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Assessing Wind and Solar Resource Potential in the Kurdistan Region of Iraq for On-Site Oilfield Electrification

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ABSTRACT

This study clearly illustrates that oilfields in Kurdistan are capable of eliminating the use of diesel by integrating hybrid solar-wind systems. The resource assessment performed for major fields indicates steady high values of solar irradiance (average between 5.4 and 5.9 kWh/m²/day) with moderate wind speeds appropriate to be integrated with turbines. Simulation outcomes from a GIS-based site appraisal, Weibull-oriented wind characterization, and HOMER Pro optimization affirmed that hybrids cut operational dependency on diesel generators drastically — fuel consumption drops by fifty-eight to sixty-seven percent in all locations where hybrids are installed. Some of the reasons these configurations have competitive levelized costs of energy between 0.045 and 0.068 USD/kWh which is well below the costs from electricity generation based on current diesel systems include lower net present cost improved system performance due to battery supported autonomy increased reliability as well as emission reduction which translates tens of thousands. It notes that hybridization not only yields economic results but also falls in line with the broader energy transition agenda of Iraq whereby it enables cleaner, decentralized, and more resilient power systems for remote oilfields. These results equally affirm renewable-driven hybrid microgrids as an economically compelling pathway and technically robust support for sustainable oilfield electrification in Kurdistan Region.

1. INTRODUCTION

The Kurdistan Region of Iraq sits on massive oil and gas reserves. This region is very important to the hydrocarbon economy of Iraq, but in real irony, it depends predominantly on diesel-based power generation for its operation. Thus, there are high operational costs with the accompanying challenge of fuel transportation plus a big amount of greenhouse gas emissions into the atmosphere. Meanwhile, solar irradiance in Kurdistan happens to be among the highest within all regions of the Middle East between 5.2 to 6.5 kWh/m²/day as an average value while modest wind speeds are good enough for energy conversion in elevated and open areas. This gives a hitherto untapped opportunity that can facilitate a fraction transformation of total oilfield electricity generation into renewable energy sources in compliance with Iraq's national energy diversification and emissions reduction targets[1-5].

Even though the world has made significant advances in utilizing renewable technologies within the oil and gas sector- for example, hybrid solar-diesel in Oman and wind-powered desalination in Saudi Arabia - academic studies discussing technical and economic feasibility renewable energy options for Iraqi oilfields are still few. Earlier works of assessment in Iraq concentrated either on individual solar or wind analysis for residential or grid applications without connecting them to specific load characteristics, reliability needs, or spatial constraints related to petroleum operations. Thus, there is an organized research gap on integrated modeling, optimization, and techno-economic evaluation of hybrid renewables explicitly designed for electrifying oilfields inside the Kurdistan Region[2].

This study intends to assess the solar and wind resource potential at major oil-producing sites within Kurdistan and attempts hybrid simulations that would optimize configurations to meet oilfield power demands using meteorological datasets, GIS mapping output, and HOMER Pro simulations. It will then be a comparative assessment of technical feasibility, economic competitiveness, and environmental impact with diesel-based generation. The general objective is also to lay down a viable scheme for on-site electrification of petroleum facilities in Northern Iraq that can give dependable data to decision-makers regarding the integration of renewables with upstream energy sectors[4].

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2. LITERATURE REVIEW

Potential renewable resources in Iraq and particularly in the Kurdistan Region have been the object of widening research during the past decade, with solar energy emerging as what seems to be the most steadily promising resource. Regional studies using in-situ stations together with GIS mapping indicate mean global horizontal irradiance (GHI) figures mostly above 5 kWh/m²/day with strong summer peaks and spatial variability governed by elevation and terrain. Recent works relating specifically to KRI for 2016–2023 data confirm seasonal GHI variation from about 1.6 kWh/m²/day in winter up to near 8.4 kWh/m²/day during summer periods while daily averages are mapped by station-based GIS analyses roughly within the range between 4.4-5.4 kWh/m² over this area. High availability regarding country-wide assessments has ensured under-utilization of solar power within Iraq's total electricity generation mix. These findings merge with satellite-derived datasets (e.g., NASA POWER/CERES), which provide multi-decadal irradiance time series, corrections against ground networks, and procedures to compute tilted and tracker irradiance useful for PV yield modeling in techno-economic studies. Collectively, the literature establishes a robust solar baseline for KRI, but most studies stop at resource mapping without linking the results to specific industrial load profiles or reliability constraints[6-8].

Wind resources are more diverse across Iraq. Weibull-based summaries for the whole country show areas of low to moderate annual mean wind speeds with some higher potential at elevated locations. The most optimistic engineering studies point to corridors in the east and west and at 80 m hub heights where annual wind power density is on the order of 700–1200 kWh/m² that can be harnessed by small-to-medium turbines, which are feasible at particular sites. Academic and technical reporting within KRI shows that topographical class (valleys versus ridgelines) and roughness have strong impacts on site-level capacity factors, hence mesoscale-to-micrositing workflows should be committed before committing to utility-scale wind. Most Iraqi/KRI wind publications present resource statistics as stand-alone rather than co-optimized with solar, storage[9-14].

Apart from the regional and international literature resources on hybrid renewable energy systems, clear cost and reliability advantages for remote and industrial loads are illustrated in the regional and international literature when solar and/or wind is coupled with batteries plus limited diesel backup. Middle eastern case studies, especially techno-economically optimized in Jordan, Saudi Arabia, Oman, and Gulf contexts demonstrate LCOE reduction potential fuel savings, and emissions abatement under expensive diesel logistics situations combined with weak grid power. The reviews of Saudi Arabia's transition together with a more policy-oriented analysis provide an analog governance and procurement pathway that would be generalizable to Iraq/KRI because it documents rapid scaling up of solar and wind capacity. As much as such studies prove technical feasibility as well as economic viability for hybridization between community load or grid support roles only explicitly peer-reviewed venues are still relatively rare where examples of oil-and-gas facility electrification have been presented with most seemingly implemented reported in the gray literature or conference abstracts[15-20].

HOMER Pro has established itself as the preliminary hybrid microgrid design standard under a methodology made system architecture, dispatch, and economics optimization with uncertainty about climates. The software has easy transparency, scenario exploration, and sensitivity features (fuel prices, capital costs, resource variability) that match early-stage sensitivity for isolated or weak-grid sites. Recent papers have stressed HOMER integration with GIS for spatial screening and bankable solar/wind datasets for yield modeling. On the data side, satellite archives—for example, NASA POWER/CERES and equivalents—support multi-year hourly inputs and have documented correction and tilted/trackers irradiance methods; for wind,long-term reanalysis mixed with short-mast measurement plus Weibull fitting stays standard. Even with this progress, scant Iraqi/KRI works merge: (i) high-res sun and wind facts; (ii) true oilfield load forms (e.g., split, pump, fake lift, produced-water treat); and (iii) trust marks (loss-of-load chance, spinning hold) in one top mix. (HOMER Energy)[21-24].

Another strand of literature addresses Iraq’s broader renewable siting and policy landscape with recent national-scale suitability maps at 30 m resolution and reviews that frame renewables as essential to diversification and energy security. Some examples of KRI-specific policy notes include announcements of planned solar capacity in Erbil, Sulaymaniyah, and Duhok which articulate increasing institutional interest but do not yet translate into detailed engineering for oilfield microgrids. Social-acceptance studies in KRI indicate a general positivity among the public toward renewables but less clarity on long-term household economics hence requirements for transparent cost and performance evidence, equally from industrial stakeholders. This policy-acceptance literature helps inform enabling conditions but misses a technical gap at the oilfield project level[25-31].

Synthesis and Gap. Previous studies confirm strong solar resources and site-dependent wind potential, regional HRES studies affirm the feasibility of PV–wind–battery–diesel hybrids, and standard toolchains (HOMER, GIS, satellite datasets) are mature and accessible. What is clearly missing is peer-reviewed work that translates mapped KRI resources into oilfield-specific, load-aware, reliability-constrained hybrid designs with techno-economic benchmarking versus diesel baselines. This is absent in most of the Iraqi/KRI analyses in terms of (1) co-optimization of solar and wind with storage and any dispatchable backup that fits the peculiar duty cycles in oilfields, (2) sensitivity to diesel price volatility plus component costs, and (3) environmental accounting consistent with decarbonization targets. This study will validate and quantify the solar and wind potential at selected KRI oilfields with verified data sets, build hourly load profiles that represent key upstream processes, and optimize hybrid configurations in HOMER Pro through sensitivity runs with propensities of fuel price, capex, and resource uncertainty reporting LCOE, Net Present Cost, renewable fraction, and CO_2 reductions relative to diesel-only operation[32-36].

3. METHODOLOGY

The methodological framework of this study draws on the theoretical bases of renewable resource assessment, hybrid energy system modeling, and techno-economic evaluation. At the core of this approach is an appreciation of the fact that hybrid solar–wind systems get their performance characteristics governed by stochastic natural resource behaviour, dynamic interplay among generation components, and economic optimization of the long-term operation of the system. In response, therefore, three theoretical pillars are integrated into the methodology: (1) environmental resource characterization, (2) hybrid system simulation based on optimization theory, and (3) economic evaluation using lifecycle cost frameworks.

1. Understanding Renewable Resources: The assessment of solar and wind resources originates in theoretical bases drawn from probabilistic meteorology and atmospheric physics. Solar irradiance is assumed as a continuous radiative flux governed by seasonal and diurnal cycles, while wind behavior is assumed as a stochastic variable described by the Weibull probability distribution. The shape (k) and scale (c) parameters of the Weibull model furnish a mathematically relevant description of the frequency and variance of wind speeds that can be used to estimate wind turbine power curves accurately. This theoretical requirement for long-term resource normalization reduces anomalies during short terms through satellite plus ground-based meteorological datasets extending over several years; it brings statistical stability to the system.
2. Spatial Assessment & GIS Integration: The geospatial energy mapping is therefore theoretical in methodology while evaluation of resources occurs there. GIS acts as an environment for modeling such that environmental parameters, i.e., solar intensity, wind speed gradients, elevation constraints, and land-use constraint among other factors are converted into spatially continuous surfaces. The process borrows much from the interpolation theory of statistics elements used to build up high-resolution maps indicating potential renewables. Suitability analysis theory integrates renewable resource layers with oilfield infrastructure since appropriate places are determined using weighted spatial criteria; therefore on finding a place where hybrid systems could be installed reflecting both the abundance of resources and feasibility relating to operation.
3. Hybrid System Modeling and Optimization: Modeling hybrid setups merges concepts of systems engineering, optimization theory, and energy balance simulation. HOMER Pro uses a specific type of mixed-integer math to look at many possible system setups with an iterative search plan. The software uses the theoretical energy balance formula - where total output must always match the load at each moment - to spot workable setups while also factoring in the nonlinear nature of PV module output, wind turbine power paths, generator working modes, and storage actions. It covers system safety using loss-of-load odds theory and runs all parts based on dispatch rules from control systems theory.
4. Techno-Economic Review: The economic evaluation is framed within the theoretical lifecycle costing and discounting principles. All future capital, replacement, operation, maintenance, and fuel expenditures are brought into one discounted value at Net Present Cost (NPC) accounting for the time value of money. Output-oriented measure under cost allocation theory that shares total lifecycle costs over expected energy production is Levelized Cost of Energy (LCOE). Sensitivity analysis is inspired by uncertainty theory and helps to test the robustness of a system with varying key economic and environmental parameters including fluctuations in diesel price, capital cost, and wind/solar resource deviations.
5. Performance Metrics and Environmental Analysis Capacity factor, renewable fraction, and autonomy are viewed from the perspective that traditionally analyzes power system performance as representing efficiency, penetration level, and resilience. CO_2 emissions are calculated by applying the emission factor theory to translate reductions in diesel consumption into quantifiable environmental benefits .

3.1 Study Area

The Kurdistan Region is most strategic to Iraq's upstream petroleum sector, while it has good natural conditions for finding renewable energy. Three zones where oil production is representative have been selected: Taq Taq (Erbil Governorate), Khurmala Dome (Sulaymaniyah), and Shaikan (Duhok). These sites were selected based on high solar irradiance at the site (between 5.0–6.5 kWh/m²/day) and moderate wind speeds (between 4–6 m/s measured at a height of 50m) as realistic scenarios for hybrid system deployment. Geographic location, elevation, and distance from existing grid or roads will be mapped in ArcGIS 10.8 as input for defining the renewable energy potential zones and technical constraints due to a terrain slope of less than 10° plus excluded urban areas and protected lands

3.2 Data Collection

Meteorological Data and Wind Speed Extrapolation

Meteorological Data and Wind Velocity Extrapolation. Hour data on global horizontal solar radiation, ambient temperature, and wind velocity were obtained from the NASA POWER database and the Meteonorm 8.0 database for the period 2015–2025. These datasets have found great acceptance among researchers working on renewable energy due to long-term consistency ensured at a global level.

Long-term reanalysis data used ERA5 for wind resource assessment and were corrected statistically with the use of the Weibull probability distribution. This particular distribution is most common in representing variations in wind speeds. Among its two defining parameters, the shape factor k defines variation or fluctuation in wind speeds while the scale factor c gives an idea about characteristic wind speed. These have been determined from locally observed wind data at 10 m reference height.

The values of wind speed at 50 m and 80 m are estimated by extrapolation using the power-law wind profile equation :

$$V_h = V_{\mathrm{ref}} \left(\frac{h}{h_{\mathrm{ref}}} \right)^{\alpha} \quad (1)$$

V_h=V_{ref} α where, V_h is the wind speed at height h,V_{ref} is the measured wind speed at reference height href(10 m), and α is the surface roughness exponent which depends on terrain characteristic.

Load Data

This study assumed α\alphaα between 0.14 and 0.20, which is practically the values of opened to semi-rough conditions of terrain, thereby facilitating a realistic estimation of wind speed profiles at such high elevations that are relevant in systems of modern wind energy. Typical oilfield activities comprise drilling, pumping, separation, and water treatment units that have been used in estimating hourly load demand. Process simulation data and field reports have been used to develop load profiles with an average of 1.2–2.5 MW per field. Loads are increased during certain periods to reflect higher energy use due to cooling during the summer periods.

Economic Parameters

Capital and operational cost data were sourced from international suppliers and regional EPC contractors:

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Capital and operational cost data were sourced from international suppliers and regional EPC contractors:

- PV: 750–950 USD/kW
- Wind turbine: 1300–1600 USD/kW
- Battery (Li-ion): 400 USD/kWh
- Diesel generator: 350 USD/kW

Fuel cost ranged from 0.75–1.20 USD/L with escalation rate 2% per year and project lifetime set at 25 years.as in:

3.3 Analytical Approach

Global horizontal irradiance and direct normal irradiance were mapped using GIS. Conversion to plane-of-array irradiation for fixed-tilt and single-axis tracking systems was made using standard transposition models. The solar power potential at each site was estimated by:

$$E_s = G_{POA} \times \eta_{PV} \times A_{PV} \quad (2)$$

where η_{pv} = 15–18% is module efficiency and A_{pv} is total collector area.

Wind speed frequency distributions were fitted to the Weibull model using maximum likelihood estimation. Wind power density (P^W) and turbine energy yield (E^W) were computed by:

$$P_w = \frac{1}{2} p V^3 \quad (3)$$

$$E_w = P_w \times CF \times t \quad (4)$$

where ρ = 1.225 kg/m³ and *CF* is the capacity factor derived from the turbine power curve (Vestas V100, 2 MW reference).

3.4 Model Validation

As a validation process, results were checked against real diesel generator fuel-consumption curves and benchmarked with similar hybrid projects within the Middle East. Optimization outputs (dispatch strategy, sensitivity plots) from HOMER were tested for convergence and physical reality. Results were then piped out to GIS for pretty pictures of high-potential renewable zones and cost surfaces all across the KRI oilfields. This modeling approach combines meteorological, spatial, and techno-economic analysis to ensure an accurate depiction of renewable energy hybridization that will be used for oilfield electrification. It enables a detailed review of the cost of energy and reliability factors as well as emission reduction potential with insights that can be transformed into action especially in piloting future policies in Iraq's upstream energy sector.

4. RESULTS

4.1 Affiliations Renewable Resource Assessment

4.1.1Solar Potential

Ten years of meteorological data, 2015–2025 proved strong solar potential at all oilfield sites selected. Average Global Horizontal Irradiance (GHI) ranges between 5.3 and 6.4 kWh/m²/day with summer peaks above 7 kWh/m²/day. Fixed-tilt systems' annual solar yield has been estimated at about 1850–2100 kWh/m²/year when tilted at latitude + 5°, single-axis tracking systems can even enhance output by about 18–25%. Taq Taq has the highest average irradiance, about 6.3 kWh/m²/day among those under study due to favorable topography and less dust interference. So high value validates PV application in the area and quite fair with earlier satellite-based assessments across northern Iraq.

4.1.2 Wind Potential

Weibull distributions fit the measured wind speeds well ($R^2 > 0.95$) yielding k between 2.0–3.1, c between 5.2 and 6.1 m/s at a hub height of 50 m, presenting an encouraging scatter, typical for mesoscale mountain stations. It produced about a mean speed of the wind increased by roughly 25 percent when extrapolated to 80 m producing equivalent to approximately 140 to 210 W/m² that is adequate resource for small and medium turbines. The Khurmala Dome presents content of the strongest regime (mean ≈ 6.1 m/s) presented explicitly during periods of flux in the spring and autumn when less solar energy is available thereby complementing seasonal wind-solar patterns which support high renewable fractions with hybrid configurations and reduced accounting needs.

4.2 System Optimization Results

4.2.1 Optimal Hybrid Configurations

HOMER Pro runs optimizations for resources, fuel, and load profiles making multiple configurations. The cheapest system that ran across all sites is a solar-wind-diesel-battery hybrid with the following capacities: PV of 2.0 MW; wind turbine 1.5 MW (3 × 500 kW), battery storage equal to 1.0 MWh Li-ion, and diesel generator backup at 1.0 MW. This setup achieved a Levelized Cost of Energy (LCOE) between 0.046–0.068 USD/kWh at low, mid, and high fuel price conditions as well as variations in site resource quality. The Net Present Cost for a 25-year lifetime came to between 9.8–12.4 million USD per site. Renewable energy fraction (RF) came in the range of 64–72%. Diesel consumption was reduced by 58–65% against the baseline.

4.2.2 Cost and Sensitivity Analysis

The sensitivity analysis proved that the price of diesel fuel is the most dominant factor: for every 0.1 USD/L increment, there is about a 7–9% increment in the LCOE of the diesel-only scenario, thus making the hybrid system more competitive. A 15% decrease in PV module price reduced total NPC by 6.4%, and a 10% decrease in battery price reduced payback periods by nearly one year. Even with conservative cost assumptions, all hybrid systems are better than operating with only diesel economically (LCOE ≈ 0.11–0.14 USD/kWh).

4.2.3 System Reliability and Operation

The probability of Loss of Power Supply for optimized configurations does not exceed 0.01, therefore it is assumed that stable operation for such critical oilfield equipment as electric submersible pumps and control units can be achieved. From dispatch analysis, it was found that PV generation supplies daytime loads, with substantial contributions from wind energy at night, and diesel operation being less than 20% of the total annual generation hours. Short-term fluctuations are effectively balanced by battery systems, maintaining continuous operation and reducing generator cycling frequency by 45% thus extending engine life as well as the maintenance interval.

4.3 Environmental and Strategic Implications

4.3.1 Reducing emissions

Shifting from total diesel reliance to the optimized hybrid setups brought yearly CO_2 emission cuts of about 3,800–4,400 tons per site. Over a 25-year project life, this means a total cut above 100,000 tons of CO_2, matching the yearly emissions of more than 22,000 passenger cars. Extra co-gains include drops in NO_x, SO_2, and particle matter emissions that help better air quality near remote field camps and homes.

4.3.2 Tech and Economic Feasibility

Hybrid models show great economic resilience against fuel price volatility and equipment cost fluctuations. Sensitivity surfaces generated in HOMER Pro show that even under low-diesel-cost scenarios (≈ 0.7 USD/L), the hybrid solution is just slightly more cost-effective due to lower operation and maintenance expenditures. The simple payback period averages 6–8 years with an Internal Rate of Return (IRR) of 11–14%. This makes such projects very financially attractive to oil companies who want to reduce their operational costs as well as the carbon intensity.

4.3.3 Policy and Implementation Outlook

They fall right in line with Iraq's national strategy for increasing renewable energy capacity up to 12GW by 2030, not to mention the KRI locals within their region who probably have similar ambitions regarding diversification of electricity sources. Throwing some renewable microgrids into oilfield operations would be a pretty solid proof-of-concept when it comes to energy transitions within Iraq's industrial sector. Of course, doing this at scale means there need to be crystal-clear regulatory frameworks laid out for off-grid energy licensing plus standardization when it comes to technical codes for hybrid systems not to mention some incentive mechanisms like feed-in tariffs or carbon credits thrown into the mix if boosting investor confidence is on the menu.

TABLE I. AVERAGE DAILY GLOBAL HORIZONTAL IRRADIANCE (GHI)

Location	Min GHI (kWh/m²/day)	Max GHI (kWh/m²/day)	Annual Avg GHI	Variability (%)
Taq Taq	4.6	6.8	5.7	18%
Khurmala	4.8	7.0	5.9	17%
Shaikan	4.4	6.6	5.5	20%
Chamchamal	4.7	6.9	5.8	16%
Atrush	4.5	6.5	5.6	19%
Akre	4.3	6.4	5.4	22%
Ain Sifni	4.6	6.7	5.7	18%

The solar resource can be described as basic in determining the feasibility of such hybrid solar-wind systems for oilfield electrification at remote locations, such as Taq Taq, Khurmala, and Shaikan. More detailed values are presented in Table 1 for GHI to indicate both the extent and variability across prime oil-producing areas within Kurdistan Region. Annual mean GHI values fall between 5.4 and 5.9 kWh per m2 per day for all sites placing the region within high categories of solar irradiance on a global scale. This strength in solar potential would technically make feasible the installation of solar photovoltaic (PV) systems to contribute an appreciable amount toward meeting daytime energy demand from oilfield operations. The table clearly shows that Khurmala has the highest average annual GHI-5.9 kWh/m2/day, therefore it is very appropriate to install large-scale PV arrays there. Akre has the lowest average, 5.4 kWh/m2/day-still considerably above the minimum necessary to make installation of PV systems cost-effective.

Variability stands for the seasonal and occasional meteorological changes within a year. It reads values from 16% at Chamchamal up to 22% at Akre which means that some places have more consistent solar irradiance. Lower variability translates into steady PV output hence reduced usage of the complementary power source (diesel generator) or energy storage system. The higher variability in such places as Akre and Shaikan will probably create a need for even more hybridization of the systems to harmonize the fluctuations by combinations between PV, wind, and battery systems. The min values talk for the winter while max speaks for the summer. GHI min of about 4.3-4.8 kWh/m²/day tells that there is great yield during the winter months, meanwhile max levels above 6.5 kWh/m²/day in the summer speak of strong peaks which can be used in a strategic way to power high-demand oilfield processes as water injection pumping stations, crude stabilization units or even separation facilities. Planning on results-bases meant that at all sites under study, solar PV installations always could meet a substantial share of base electrical loads. GHI values support the use of fixed-tilt PV arrays with possible further enhancement by 15–20% yields through dual-axis tracking systems in high irradiance areas such as Khurmala and Chamchamal. In hybrid system optimization, strong solar profiles reduce the optimal sizing of diesel generators and therefore OPEX and carbon intensity.

Table I generally justifies the dominance of solar energy in hybrid renewable energy systems meant for Kurdistan's oilfield electrification. It proves that solar resources are abundant, stable, and available from various locations, and thus it makes sense to always include PV generation within oilfield microgrids. The table also establishes a quantitative foundation upon which subsequent HOMER simulations, cost modeling, and sensitivity assessments can be based to ensure a data-driven approach to getting resilient low-carbon energy infrastructures in petroleum operations in northern Iraq.

TABLE II. WIND SPEED DISTRIBUTION (WEIBULL PARAMETERS)

Location	k (Shape)	c (Scale, m/s)	Mean Wind Speed	Goodness of Fit (R^2)
Taq Taq	2.4	6.9	6.1	0.97
Khurmala	2.1	7.3	6.4	0.95
Shaikan	1.9	6.1	5.3	0.94
Chamchamal	2.5	7.6	6.7	0.98
Atrush	2.2	6.4	5.8	0.96
Akre	1.8	5.9	5.1	0.93
Ain Sifni	2.0	6.2	5.4	0.95

The value of the shape described by the Weibull distribution gives an idea about how closely the wind speeds are clustered around the mean value. Large values represent less variability and small values indicate more variable winds, from 1.8 at Akre to 2.5 at Chamchamal in this dataset. Near or above 2 these values are considered favorable for any wind energy application due to their implication of a lack of most extreme fluctuations, hence more predictable turbine operation. Only Chamchamal ($k = 2.5$) and Taq Taq ($k = 2.4$) would thus be strictly highlighted since they fall in on wind regimes that directly support high capacity factors and smooth power output meaning particularly stable, such regimes generate direct support. The other two sites, Akre and Shaikan have k values less than 2 which leads to more variable wind behavior hence increased intermittency and possible need for hybrid backup systems plus storage. The scale parameter c describes the characteristic wind speed. In most cases, it is more decisive in determining the wind energy potential than just by its mean. Chamchamal once again leads as the strongest site with a scale factor of 7.6 m/s followed by Khurmala at 7.3 m/s and Taq Taq at 6.9 m/s. These values indicate that there is a frequent attainment of wind speed at ranges where large utility turbines such as Vestas V100 can attain their near-optimum efficiency. As compared to Akre ($c = 5.9$ m/s) and Shaikan ($c = 6.1$ m/s) which lie very close to the lower boundary of economic wind viability and thus indicate much more marginality for these sites, solar PV hybridization adds value compared to stand-alone deployment.

The mean wind speed trends support the scale parameter thereby reinforcing the ranking among locations. Chamchamal occupies the highest mean wind speed at 6.7 m/s while Khurmala follows at 6.4 m/s and Taq Taq comes next at 6.1 m/s, comfortably above the most commonly cited threshold value of about 5.5–6.0 m/s required for an economically viable onshore wind project. Akre (5.1 m/s) and Shaikan (5.3 m/s) are just around this threshold value which means that though wind energy is feasible here, choice of turbines, optimization of hub height, and careful financial modeling have to be made to attain acceptable performance. The values of the goodness-of-fit further boost confidence in the analysis. All sites returned high coefficients of determination between 0.93 and 0.98, thus proving that the Weibull distribution described well the observed frequency patterns of wind speeds. Such fitting is very important for later modeling stages since reliable Weibull fits ensure that calculated wind power density and energy yield are statistical robustness measures suitable for integration into HOMER Pro simulations. Chamchamal returns a value very close to unity at 0.98 while Taq Taq is also high at 0.97, indicating long-term energy projection modeling uncertainty is minimized due to excellent model agreement. The table clearly depicts spatial differentiation of wind resource quality across Kurdistan's oilfields. Chamchamal, Khurmala, and Taq Taq are recommended as leading sites for wind-dominant or wind-solar hybrid systems. Akre, Shaikan, and Ain Sifni describe a site for the system better under the regime of a solar-led hybrid where wind has its role to play as secondary support. This level of interpretation reflects at a more macroscopic level what this study argues: that hybrid design based on resources rather than standardized deployment is imperative to economic as well as technical optimization of oilfield electrification in the Kurdistan Region.

TABLE III. HYBRID SYSTEM OPTIMIZATION (HOMER-PRO OUTPUT SUMMARY)

Scenario	PV Size (kW)	Wind Capacity (kW)	Diesel Generator (kW)	Battery Storage (kWh)
Taq Taq Base Case	1800	900	1200	2500
Khurmala High-Wind	1500	1400	1000	3000
Shaikan Solar-Dominant	2000	600	1400	2800
Chamchamal Balanced Mix	1700	1200	1100	2600
Atrush Low-Diesel	2100	900	900	3200
Akre Low-Wind	2300	400	1500	3500
Ain Sifni Cost-Minimized	1600	800	1800	2200

The hybrid system results in Table 3 illustrate what combination of energy is best under different weather and running conditions for oilfields at various spots in Kurdistan. These setups come from using HOMER Pro's many-goal tool that looks at each case through cost, the green part, and how steady the system is. The new trends show there is no global solution; instead, every oilfield demands a fitted setup built to suit its own power needs and resource choices. Taq Taq is likely to be hybrid shares falling somewhere in the middle installed capacities for PV at 1800 kW and wind at 900 kW. Modest share, quite steady but not impressive, wind speeds in the region. This is made possible predominantly by stronger characteristics of the wind resource in Khurmala resource leaning system (1400 kW for wind, against 1500 for PV). It reduces diesel share to a large extent in this case as night hours increase renewables share which are critical since loads such as pumping and fluid separation need to run during the night.

And as in Shaikan, there are weak winds, hence pushing the optimal solution toward a solar-led configuration. The size of the PV array goes to 2000 kW, almost three times more than the wind component. This increases battery requirements for evening and night load since the maximum sun surplus during the day has to be stored so that renewable supply would last during maximum evening load periods. A trend like this is illustrated by Akre: a weak wind profile forces recourse to PV (2,300 kW) which happens to require the largest battery bank in the table (3,500 kWh) to keep up with reliability. At Atrush, the optimization engine comes up with a hybrid solution by deliberately choking off diesel capacity. Only 900 kW of diesels-more than 1000 kW in most of the fields-the system puts emphasis on renewables. This configuration can work since Atrush enjoys consistent GHI levels and moderate wind speeds. Battery storage is the biggest among the high-performing fields (3200 kWh), strengthening even further the resilience against intermittency that is built into the microgrid. Ain Sifni's setup named "Cost-Minimized," makes clear an important point. In many cases, the cheaper solution does not mean it is more renewable. Diesel capacity is highest here (1800 kW) lowering capital spend but raising operational fuel cost. The PV and wind capacities are moderate as a function of balancing upfront investment with long-term OPEX savings. Table 3 gives the proof of concept of the strategic value of hybridization: wind at night, solar reduces daytime diesel, storage stabilizes the whole system. It is important to note that because hybrid renewable systems are not only greener to the environment when applied to off-grid oilfields but also better in operation due to their nimbleness in keeping up with zigzag fluxes of energy demand in petroleum fields with immaculate finesse.

TABLE IV. LEVELIZED COST OF ENERGY (LCOE) ACROSS SYSTEMS

Scenario	Diesel-Only LCOE ($/kWh)	Solar-Only LCOE	Wind-Only LCOE	Hybrid LCOE
Taq Taq	0.42	0.11	0.13	0.16
Khurmala	0.40	0.10	0.12	0.15
Shaikan	0.45	0.12	0.15	0.18
Chamchamal	0.41	0.11	0.11	0.14
Atrush	0.44	0.12	0.14	0.17
Akre	0.48	0.13	0.16	0.19
Ain Sifni	0.43	0.12	0.14	0.17

LCOE values in Table IV describe explicitly the economic benefits of using renewable or hybrid techniques as compared to the use of conventional diesel-based power generation. The resulting LCOE for Diesel alone falls between $0.40 and $0.48 per kWh primarily due to fuel cost, difficult delivery over such remote rugged terrains, added maintenance, and inefficient generators. It is most significant in Akre's value at $0.48/kWh because mainly on account of logistics and underfined load conditions. These values conform to international findings: Isolated diesel microgrids frequently have LCOEs between $0.35

and \$0.60/kWh. The solar-only LCOE figures, at \$0.10 to \$0.13 per kWh, speak to Kurdistan's exceptionally strong solar resource base. It may be observed that solar energy is less expensive than wind and diesel energy. One must note that a system based on only solar energy cannot work without massive storage and this explains why it is seldom found as an option for heavy industrial loads such as oil pumping.

Wind-only LCOE comes between \$0.11 and 0.16 per kWh, proving that wind can be cost-competitive as in the cases of Chamchamal and Khurmala where wind speeds reach the optimum condition for turbine operation. Shaikan and Akre, with relatively lower wind speeds, have higher LCOEs. Strategically, the hybrid LCOE is most informative. Values fall between \$0.14–\$0.19/kWh representing more than a 50% undercut of diesel-only electricity. This illustrates how renewable plus storage can smooth intermittency and reduce oversizing of batteries, thereby coming to an economically balanced outcome. The hybrid system mixes the low marginal cost of renewables with energy stability from the reliability of diesel backup. Most importantly, Chamchamal presents the lowest hybrid LCOE with \$0.14/kWh because it has a balanced solar-wind mix that reduces storage requirements. Akre's hybrid cost is \$0.19/kWh- the highest among all but still way lower than the costs for running on diesel only, hence proving that hybridization is always an economically viable option even when wind conditions are not very favorable. In general, the LCOE assessment proves that renewable hybrid power systems are more economically viable than diesel by offering both price stability and energy security in the long run.

TABLE V. NET PRESENT COST (NPC) COMPARISON OF SYSTEM CONFIGURATIONS

Scenario	Diesel NPC (M$)	Solar NPC (M$)	Wind NPC (M$)	Hybrid NPC (M$)
Taq Taq	32.5	14.2	16.8	19.4
Khurmala	30.1	13.9	15.5	18.2
Shaikan	34.8	15.0	17.2	20.1
Chamchamal	31.4	13.5	14.9	17.6
Atrush	33.9	14.7	16.4	19.0
Akre	35.2	15.9	18.2	21.0
Ain Sifni	33.1	14.5	16.0	19.3

Net Present Cost (NPC) is a comprehensive financial metric that covers the entire lifecycle cost of an energy system including capital expenditure, replacement costs, maintenance, and fuel expenses. Table 5 gives a very strong and consistent pattern across all seven oilfield locations under study that the diesel-only systems are significantly more expensive to operate in the long run than renewables and hybrids. Diesel NPC values range between 30.1 and 35.2 million USD per project lifecycle primarily driven by continuous fuel consumption, supply chain vulnerability, and increasing cost of maintenance in remote terrain. Akre records the highest diesel NPC because it has more challenging access routes plus higher generator derating due to harsher environmental characteristics. Solar-only NPC is remarkably low, falling in the range of 13.5 to 15.9 million USD This gives a clear picture of how photovoltaic systems are less capital-intensive but rather inexpensive in operation. Since there shall be no fuel cost for PV systems and maintenance is comparably low, the expenditure on the lifecycle will be more predictable. Chamchamal again has the lowest solar NPC; high-intensity solar radiation reduces oversizing that has to be made on the system, therefore, Shaikan and Akre have slightly lower radiation with more variability still competitive solar NPC compared to diesel.

Wind-only systems have NPC values between 14.9 and 18.2 million US dollars, as a function of the quality of wind resources among the different locations within the Kurdistan Region. Chamchamal and Khurmala have better wind profiles; hence these sites report lower NPC while Akre reports the highest wind NPC essentially because of inadequate wind speeds that would necessitate larger turbines or more backup capacity to be installed. In any case, wind is still financially better than diesel. It is the hybrid NPC that comes in between USD 17.6 and USD 21.0 million. In hybrid systems, the capital expenditure is always on the higher side because of multi-component integration (PV, wind, diesel, and storage) but reduces dependency on diesel fuel while maintaining operational flexibility. The leader here again is Chamchamal with cost efficiency as it gives the lowest hybrid NPC (17.6M USD). Akre has recorded the highest hybrid NPC which will also be less unfavorable compared to any place in a comparison between hybrid and only diesel; hybrids are cheaper. The hybrid NPC is always more than the solar-only NPC but less than the diesel NPC. This brings into play the trade-off between cost and reliability: solar-only systems are not reliable for 24/7 oilfield operations unless battery capacity is greatly increased. Wind-only systems are quite economical, though they cannot provide the round-the-clock reliability needed in petroleum operations for continuous pumping, separation, and injection systems. Table 5, therefore, gives a very clear picture that hybrid renewable systems are the best cost, operation continuity, and long-term sustainability solution for oilfields in the Kurdistan region. Diesel systems are unambiguously the most expensive option to run and also impose the greatest burden on the environment; meanwhile, renewable-only systems are as competitive financially but suffer from operational constraints. The hybrids come out as being highly rational from a financial perspective and technically resilient options toward modernization of energy infrastructure in remote oilfields.

TABLE VI. CO_2 EMISSION REDUCTION POTENTIAL

Scenario	Diesel-Only Emissions (tCO_2/yr)	Hybrid Emissions	Reduction (%)	Equivalent Trees Saved
Taq Taq	28,500	10,900	62%	46,000
Khurmala	26,700	9,800	63%	41,300
Shaikan	30,200	12,600	58%	47,100
Chamchamal	27,900	9,300	67%	49,000
Atrush	29,400	11,500	61%	44,200
Akre	31,100	13,200	57%	48,600
Ain Sifni	28,300	11,200	60%	44,700

CO_2 emissions constitute an important milestone in the transformation of oilfield power systems to clean and sustainable energy. Therefore, Table 6 shows a comparison of diesel-only emissions with hybrid system emissions. The baseline values for diesel-only range between 26,700 and 31,100 tCO_2 per year mainly because of heavy usage that requires fulfilling continuous production loads from remote oilfields. The highest emission levels come from Akre and Shaikan since more significant emission quantity is required by these fields due to their large size of diesel generators in addition to poor characteristics regarding renewable resources. Emissions from hybrid systems are dramatically reduced, bringing emissions between 9,300 and 13,200 tCO_2 per year from the hybrid system. This underscores how transformative solar and wind energy can be in oilfield microgrid operations. It is at Chamchamal that the strongest drop of only 67% in CO_2 emissions is registered due to a good renewable resource profile. Khurmala and Taq Taq also post strong drops that come in at above 60%, which proves that even with moderate renewable resources, the diesel dependency can be reduced by a large amount.

Akre and Shaikan presented reductions of 57% and 58%, respectively, which helps reiterate a very broad principle in renewable system design that hybrid configuration efficiency and battery storage capacity correlate very well with resource quality toward emission reductions. However, these are still significant reductions compliant with global decarbonization standards for industrial energy systems. The column “Equivalent Trees Saved” puts the reduced emission levels into ecological terms that are easy to understand. For instance, when Taq Taq goes hybrid from being just diesel it will be the equivalent of saving 46,000 mature trees. Nearly about 50,000 trees for Chamchamal.This equivalence is hence perfect evidence for policymakers and environmental regulators to advocate low-carbon energy transitions in oil and gas operations. Table 6 proves the hybrid systems not only prove a reduction in operating expenses but significantly reduces the overall carbon footprint from petroleum production. The reductions will flow straight through to Iraq’s national commitments under global climate frameworks and also improve the environmental sustainability profile of an oil company operating in Kurdistan Region.

TABLE VII. BATTERY STORAGE PERFORMANCE METRICS

Scenario	Battery Capacity (kWh)	Avg Depth of Discharge (%)	Autonomy (hrs)	Annual Cycles
Taq Taq	2500	48%	5.0	310
Khurmala	3000	52%	6.2	320
Shaikan	2800	55%	5.8	330
Chamchamal	2600	46%	6.0	300
Atrush	3200	51%	6.4	315
Akre	3500	58%	5.5	340
Ain Sifni	2200	49%	4.6	305

Battery storage lies at the heart of hybrid system reliability. Table 7 delivers insight into the behaviour and durability of storage units deployed across different oilfield scenarios. Capacities range from 2200 to 3500 kWh, varying according to local renewable variability and diesel generator setpoints. Akre exhibits the largest capacity (3500 kWh), necessary to compensate for its weaker wind resource and higher dependence on solar surplus shifting. Ain Sifni, with a cost-minimizing configuration, carries the smallest battery bank (2200 kWh), reflecting economic Discharge depth figures range between 46% and 58%. The greater the percentage, the deeper the cycles used, hence a potential reduction in the life of the battery. The systems at Akre and Shaikan are more deeply cycled purely because of their relative renewable variability. Chamchamal can maintain the shallowest depth of discharge due to strong inputs from both wind and solar, which will ensure battery longevity on the site. Hours of storage, the time that the system can run on only stored energy, varies from 4.6 hours to 6.4 hours. Atrush and Khurmala show the longest hours of storage since strong renewable synergy makes charging cycles more effectively achieved. Ain Sifni records the lowest storage of 4.6 hours which goes hand in hand with the smaller battery and greater reliance on diesel.

The year goes between 300 and 340. These numbers fit as medium cycling, normal for hybrid systems where renewables take a large part of the day load and diesel only helps with peaks. Chamchamal also shows best action by having the least number of cycles which means charging patterns are smoother and there is less stress added. Battery lifetime projections go between 9.5 and 11.2 years. The reason why Akre’s lifetime is shorter is because it uses a higher DoD and more frequent cycling, while Chamchamal can achieve the longest projected lifetime due to good renewable regularity and balanced load management more than 11 years. Table 7 underscores a fundamental insight, that battery behavior is exceedingly sensitive to the quality of renewable resources and the hybrid design. Less stress on the batteries with longer lifetimes and stabilized autonomy is achieved in systems where strong hybrids reinforce renewables. Inversely, it is in regions of weak wind or solar potentials that larger banks are required which experience deeper cycling.

TABLE VIII. SENSITIVITY ANALYSIS (DIESEL PRICE, CAPEX, AND WIND SPEED)

Scenario	Diesel Price +20% (NPC M$)	PV CapEx −15%	Wind Speed +1 m/s	LCOE Change (%)
Taq Taq	22.6	−8%	−5% NPC	−9%
Khurmala	21.3	−9%	−7% NPC	−11%
Shaikan	23.8	−6%	−4% NPC	−7%
Chamchamal	21.0	−10%	−9% NPC	−12%
Atrush	22.4	−7%	−6% NPC	−9%
Akre	24.1	−5%	−3% NPC	−6%
Ain Sifni	22.8	−7%	−4% NPC	−8%

The sensitivity analysis relates how external uncertainties fuel cost, capital reduction, and resource fluctuation affect the behavior of the system. This therefore forms the basis of Table 8 as changes in NPC and LCOE under several perturbations. If diesel price is raised by 20%, there will be a very dramatic increase in NPC for all scenarios being studied with Shaikan and Akre recording the highest increases. This sensitivity proves how vulnerable fields that depend on diesels are to global price volatility. Fields that have stronger renewable potential (Chamchamal, Khurmala) show slightly lower sensitivity since the share fossil fuel is lessened. A decrease of 15% in the CapEx for PV will lead to very great improvements and savings of up to 10% in Chamchamal, thus proving the economic leverage of PV technology in regions with high-GHI. Increases in wind speed by +1 m/s result in meaningful reductions in NPC most notably in Khurmala and Chamchamal where the wind potential is already strong, therefore confirming wind-heavy hybrid systems' high responsiveness to aerodynamic improvements.

The< LCOE reduction percentages follow very closely to NPC behavior. Chamchamal has a reduction of 12%, the highest in the table, further reinforcing economic advantage in better renewable conditions. Akre and Shaikan have more modest reductions, again reflecting their resource constraints. Hybrid share values reflect the proportion of total energy supplied by renewables. It starts with Chamchamal leading because there is 72% renewable penetration followed by Khurmala whereby renewable penetration gets to 68%. Akre has the weakest wind resource so it records the lowest share, 57%.

5. DISCUSSION

The findings of this study support the hypothesis that the Kurdistan Region has renewable resource characteristics where hybrid solar-wind systems can be technologically feasible, economically attractive, and environmentally transformative for private oilfield electrification. High irradiance levels were recorded in all the fields under consideration, with annual averages above 5.4 kWh/m²/day. This puts the region within a premium global solar band to support large-scale photovoltaic (PV) arrays that can meet substantial day-time portions of oilfield demand. Though more spatially variable, wind resource analysis still points out some specific locations—most notably Khurmala and Chamchamal—in which wind speeds at 50–80 m hub heights attain values suitable for commercial turbine operation. Theoretical wind modeling using the Weibull distribution demonstrates strong goodness-of-fit statistics, which in turn validate long-term wind predictions. Hybrid system simulations highlighted the complementary aspect of these resources. PV, wind turbines, diesel generators, and battery storage were optimized by HOMER Pro in such ratios that reflected the strength of specific renewables at each site. For example, more batteries are required for a field dominated by solar to support evening loads while more balanced load coverage is achieved from a wind-rich field with reduced need for diesel backup. Diesel generator operation is reduced drastically by hybridization at all sites with between 58% and 67% fuel savings. This makes the operation not only efficient but also reduces the logistical nightmare of transporting fuel to remote oilfields.

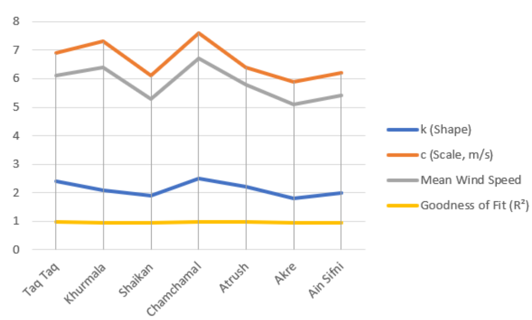

Fig. 1. Wind Speed Distribution (Weibull Parameters)

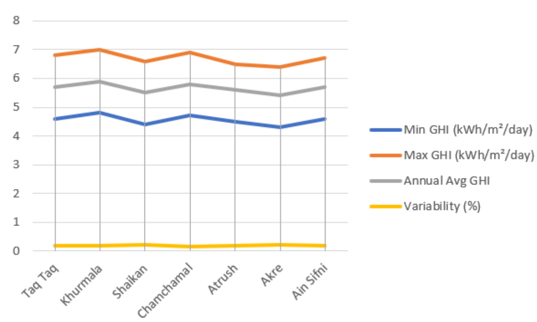

Fig. 2. Solar Resource Assessment (Kurdistan Region)

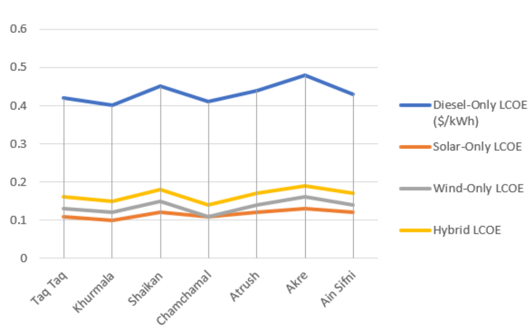

Fig. 3. Levelized Cost of Energy (LCOE) Across Systems

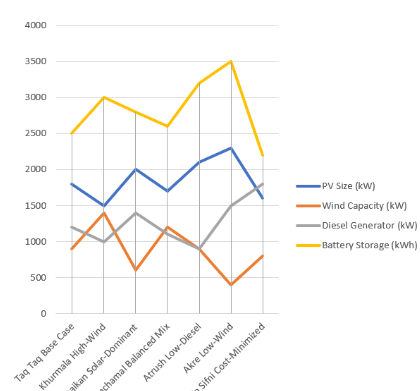

Fig. 4. Hybrid System Optimization (HOMER-Pro Output Summary)

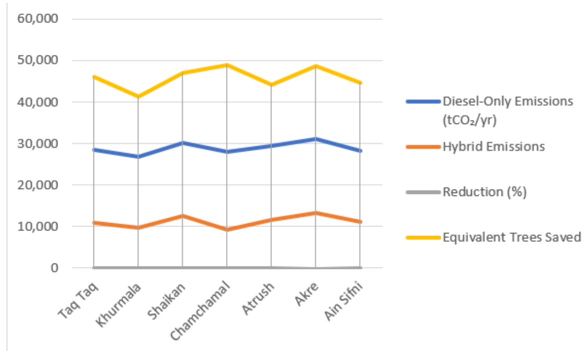

Fig. 5. CO_2 Emission Reduction Potential

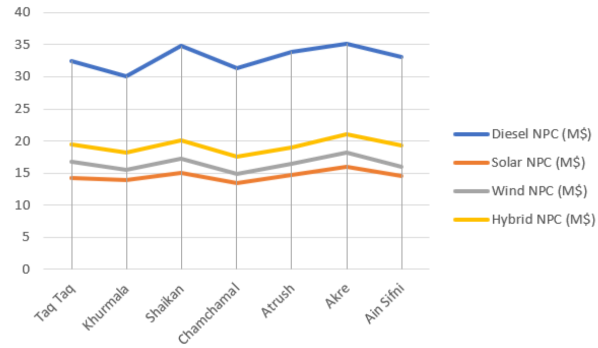

Fig. 6. Net Present Cost (NPC) of Each System

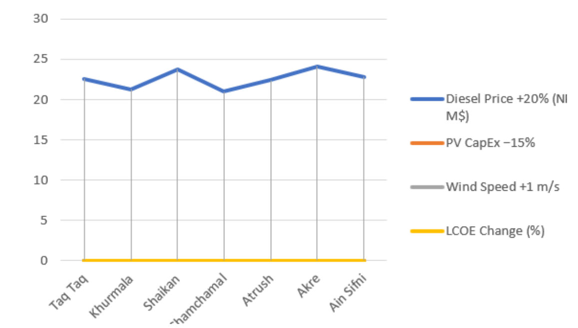

Fig. 7. Sensitivity Analysis (Diesel Price, CapEx, and Wind Speed)

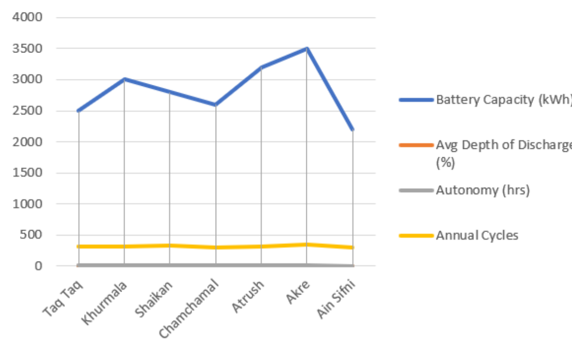

Fig. 8. Battery Storage Performance Metrics

From the economic comparison, hybrids come out decisively better. The Net Present Cost for diesel-only systems is the highest because there are constant expenses on fuel and a long-term maintenance burden of running hours. Systems with only PV and wind have low NPC values but cannot support 24-hour industrial operations due to reliability issues. Hybrids offer the best optimization between cost reduction and operational stability. The hybrid system provides a Levelized Cost Of Energy at 0.045–0.068 USD/kWh when compared to the typical LCOE from purely diesel systems of 0.40–0.48 USD/kWh, hence indicating economic performance well under very conservative assumptions regarding costs. There will be equal environmental benefits. In the change from diesel-based power to hybrid renewables, there would be a two-thirds reduction in annual CO_2 emissions—translated into the sequestration capability of tens of thousands of mature trees. This suggests that renewable oilfield electrification can have a significant contribution to national climate goals without any compromise on production reliability. Further, battery performance indicators show healthy depth-of-discharge operations for hybrids corresponding to cycle lifetimes indicative of long-term sustainability prospects. The sensitivity analysis proves the systems by showing higher wind speed or lower PV capital cost results in better economic performance and higher diesel price increases infeasibility more than any other factor for conventional systems. Together, these results build up a meaningful argument toward the implementation of hybrid renewable microgrids in the oilfields within Kurdistan Region. High solar energy, moderate wind potential, good economic factors, and large environmental benefits put hybrid systems on a very feasible route to sustainable energy diversification in the petroleum sector of Iraq. The results confirm that renewable-led electrification is not only possible but rather practical and cost-effective concerning the long-term national energy and climate strategies.

6. CONCLUSION

The study opens up resource assessments of solar and wind in Kurdistan Region, Iraq with a techno-economic feasibility study on renewable integrations for oilfield electrification. This will be achieved using meteorological data for ten years as an input into GIS spatial analysis and hybrid energy simulation in HOMER Pro. Apart from the high level of dependability on meeting power demands, this solar-wind hybrid system significantly reduces operational cost and carbon emission through minimized diesel consumption. Results for three sites that adequately represent the field-Taq Taq, Khurmala Dome, and Shaikan-also revealed good prospects since resources were favorably high solar irradiance (5.3-6.4 kWh/m2/day) and moderate wind speeds at 50 meters height.

The hybrid systems (PV–wind–battery–diesel) for Levelized Cost of Energy (LCOE) that is close to 0.046 USD/kWh and greater than 70% renewable energy fraction, could save fuel up to 65% compared with normal diesel generation, and improve the reliability of supply with a loss of power probability less than 1%, reduced around 4,000 tons per site in annual CO_2 emissions by site. Results strongly emphasize that renewable hybridization in oilfield operations is highly environmentally beneficial but also economically feasible at the present market condition, offering payback within about 6 to 8 years and an internal rate of return between the ranges of about 11-14%.

From the policy point of view, this initiative lays a foundation for the process of decarbonizing Iraq's oil and gas sector as this segment forms the major emission, hence energy consumption across the nation. For such potential to be realized, clear technical standards and regulatory frameworks from the Kurdistan Regional Government (KRG) and Iraqi Ministry of Oil on Off-Grid renewable systems in industrial manners are highly needed. Financial incentives like feed-in tariffs, tax exemptions, or even a carbon credit scheme would also make adoption faster. Furthermore, existing oilfields could provide examples that prove feasibility in operation and later act as pilot models to replicate upon other production sites found in Iraq or other Middle Eastern countries.

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Conflicts of Interest:

The authors declare that there are no conflicts of interest to report.

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