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Comprehensive Assessment of Wind and Solar Energy Potential Toward a Sustainable Future: A Case Study of the GMMR, Libya

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ABSTRACT

The Great Man-Made River (GMMR) wellfields in southern Libya are critical water supply sites yet rely entirely on fossil-fuel electricity, making them vulnerable to outages and environmental impacts. This study presents a first multi-site assessment of solar and wind energy potential across five main wellfields, Sarir, Tazerbo, Jabal Al-Hasouna, Al-Kufra, and Ghadames, using a decade of data (2014-2024) and established models. Wind resources were characterized via the statistical two-parameter Weibull distribution function at hub heights of 10, 50, and 100 m, while solar potential was evaluated with the Angstrom-Prescott model. Results indicate that the annual mean of the Weibull shape (k) and scale (c) parameters for all wellfields varied in the ranges 2.49-2.97 and 6.83-8.04 m/s, respectively, indicating stable and moderate-to-strong winds suitable for energy production. Among the five wellfields, Ghadames exhibited the highest wind power density, with P/A values ranging from 69.12 W/m² at 10 m to 324.4 W/m² at 100 m, surpassing the other wellfields. Wind energy densities reach up to 2,849 kWh/m². Solar results indicate that Al-Kufra exhibits the highest annual mean daily global solar radiation, whereas Al-Hasouna records the lowest, with the mean across all sites approximately 6.5 kWh/m²/day. Clearness indices remain consistently around 0.7, reflecting persistently clear desert skies. These findings highlight the complementary potential of solar and wind resources for hybrid or standalone renewable systems, offering pathways to reduce fossil fuel dependence, enhance energy self-sufficiency, and improve operational resilience at these strategically important wellfields.

KEYWORDS Wind energy, Solar energy, Weibull distribution, Angstrom-Prescott model, GMMR, Libya

1. Introduction

The global energy system is undergoing a profound transition driven by the twin imperatives of energy security and climate mitigation. Conventional fossil resources are finite and increasingly unsustainable, while their combustion emits greenhouse gases that exaggerate climate change (Alzahrani *et al.* 2021). As economies grow, electricity demand is projected to rise, amplifying the urgency to deploy renewable energy (RE) at scale. Over the past two decades, research and policy have converged on RE as a technically viable and environmentally preferable pathway to decarbonize power systems (Shivarama Krishna and Sathish Kumar 2015). Costs have fallen rapidly and, in many regions, renewables are now the least-cost option for new capacity. By 2023, RE accounted for about 30% of global installed capacity, with a record-breaking annual increase of approximately 473 GW,

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underscoring their growing importance and momentum in the global energy transition (REN21 2024).

Libya illustrates the challenges and opportunities of the energy transition. Despite abundant solar and promising wind resources, the country's energy sector and public finances remain heavily dependent on fossil fuels, particularly natural gas (Ember 2024) & (İnal *et al.* 2022). As a consequence, Libya records one of the highest per-capita GHG emissions in Africa, averaging about 11.1 tons of carbon per person annually, with the energy sector responsible for 90% (World Bank Group 2024). Political instability has reduced investment and constrained system performance, while modernization, industrial expansion, and population growth have intensified electricity demand (UNDP 2023). Since 2014, frequent outages persist due to inadequate generation, capacity shortfalls, aging assets, and limited operational flexibility, with especially severe impacts in outlying districts of the national grid (Almaktar and Shaaban 2021a). Supply in distant locations is more vulnerable to interruptions, and southern and south eastern regions experience heavier load shedding because most grid assets and power plants are concentrated along the coast (Almaktar *et al.* 2021b). In line with SDG 7 (Affordable and Clean Energy), diversifying the generation mix with RE offers a credible path to reduce outages, lower emissions, and expand reliable access (Bekçi and Koca 2024; Ahmed *et al.* 2024). Energy interruptions are not isolated technical events. Persistent power cuts affect nearly every sector and propagate across critical infrastructure, creating cascading risks. The Great Man-Made River project demonstrates this exposure. As the primary system conveying water from deep southern desert to major population centres along the coast, it is a lifeline for millions of Libyans and accounts for a substantial share of national water and energy demand (Almaktar and Shaaban 2021a; Nassar *et al.* 2024). Continuous power is essential for pumping and conveyance. Load shedding, distribution failures, and blackouts each have multiple underlying causes and can result in a range of negative outcomes, the longer and broader the outage, the greater the impact. When electricity falters, pumping halts within minutes and disruptions can rapidly turn into water shortages that affect households, hospitals, agriculture, and industry, with implications for public health and economic stability (Hachem-Vermette and Yadav 2023). These conditions underscore the need for resilient, low impact on site renewable supply at the southern GMMR wellfields.

Population geography further complicates reliable service. Libya's population is concentrated along the Mediterranean coast while inland communities are sparse, which raises the cost and complexity of extending and maintaining robust service. Although grid access reportedly reaches most of the population, infrastructure is unevenly distributed and densest on the coast, with long transmission paths required to serve the south and southeast, where technical losses and voltage drops degrade reliability at the receiving end (Elmnifi *et al.* 2024). However, recent policy statements indicate that Libya intends to meet a growing share of electricity demand with renewable energy (NSREEE 2023). Investing in domestic renewable resources offers a critical opportunity to reduce dependence on fossil fuels and curb emissions. Harnessing these resources can support sustainable development and enhance energy self-sufficiency (Hassane *et al.* 2022). Given current and projected conditions in the power sector, renewables are well positioned to play a transformative role by meeting rising demand, mitigating frequent outages, and lowering environmental impacts (Makken 2022).

Climatically and geographically, Libya is well positioned for RE deployment. The country lies within the 15°-35° N solar belt, with national-scale solar potential exceeding 6.5 kWh/m^2/day and the Sahara region receiving roughly 3,500 sunlight hours per year, among the world's highest (Wheida and Verhoeven 2007; Hachem-Vermette and Yadav 2023). Vast land area (1,759,540 km^2), mostly uninhabited, sparsely populated desert areas, generally flat topography, and a long Mediterranean coastline (1,900 km) further support utility-scale photovoltaic and wind development (Sbeta and Sasi 2012; Shebani and Iqbal 2017). Assessments by both government authorities and researchers have identified several regions, particularly along the northern coast such as Jabal Akhdar, Dernah, Al-maqrum, Benghazi, Al-Zawiya, Sirt, Tripoli, Nault, and Esspeea and in southern desert areas, with

average wind speeds and power densities suitable for commercial-scale wind farms (Makken 2022; Nassar *et al.* 2023). Reported wind power densities on the order of 164 to 426 W/m^2 and Average wind speeds of approximately 5.7 m/s in the southern regions further southern areas indicate substantial technical potential (Jenkins *et al.* 2019; Sbeta and Sasi 2012). Taken together, these findings position wind as a complementary resource alongside solar across Libya. In addition to large-scale resource assessments, several studies have examined the aerodynamic performance of wind turbines suitable for moderate wind regimes. For example, CFD-based investigations of vertical axis turbines have demonstrated how flow behaviour and rotor geometry influence power extraction efficiency under variable wind conditions (Didane *et al.* 2022). Such findings reinforce the importance of accurate wind speed characterization, such as the Weibull parameters used in the present study, when evaluating the feasibility and performance of wind energy systems in resource-constrained regions. Broader assessments likewise document strong solar potential and significant opportunities for large scale deployment (Hachem-Vermette and Yadav 2023).

However, the existing literature is fragmented, with solar analyses often geographically restricted and wind assessments rarely considering elevation effects. Most studies focus on coastal urban centres and give limited attention to southern rural areas. The Great Man-Made River wellfields are strategically important yet electrically challenging as remote and energy-intensive pumping sites where outages carry direct social and economic costs. To the authors' knowledge, no prior work has assessed renewable energy potential at these wellfields in southern Libya. An integrated multi-site evaluation of solar and wind resources across Sarir, Tazerbo, Jabal Al-Hassouna, Al-Kufra, and Ghadames is therefore warranted to inform planning for photovoltaic, wind, or hybrid systems that reduce fuel logistics, improve reliability, and lower emissions. In the present study, a consistent multiyear resource baseline is developed using openly available datasets and transparent methods.

In the absence of meteorological stations near the wellfields, wind and solar resources were characterized using established gridded meteorological datasets. Wind regimes were derived from hourly NASA POWER fields based on the MERRA-2 reanalysis. For the solar assessment, NASA POWER hourly direct normal irradiance (DNI) was used to derive bright-sunshine duration according to the World Meteorological Organization threshold of 120 W/m^2, while the corresponding NASA POWER all-sky surface shortwave downward radiation was used to calibrate the Angstrom-Prescott relationship. The assessment spans 2014-2024, with wind potential analysed at multiple heights using the two-parameter Weibull distribution and solar potential characterized using the calibrated Angstrom-Prescott model.

To the best of the authors' knowledge, this study is the first comprehensive multi-site assessment of both wind and solar energy potential at the southern GMMR wellfields. Unlike prior research focused on coastal or urban regions, this work addresses remote, energy-intensive pumping sites where reliable electricity is critical. By integrating a decade of high-resolution meteorological data with established analytical models, the study provides a robust resource baseline. Furthermore, the findings offer practical implications for decentralized renewable energy planning, highlighting pathways to reduce fossil fuel dependence, enhance energy self-sufficiency, and improve operational resilience at these strategically important wellfields.

2. Site description

The Great Man-Made River project represents the Libyan National Plan (LNP) to address water scarcity and meet people's needs. The initiative designed to relocate the substantial amounts of groundwater from the transboundary aquifers located within the main geological basins in southern Libya to the heavily populated coastal regions. The system operates around the clock to maintain hydraulic stability and secure supply, and it currently does not employ renewable energy systems. Each wellfield's electrical load includes production pumps, control and communication systems, reservoirs, and facilities for operations, maintenance, and support. According to Great Man-Made River Authority records, the wellfields employ combinations of submersible and centrifugal pumps

with extensive O & M infrastructure. Total daily electricity demand is substantial, reflecting the scale of groundwater abstraction and the auxiliary systems required to sustain uninterrupted operation.

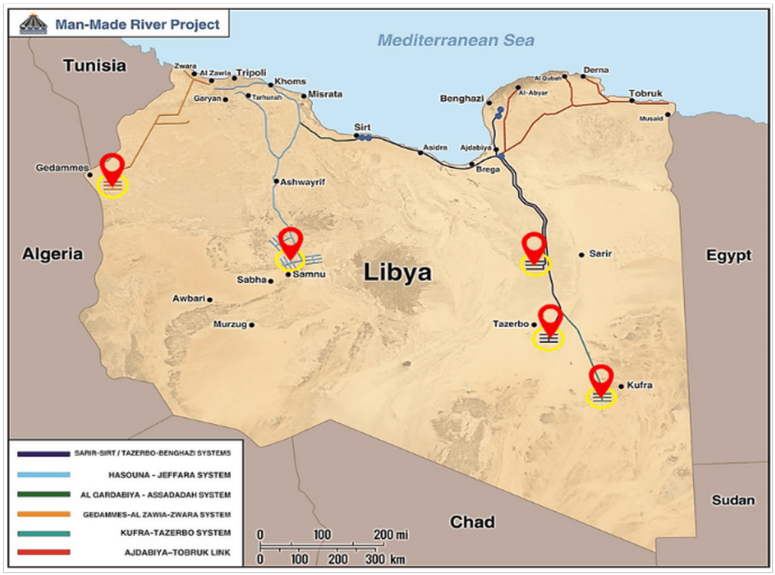

Figure 1. The map of GMMR's wellfields, Libya.

Table 1. The geographical coordinates of the five wellfields.

Wellfield	Latitude (°N)	Longitude (°E)	Altitude (m)
Sarir	27.30	21.6	121
Tazerbo	25.55	21.6	288
E & NE Jabal Hasouna	28.51	16.07	607
Al-Kufra	23.33	22.08	392
Ghadames	30.12	9.53	589

The wellfields are organised into five zones comprising numerous production wells with associated facilities. These zones lie in remote desert regions hundreds of kilometres from the nearest coastal meteorological stations. Climatically, the sites are within the Saharan desert and exhibit hyper arid conditions with minimal rainfall, clear skies, and large diurnal temperature ranges. Resource characterisation therefore relies on established satellite and reanalysis products. Five primary wellfields are assessed Sarir, Al Kufra, Tazerbo, Jabal Al Hassouna, and Ghadames. Fig 1 illustrates the geographic distribution of these selected GMMR wellfield sites in southern Libya, while their specific coordinates are detailed in Table 1. These sites constitute the main supply zones of the Great Man-Made River and were chosen for their diversity and the presence of substantial untapped wind and solar potential.

3. Methods, Theoretical, and Mathematical Models

Reliable assessment and prediction of renewable energy resources are fundamental to effective system design and integration. Data scarcity and regional variability often complicate implementation (Shreif *et al.* 2019). Statistical modelling improves precision and comparability. For wind, the two parameter Weibull distribution provides a flexible representation of speed variability and supports energy yield estimation, while for solar, the Angstrom-Prescott relation links sunshine duration to global radiation (Kaplan 2018). Composed these methods enable robust resource characterisation and informed planning for sustainable infrastructure. The following subsection outlines the datasets, pre-processing steps, and metrics used to characterise solar and wind potentials at the selected GMMR wellfields.

3.1. Wind resource assessment

Assessment of wind energy potential employed power density calculations with wind speed distributions modelled using the two-parameter Weibull method. Hourly wind resource data from NASA's Prediction of Worldwide Energy Resources (POWER) project, based on the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), were used to estimate wind potential at each site. The NASA POWER wind dataset (MERRA-2 based) provides hourly temporal resolution and a spatial resolution of 0.5° latitude × 0.625° longitude (approximately 50-65 km across Libya). These resolutions are appropriate for regional-scale renewable resource assessment in remote desert settings. Previous comparison with mast measurements across Libya, including Al-Kufrah, showed that MERRA-2 can provide comparatively useful wind estimates for preliminary resource assessment, although the magnitude of errors varies substantially by location (Kassem *et al.* 2024). Meteorological data spanning a ten-year period (2014 - 2024) were analysed for the five selected wellfields, including wind speed, and related parameters.

Wind speed varies with altitude due to wind shear, so resource data must be referenced to the intended hub height. Standard observations are often reported at 10 m, below typical turbine hub heights. In this study, NASA POWER provides hourly wind fields at 10, 50, and 100 m, allowing direct characterization at application-relevant heights and reducing reliance on extrapolation. Average monthly wind speeds were compiled for each site and height to support reliable estimation of energy yield and turbine siting.

3.2. Weibull distribution function

Accurate wind resource appraisal requires a compact model of wind speed variability. The Weibull distribution is widely adopted owing to its flexibility and robustness across diverse climates and terrains (Adun *et al.* 2022; Al-Ghriybah *et al.* 2019; Kassem *et al.* 2023). Comparative studies show that Weibull generally yields more accurate probability and power density estimates than alternatives such as the Rayleigh model (Serban *et al.* 2020). Applications in coastal and inland sites, as well as arid regions in Chad and Egypt, demonstrate its reliable performance for site screening and system design (Belgasim *et al.* 2018; Kassem *et al.* 2020; Didane *et al.* 2016; Aghahosseini *et al.* 2020). In this study, the probability density function (PDF) and cumulative distribution function (CDF) are respectively expressed in Eqs (1) and (2) were used to represent the empirical wind-speed distribution at each wellfield. The Weibull parameters were estimated using the widely adopted empirical wind power density method based on the ratio of the standard deviation to the mean wind speed (Mondal *et al.* 2022).

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

Where:

- v = wind speed
- k = dimensionless shape parameter
- c = scale parameter (m/s)

Accordingly, The Weibull parameters k & c can be projected using Eqs (3) and (4) respectively.

$$k = 1 + \left(\frac{\sigma}{\overline{v}}\right)^{-1.086} \tag{3}$$

$$c = \frac{\overline{v}}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{4}$$

Where:

- $\overline{v}$ = mean wind speed
- σ = standard deviation
- Γ = gamma function

3.3. Wind power and energy density

Wind power density (WPD) is computed directly from observations or from a Weibull fit, using Eqs. (5) and (6).

$$\overline{P} = \frac{1}{2n}\rho\sum_{i=1}^{n} v_i^3 = \frac{1}{2}\rho\overline{v^3} \tag{5}$$

Where:

- n = number of observations
- $\overline{v}$ = mean wind speed
- ρ = air density (1.125 kg/m^3)

$$\overline{P} = \frac{1}{2}\rho c^3\Gamma\left(\frac{k+3}{k}\right) \tag{6}$$

The wind energy density over duration, T is predicted via Eq (7).

$$\overline{E} = \overline{P}\,T \tag{7}$$

3.4. Solar resource assessment

Solar radiation is a fundamental indicator of photovoltaic energy potential; however, long-term ground-based measurements of global solar radiation and sunshine duration are unavailable at the selected GMMR wellfields. The Angstrom-Prescott model was therefore retained as an empirical framework for relating global radiation to relative sunshine duration under a consistent methodology across the five sites.

Hourly solar data for 2014-2024 were obtained from NASA POWER. Bright-sunshine duration S was derived from hourly direct normal irradiance (ALLSKY_SFC_SW_DNI), with an hour classified as bright sunshine when DNI was equal to or greater than the World Meteorological Organization threshold of 120 W/m^2. The corresponding maximum possible sunshine duration S_0 and extraterrestrial radiation H_0 were calculated from standard solar-geometry relationships. NASA POWER all-sky surface shortwave downward radiation (ALLSKY_SFC_SW_DWN), converted to daily global horizontal radiation H, was used as the reference gridded radiation dataset for calibration of the Angstrom-Prescott coefficients (Ogab *et al.* 2025; Mohtasim *et al.* 2025). Thus, the gridded radiation data and the Angstrom-Prescott model were not treated as two independent estimates of the same quantity; rather, the former provided the regional radiation reference required to calibrate the empirical sunshine–radiation relationship in the absence of local pyranometer measurements.

3.5. Estimation of solar radiation using the Angstrom-Prescott relation

Angstrom in 1924 introduced the first empirical sunshine-based model for solar radiation using station sunshine records. Prescott in 1940 reformulated the relationship in terms of the clearness index and the sunshine fraction, and Page 1961 extended its monthly mean application (Adun *et al.* 2022; Azad *et al.* 2014). The standard form is expressed as,

$$\frac{H}{H_0} = \left(a + b\frac{S}{S_0}\right) \tag{8}$$

where H is the monthly mean daily global horizontal radiation, H_0 is the extraterrestrial radiation, S is the bright-sunshine duration derived from hourly DNI, S_0 is the maximum possible sunshine duration, and a and b are empirical Angstrom-Prescott coefficients. The extraterrestrial radiation H_0 was calculated using Eq. (9). The Angstrom-Prescott coefficients were calibrated by least-squares regression using the monthly clearness index (H/H_0), obtained from NASA POWER global horizontal radiation, and the corresponding relative sunshine duration (S/S_0), derived from hourly DNI. The calibration comprised 60 monthly climatological observations representing 12 months at each of the five GMMR wellfields.

Where H_0, a, b, and S_0 can be estimated using the following Eqs.

$$H_0 = \frac{24\times 3.6\times 10^{-3} I_{sc}}{\pi}\left(1 + 0.033\cos\left(\frac{360\, D_y}{365}\right)\right)\left(\cos L\cos\delta\sin\omega_s + \omega_s\sin L\sin\delta\right) \tag{9}$$

$$a = -0.110 + 0.235\cos L + 0.233\left(\frac{S}{S_0}\right) \tag{10}$$

$$b = 1.449 - 0.533\cos L - 0.694\left(\frac{S}{S_0}\right) \tag{11}$$

$$S_0 = \frac{24}{\pi}\cos^{-1}\left(-\tan L\tan\delta\right) \tag{12}$$

Where I_{sc} as the solar constant, 1367 W/m^2, D_y is the day of the year, L is the latitude, and δ and ω_s are respectively the solar declination angle and the sunset hour angle that are estimated using following Eqs.

$$\omega_s = \frac{\pi S_0}{24} \tag{13}$$

$$\delta = 23.45\sin\left(280.1 + 0.986\, D_y\right) \tag{14}$$

The calibrated relationship showed strong agreement with the NASA POWER global-radiation climatology, with (R^2 = 0.986), RMSE = 0.17 kWh/m^2/day, MAE = 0.14 kWh/m^2/day, MAPE = 2.42%, and a mean bias of approximately −0.03 kWh/m^2/day.

$$H_{AB} = H_0\left(0.54945 + 0.1746\frac{S}{S_0}\right) \tag{15}$$

where H_{AB} represents the global horizontal solar radiation estimated using the calibrated Angstrom-Prescott model.

The NASA POWER wind and solar datasets used in this study are gridded meteorological products and are therefore subject to uncertainties associated with spatial resolution, spatial averaging, reanalysis modelling, and the representation of local surface and atmospheric conditions. Long-term, temporally coincident in-situ wind-speed and solar-irradiance measurements are not available within the selected GMMR wellfields for the 2014–2024 study period; consequently, direct site-specific validation could not be performed. Nevertheless, the reliability of MERRA-2 for the Libyan context can be assessed from previous measurement-based studies. Kassem *et al.* (2024) compared six gridded wind datasets with mast measurements from nine Libyan stations, including Al-Kufrah, and found that MERRA-2 provided the best comparative performance at Al-Kufrah according to RMSE/MAE, RRMSE, and MAPE rankings. However, relatively high errors were still reported at Al-Kufrah, demonstrating that the accuracy of gridded wind products remains site-dependent. This observation is consistent with the broader validation of MERRA-2 by Carvalho (2019), who found its surface-wind performance to be generally comparable with other contemporary reanalyses, while identifying a tendency for reanalysis products to overestimate inland wind speeds and exhibit larger errors over land and complex surface environments. For the solar resource, the absence of local pyranometer observations at the GMMR wellfields prevents independent site-specific validation of the NASA POWER global-radiation data. Accordingly, the wind and solar results presented here should be interpreted as regional-scale resource estimates suitable for preliminary renewable-energy assessment rather than bankable site-specific measurements. Site-specific meteorological monitoring using calibrated anemometers and pyranometers is therefore recommended prior to detailed engineering design and investment decisions.

4. Results and Discussion

The results are organised in two parts for continuity and clarity. The first assesses wind resources, while the second evaluates solar potential across the GMMR wellfields. Wind metrics are reported at 10, 50, and 100 m to capture vertical shear and hub-height conditions. This structure facilitates identification of sites with the most favourable potential for wind, solar, or hybrid deployment.

4.1. Seasonal wind speed variation

Across all five wellfields, mean wind speed increases with height, reflecting persistent vertical shear and the benefits of higher hub heights for energy yield. The annual mean wind speed across the five GMMR wellfields ranges from 3.80 - 4.25 m/s at 10 m and 6.83 - 8.04 m/s at 100 m, confirming a consistent increase with height. As shown in Figs. 2 - 4, monthly means at 10 m generally fluctuate between 3.2 and 4.7 m/s across sites, while at 100 m, they span 6.2 to 8.8 m/s. At 100 m, the highest annual means occur at Sarir (8.04 m/s) and Tazerbo (7.69 m/s), followed by Al-Kufra (7.19 m/s), Ghadames (7.04 m/s), and Jabal Al-Hasouna (6.83 m/s).

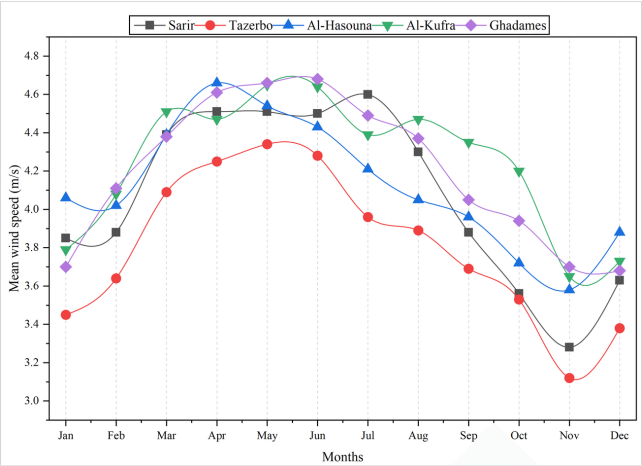

Figure 2. Monthly average wind speed variation at 10 m.

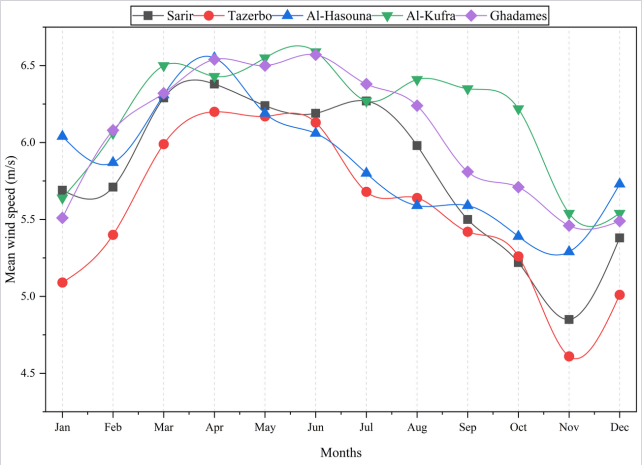

Figure 3. Monthly average wind speed variation at 50 m.

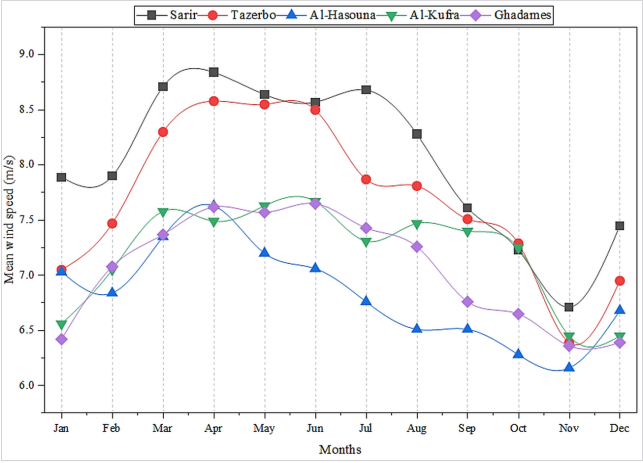

Figure 4. Monthly average wind speed variation at 100 m.

Moreover, a clear seasonal cycle is evident across sites, with speeds typically peaking from March to June and reaching minimum in November and December. While Ghadames and Jabal Al-Hasouna exhibit slightly lower annual means, all sites attain operationally relevant speeds at elevated hub heights, supporting the feasibility of commercial-scale turbines. While Ghadames and Jabal Al-Hasouna exhibit slightly lower annual means, all locations achieve comparatively strong resource

potential, supporting the feasibility of commercial-scale wind turbines. In operational terms, these conditions indicate that wellfield-scale wind generation could materially reduce exposure to grid shortfalls and enable partial self-supply during the spring, early-summer wind maximum.

4.2. Weibull parameters

The annual mean wind speed, as well as the scale and shape parameters of the Weibull distribution for all studied wellfields, are presented in Table 2. These Weibull parameters were evaluated at elevations of 10, 50, and 100 meters above ground level. Both the probability density function (PDF) and cumulative distribution function (CDF) were calculated for each wellfield, providing insight into wind speed variability. The statistical analysis shows that, the estimated Weibull shape parameter (k) lies between 2.3 at 10 m and 2.8 at 100 m for Sarir, Tazerbo, Jabal Al-Hasouna, and Ghadames, while Al-Kufra exhibits a higher value of 3.28 at 10 m and decreases to 2.97 at 100 m. Given that, Stable and persistent winds are typically indicated by a Weibull shape parameter k in the 1.5-3 range, all five wellfields fall within or near this stability band across most heights, indicating tighter clustering of wind speeds around the mean and therefore more stable production.

Table 2. Annual mean site characteristics at different heights.

Wellfield	Height (m)	V_{avg} (m/s)	k	c	P/A (W/m²)	E/A (kWh/m²)
Sarir	10	3.89	2.38	4.39	51.94	456.26
	50	5.59	2.64	6.29	162.38	1426.38
	100	6.18	2.76	6.94	213.87	1878.44
Tazerbo	10	3.7	2.51	4.15	48.81	425.24
	50	5.43	2.59	6.11	150.9	1325.70
	100	6.33	2.56	7.12	240.13	2109.38
Al-Hasouna	10	4.12	2.39	4.64	69.43	609.88
	50	5.86	2.57	6.58	189.12	1661.32
	100	6.82	2.55	7.67	300.07	2635.86
Al-Kufra	10	4.21	3.28	4.69	61.17	537.35
	50	6.14	2.97	6.87	199.67	1753.88
	100	7.15	2.97	8.01	315.65	2772.71
Ghadames	10	4.15	2.47	4.67	69.12	607.12
	50	5.96	2.5	6.72	204.35	1795.04
	100	6.95	2.49	7.82	324.4	2849.58

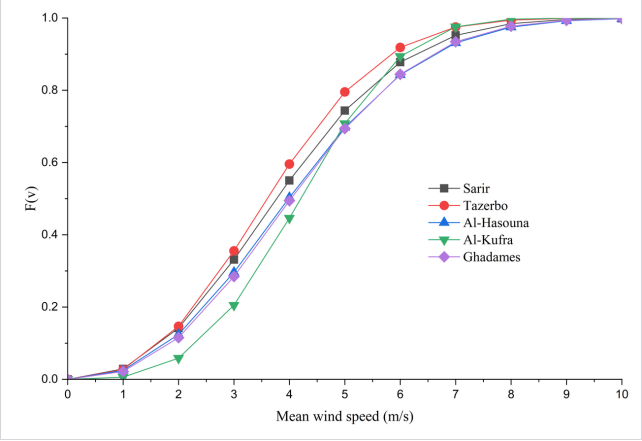

Figure 5. Cumulative distributions at 10 m.

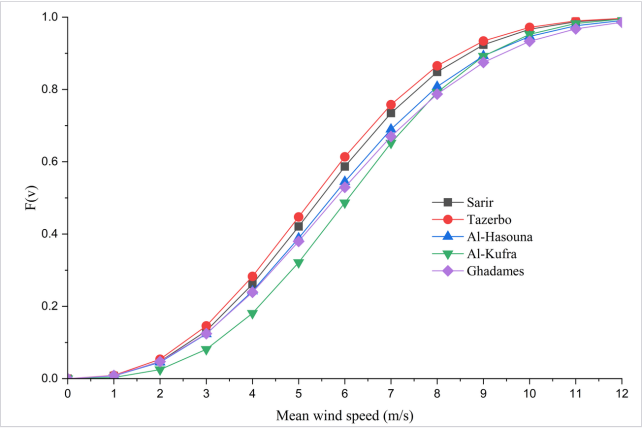

Figure 6. Cumulative distributions at 50 m.

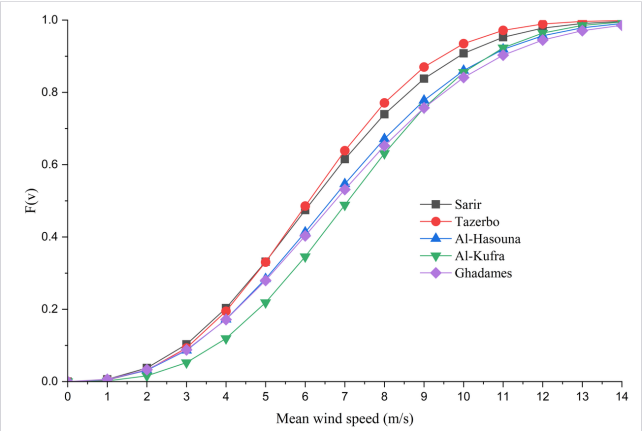

Figure 7. Cumulative distributions at 100 m.

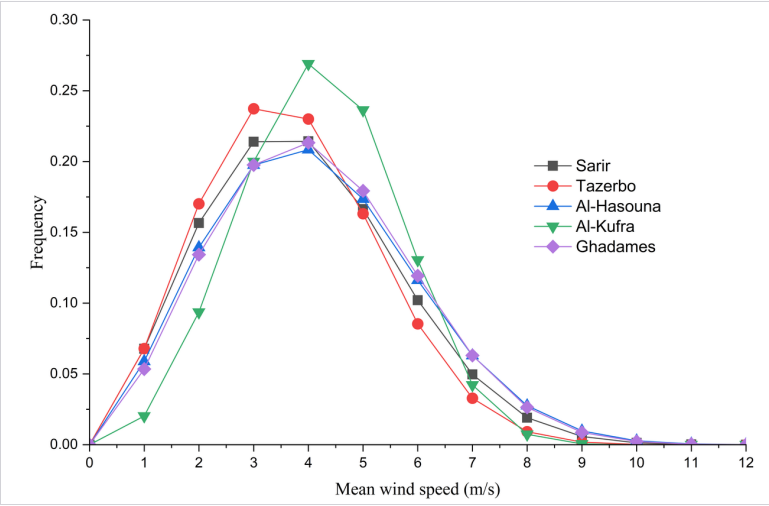

Figure 8. Frequency distributions at 10 m.

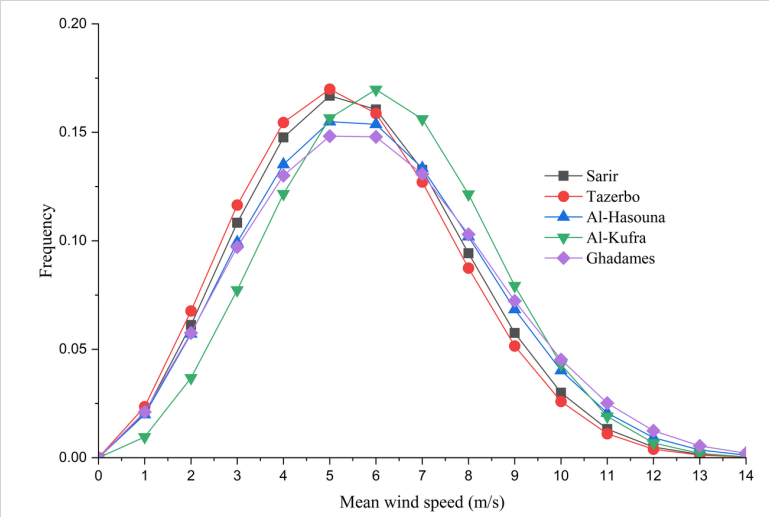

Figure 9. Frequency distributions at 50 m.

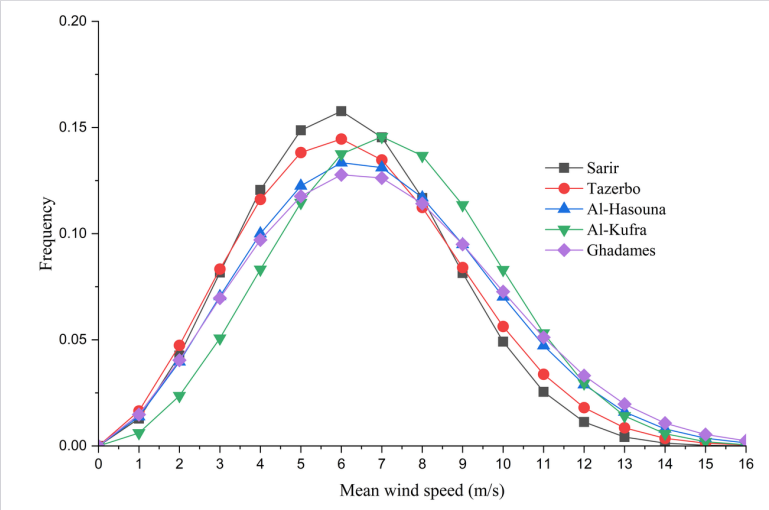

Figure 10. Frequency distributions at 100 m.

4.3. Wind power and energy density

The yearly averages wind energy density was determined according to Eqs. (5) and (6). The calculated outcomes for the five wellfields, evaluated at various elevations of 10 m, 50 m and 100 m, are summarized in Table 3 and visually represented in Fig 11. At all sites, the mean wind speed rises from approximately 4 m/s at 10 m to over 6 m/s at 100 meters, with Al-Kufra and Ghadames recording the highest values. This escalation in wind speed with height directly influences the energy output, as the wind energy density at 100 meters are typically five times greater than those observed at 10 meters. For instance, at Ghadames, the annual wind energy density increases from 607.12 kWh/m^2 to 2849.58 kWh/m^2. These values indicate that higher elevations are far more favourable for wind energy exploitation, providing significantly more energy yield for the same surface area.

Table 3. Wind energy density at different heights.

Wellfields	10 m	50 m	100 m
	E/A (kWh/m²)		
Sarir	456.26	1426.38	1878.44
Tazerbo	425.24	1325.70	2109.38
Al-Hasouna	609.88	1661.32	2635.86
Al-Kufra	537.35	1753.88	2772.71
Ghadames	607.12	1795.04	2849.58

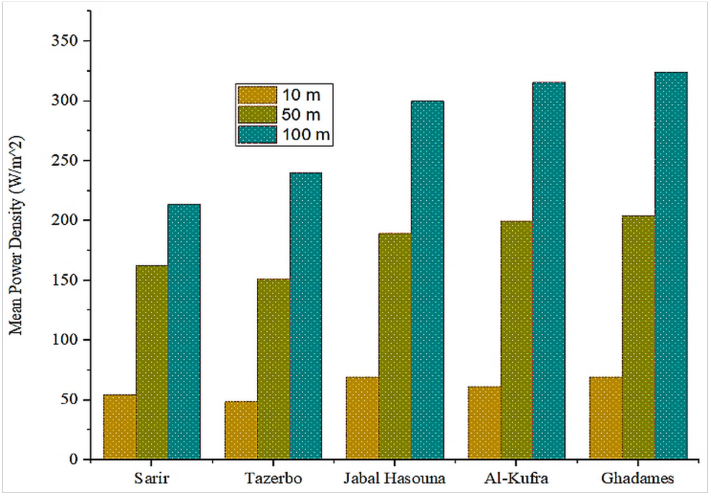

Figure 11. Wind energy density at different heights.

4.4. Analysis of solar parameters

Global solar radiation at the five GMMR wellfields was estimated over the 2014–2024 period using the calibrated Angstrom–Prescott model, with bright-sunshine duration derived from NASA POWER hourly DNI using the WMO threshold of 120 W/m^2, while extraterrestrial radiation H_0 and maximum possible sunshine duration S_0 were calculated from standard solar-geometry relationships. The calibrated coefficients a =0.5495 and b =0.1746 were then applied to estimate global horizontal solar radiation H_{AB}. The resulting seasonal variations in sunshine duration, global solar radiation, and clearness index are presented in the following

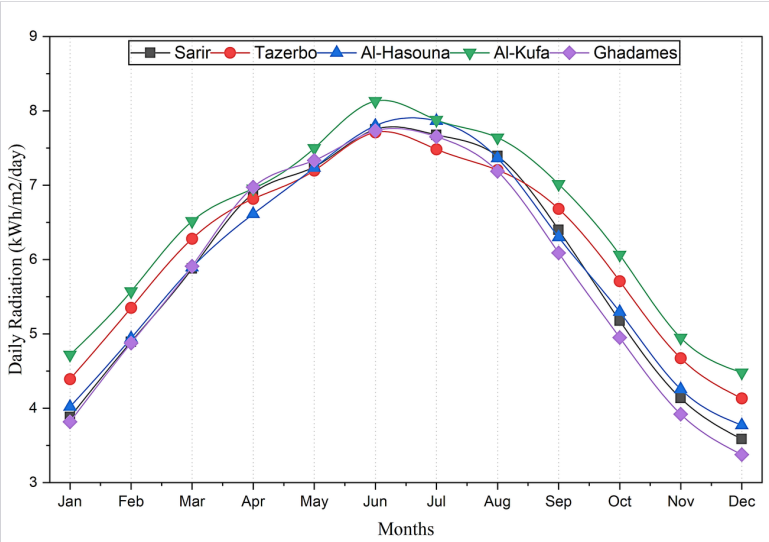

Figure 12. Annual average global solar radiation (H) for selected GMMR wellfields.

Figure 14 presents the monthly mean daily bright-sunshine duration across the five GMMR wellfields. Sunshine duration generally ranges from approximately 10 to 12 h/day, with longer durations during late spring and summer and shorter durations during winter. Figure 12 presents the global horizontal solar radiation estimated using the calibrated Angstrom–Prescott relationship. The annual mean daily H_{AB} values were approximately 6.45 kWh/m^2/day at Al-Kufra, 6.33 kWh/m^2/day at Tazerbo, 6.22 kWh/m^2/day at Sarir, 6.17 kWh/m^2/day at Jabal Al-Hasouna, and 6.05 kWh/m^2/day at Ghadames, giving an overall mean of approximately 6.25 kWh/m^2/day. The solar resource exhibits a clear seasonal pattern, with higher radiation during spring and summer and lower values during winter. Figure 13 shows the corresponding clearness index k_t, which remains relatively high throughout the year, reflecting the predominantly clear-sky conditions of the Saharan environment. The consistently high radiation levels across all five sites confirm their strong potential for photovoltaic energy applications.

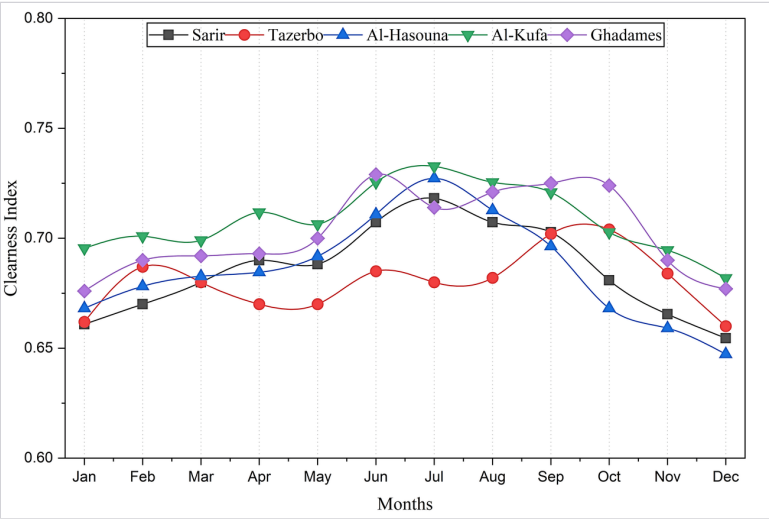

Figure 13. Annual average clearness index (k_t) for selected GMMR wellfields.

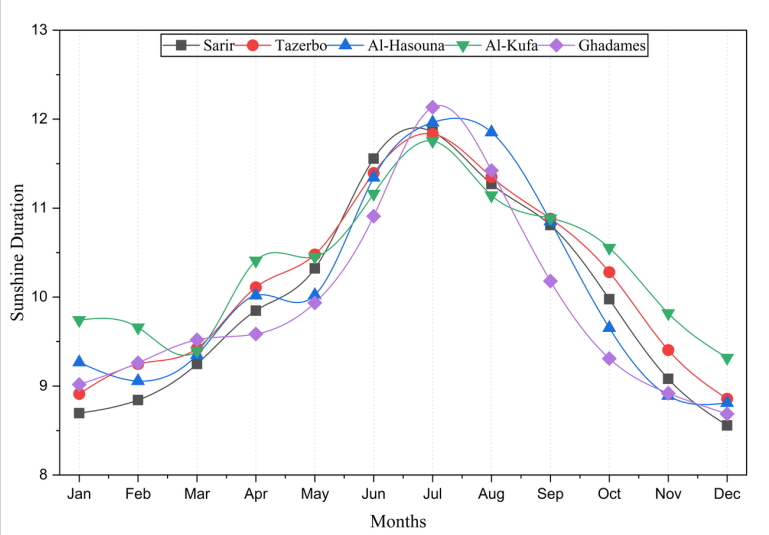

Figure 14. Annual average sunshine duration per day for selected GMMR wellfields.

5. Conclusion

In this assessment, long-term meteorological data spanning ten years (2014-2024) for five main GMMR wellfields in southern Libya, Sarir, Tazerbo, Jabal Al-Hasouna, Al-Kufra, and Ghadames, have been analysed. The main goal of the study was to determine the prospects for renewable energy and provide the first comprehensive multi-site assessment of wind and solar resources energy potential at these strategically important sites. The statistical two-parameter Weibull distribution function and the Angstrom-Prescott model were used to determine wind and solar energy potentials, respectively.

At a hub height of 100 m, the annual mean wind speed ranges from 6.83 m/s at Jabal Al-Hasouna to 8.04 m/s at Sarir, with the Weibull shape (k) parameter varying between 2.49 and 2.97 and the scale (c) parameter between 6.83 and 8.04 m/s. The mean power density (P/A) lies between 213.87 W/m^2 and 324.4 W/m^2, with Ghadames exhibiting the highest wind energy density, followed by Al-Kufra, Al-Hasouna, Sarir, and Tazerbo. Seasonal variations indicate stronger wind speeds during spring and early summer, and weaker winds in late autumn to winter, while wind energy densities increase substantially with height from 10 to 100 m.

Regarding solar potential, Al-Kufra recorded the highest annual mean daily global solar radiation, whereas Al-Hasouna exhibited the lowest, with the mean across all sites approximately 6.5 kWh/m^2/day. Clearness indices were consistently around 0.7 throughout the year, reflecting persistently clear desert skies. Together, the solar radiation and clearness index values confirm strong solar potential across all GMMR wellfields, reinforcing their suitability for photovoltaic deployment.

Collectively, the findings confirm that all five wellfields possess outstanding renewable energy potential. Strong wind regimes at elevated hub heights and persistent solar availability make them well suited for photovoltaic, wind, or hybrid system deployment. These findings establish a robust evidence base for transitioning the GMMR's power supply toward sustainable, reliable, and low-carbon energy. Integrating renewables at the wellfields would not only enhance energy security and reduce operational risks but also support Libya's broader goals of decarbonization and sustainable development.

Future efforts should focus on optimizing site-specific hybrid PV-wind configurations that align renewable generation with GMMR operational demands. Demonstration projects at selected wellfields could verify technical feasibility and support the broader adoption of decentralized renewable systems across Libya's remote regions. Moreover, integrating wind and solar systems into Libya's energy framework will require the development of supportive policies, regulatory mechanisms, and financial incentives to attract investment and promote long-term renewable energy growth.

Declarations

Author contributions. Mohammed Ogab: Methodology, Investigation, Formal analysis, Data curation, Writing (original draft), Visualization, Software. Djamal Hissein Didane: Conceptualization, Methodology, Investigation, Formal analysis, Writing (original draft), Writing (review and editing), Supervision, Software, Funding acquisition, Project administration. Wanis Mustafa Edukali Shibani: Investigation, Formal analysis, Visualization, Software, Data curation, Methodology, Resources. Ousama A Shaaban: Formal analysis, Visualization, Software, Data curation, Methodology, Resources. Abdelazeem A. Amin: Formal analysis, Visualization, Software, Data curation, Methodology, Resources.

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Conflicts of interest. The authors declare no competing interests.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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