behler, K. (2023). 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://www.researchgate.net/publication/374337647_
Kim, H., Baek, S., Park, E., & Chang, H. J. (2014). Optimal green energy management in Jeju, South Korea–On-grid and off-grid electrification. *Renewable Energy*, *69*, 123-133. https://doi.org/10.1016/j.renene.2014.03.004
KRG. (2025). *The Kurdistan Regional Government (KRG) has started work on a new solar power project on Thursday 18 May.* Retrieved June 14, 2025 from
Mahmood, A. (2019). Design and simulation of stand-alone pv system for electronic and communications engineering department laboratories in Al-Nahrain University. *EAI endorsed Transactions on Energy web*, *6*(22), e9-e9 https://doi.org/10.4108/eai.13-7-2018.156438 .
Mahmood, A. L., Shakir, A. M., & Numan, B. A. (2020). Design and performance analysis of stand-alone PV system at Al-Nahrain University, Baghdad, Iraq. *International Journal of Power Electronics and Drive Systems*, *11*(2), http://ijpeds.iaescore.com
Mawlood, A. T., & Hamarash, I. I. (2023). Design and Simulation of a Hybrid Wind/Solar/Diesel/Battery Off-Grid System for Rural Areas: A case Study in Al-Mahmudiyah Tribal Zone of Iraq. *Zanco Journal of Pure and Applied Sciences*, *35*(2), 9-21. http://dx.doi.org/10.21271/zjpas
Mohamed, M. A., Eltamaly, A. M., & Alolah, A. I. (2017). Swarm intelligence-based optimization of grid-dependent hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, *77*, 515-524.https://doi.org/10.1016/j.rser.2017.04.048
Ndwali, K., Njiri, J. G., & Wanjiru, E. M. (2020). Multi-objective optimal sizing of grid connected photovoltaic batteryless system minimizing the total life cycle cost and the grid energy. *Renewable Energy*, *148*, 1256-1265. https://doi.org/10.1016/j.renen
Omar, M. A. (2025). Techno-Economic Analysis of PV/Diesel/Battery Hybrid System for Rural Community Electrification: A Case Study in the Northern West Bank. *Energy*, 134770. https://doi.org/10.1016/j.energy.2025.134770
Project-Runaki. (2025). *Ronaki Project* Retrieved June 13,2025 from https://runaki.gov.krd/en/
Qasim, M. A., Yaqoob, S. J., Bajaj, M., Blazek, V., & Obed, A. A. (2025). Techno-Economic Optimization of Hybrid Power Systems for Sustainable Energy in Remote Communities of Iraq. *Results in Engineering*, 104283. https://doi.org/10.1016/j.rineng.2025.104283
Ramoliya, J. V. (2015). Performance evaluation of grid-connected solar photovoltaic plant using PVSYST software. *Journal of Emerging Technologies and Innovative Research (JETIR)*, *2*(2), 7. https://doi.org/www.jetir.org
Ren, H., Wu, Q., Gao, W., & Zhou, W. (2016). Optimal operation of a grid-connected hybrid PV/fuel cell/battery energy system for residential applications. *Energy*, *113*, 702-712. https://doi.org/10.1016/j.energy.2016.07.091
Salim, H. A., & Rashed, J. R. (2025). Feasibility Study of Off-Grid Rural Electrification in Iraq: A Case Study of the AL-Teeb Area. https://doi.org/10.37917/ijeee.21.1.24
Shafaq-News. (2025). Retrieved June 14, 2025 from https://shafaq.com/en/Kurdistan/Solar-power-revolution-Erbil-villages-embrace-clean-energy
Shahveran, E., & Yousefi, H. (2025). Replacing fossil fuel-based power plants with renewables to meet Iran's environmental commitments in the electricity sector. *Renewable and Sustainable Energy Transition*, *7*, 100102. https://doi.org/10.1016/j.rset.2024.100102
Usman, H. M., Sharma, N. K., Joshi, D. K., Kaushik, A., Kumhar, S., Saminu, S., & Yero, A. B. (2024). Techno-Economic Optimization and Sensitivity Analysis of a Hybrid Grid-Connected Microgrid System for Sustainable Energy. *Jurnal Ilmiah Teknik Elektro Komputer dan Informatika (JITEKI)*, *10*(4), 704-722. https://doi.org/10.26555/jiteki.v10i4.30221
Wang, Q., Jiang, X.-t., Yang, X., & Ge, S. (2020). Comparative analysis of drivers of energy consumption in China, the USA and India–a perspective from stratified heterogeneity. *Science of the total environment*, *698*, 134117. https://doi.org/10.1016/j.scitotenv.2019.134117