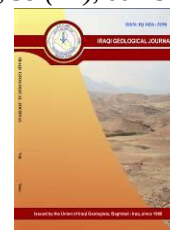




Iraqi Geological Journal

Journal homepage: <https://www.igi-iraq.org>



Land Surface Roughness and Its Impact on Wind Energy Potential in the Arid Terrains of Western Iraq

Ali K. Resen^{1*} , Omar A. Abdulrazzaq² , Yasir A. Abood² , and Zina A. Khadim² 

¹ Scientific Research Commission, Baghdad, Iraq

² Renewable Energy and Environment Research Center, Corporation of Research and Industrial Development, Iraq

* Correspondence: dr.aliresen@src.edu.iq

Received:
27 January 2026
Accepted:
14 April 2026
Published:
30 June 2026

Abstract

Surface roughness is a critical parameter in wind resource assessment, which determines the vertical wind speed profile and has a significant impact on the intensity of turbulence and extrapolation of energy yield estimates. Unlike in the preceding studies that have overlooked the terrain roughness aspect in the estimation of the wind resources in Iraq, this study provides a rigorous and systematic evaluation that directly incorporates surface roughness parameters in the determination of the site suitability as well as the prediction of potential wind farm energy output. A key feature of this approach is the use of the Wind Atlas Analysis and Application Program WAsP methodology integrated with the Global Wind Atlas dataset. The impact of surface roughness on wind characteristics and energy production from wind turbines was analyzed at three sites in Anbar Province, namely Al-Nukhayb, Al-Qa'im, and Al-Haqlaniyah, western Iraq. Wind shear, mean wind speed, power density, the Weibull parameters, and the sensitivity of these parameters to surface roughness variations were evaluated. The results indicate that changes in surface roughness led to changes in mean wind speed, Weibull scale parameter, and shear coefficient, which showed a logarithmic increase with respect to surface roughness. It observed that the prevailing wind direction originates mainly from the northwest, and the study succeeded in determining the various capacity factors for wind turbines according to different surface roughness. The capacity factors reached 30.5% at the first site, 19.2% at the second and 31.7% at the third. This highlights the substantial influence of surface roughness on evaluating the suitability of wind turbines sites. The results provide useful insights for accurately assessing wind resources and efficiently installing turbines in the initial planning stage.

Keywords: Wind energy; Land surface; Surface roughness; Arid terrains; Iraq

1. Introduction

Most of the greenhouse gases that trap heat in the Earth's atmosphere come from burning fossil fuels to produce energy, mainly for electricity and heat. This energy transition is critical to tackling the climate crisis, as fossil fuels still provide 80 percent of the global energy supply. Therefore, the transition to renewable energy is essential (Asif, 2022; Li et al., 2022; Ezekiel et al., 2024; Ibrahim et al., 2025). Renewable energy is a significant component in the fight against climate change, reducing reliance on fossil fuels that release carbon dioxide (Ezekiel et al., 2024; Bandória et al., 2025). Energy production is responsible for approximately 72% of total global artificial greenhouse gas emissions,

making the energy sector a critical focus for decarbonization (Lee et al., 2021). Across the Middle East and North Africa (MENA), the expansion of solar photovoltaics and wind power has become a strategic priority in energy policy. The Global Wind Energy Council's (GWEC) flagship global wind report shows that 2024 was a record year for new capacity, with 117 GW of wind energy installed across the world. A transition toward renewable energy is underway, driven by the implementation of strategic policies by regional governments. Several high wind sites in MENA have been identified for development, including Egypt's Gulf of Suez, Morocco's Atlantic coast, northwestern Saudi Arabia, and southern Oman, all of which exhibit excellent wind conditions (with typical wind speeds well above 7-8 m/s and peaks over 10 m/s) (Dourian, 2023). Saudi Arabia has recently completed its first utility-scale wind farm, and new projects are on the way (Dumat Al Jandal, 400 MW), which is the largest in the Middle East and began feeding electricity into the grid in 2021 (Jazeera, 2021). Wind installations have been launched in Jordan and Oman, and several Gulf states are in the process of planning their initial wind projects (Coleman, 2024).

Iraq is a prime example of a country with promising wind energy but still lacks development on a national scale. Iraq's energy sector relies on oil and gas for 80% of its electricity generation, and the country faces chronic power shortages and unmet peak demand. Iraq announced plans to add roughly 10-12 GW of renewable capacity by 2030 (Kapoor, 2025), aiming to reach about 20% of generation from clean sources. Accurate wind resource assessment is essential for wind energy projects, as it identifies suitable turbine sites, suitable turbine characteristics such as blade design (Kadhim et al., 2022), and supports early economic evaluation of the required capital investment (Ucar & Balo, 2010; Kucukali & Dinçkal, 2014; Ayik et al., 2021). Several peer-reviewed studies assessing wind energy potential in Iraq have demonstrated substantial spatial and temporal variability in wind speed and energy density. It is noted that wind speeds tend to be highest in the middle of the day, which is when we also see peak values between 5 to 10 m/s. Also, wind speeds in summer exceed those of winter, which at the same time sees greater electricity demand for cooling in the hot months (Darwish et al., 2019). Iraq can be divided into three wind speed regions: 2–3 m/s, 3.1–4.9 m/s, and above 5 m/s, with about one-sixth of the country experiencing annual wind speeds greater than 5 m/s, making these areas suitable for wind farm development (Hasan & Genç, 2022). The potential for wind energy increases from the north to the center and southern parts of Iraq, especially at heights of 30–50 m, where wind speeds can exceed 8 m/s (Resen, 2024). Surface roughness is a critical factor in wind resource assessment because it directly affects the wind speed at the turbine hub height (Drobinski, 2026). Inaccurate estimation of surface roughness can introduce errors in wind speed measurements, which in turn affect energy output calculations. For instance, even a small 1% error in wind speed may result in nearly a 2% deviation in the estimated energy production (Rehman et al., 2007). Therefore, studying surface roughness in wind energy projects is critically important. Existing literature on wind assessments has received comparatively limited attention (Nassif et al., 2024), and systematic investigation of surface roughness effects on wind resource characterization is often overlooked, particularly in desert and semi-arid environments with heterogeneous terrain. Iraq has diverse terrain even within a single geographical area. In western Iraq (the study area), there are open desert areas as well as agricultural areas with residential areas, which we present as a representative case study for looking at roughness effects.

This study makes three principal contributions to wind resource assessment methodology and renewable energy development in arid regions. First, it takes into account the effect of surface roughness on the assessment of wind energy resources. Second, it studies the effect of roughness on the power output of turbines and calculates the capacity factor. Third, it employs the WAsP programme as a working method and integrates data from the Global Wind Atlas as a data source. This work represents an original contribution to a region with untapped wind energy potential.

2. Study Area

The analysis within Al Anbar Governorate, as shown in Fig. 1, the largest governorate in Iraq. This region also covers most of the western border of the country and borders with Syria in the Northwest, Jordan in the West, and Saudi Arabia in the Southwest. Al Anbar, like the other places in Iraq's western deserts, has a dry continental climate, and much of the governorate lies within the Syrian Desert ecosystem, characterized by steppe and desert landforms, low annual precipitation, large diurnal temperature variation, and low humidity. The temperature rises in summer to 52°C, and decreases to approximately 9°C in winter. The winds are northwesterly and southwesterly (Muslih and Abbas,2024).

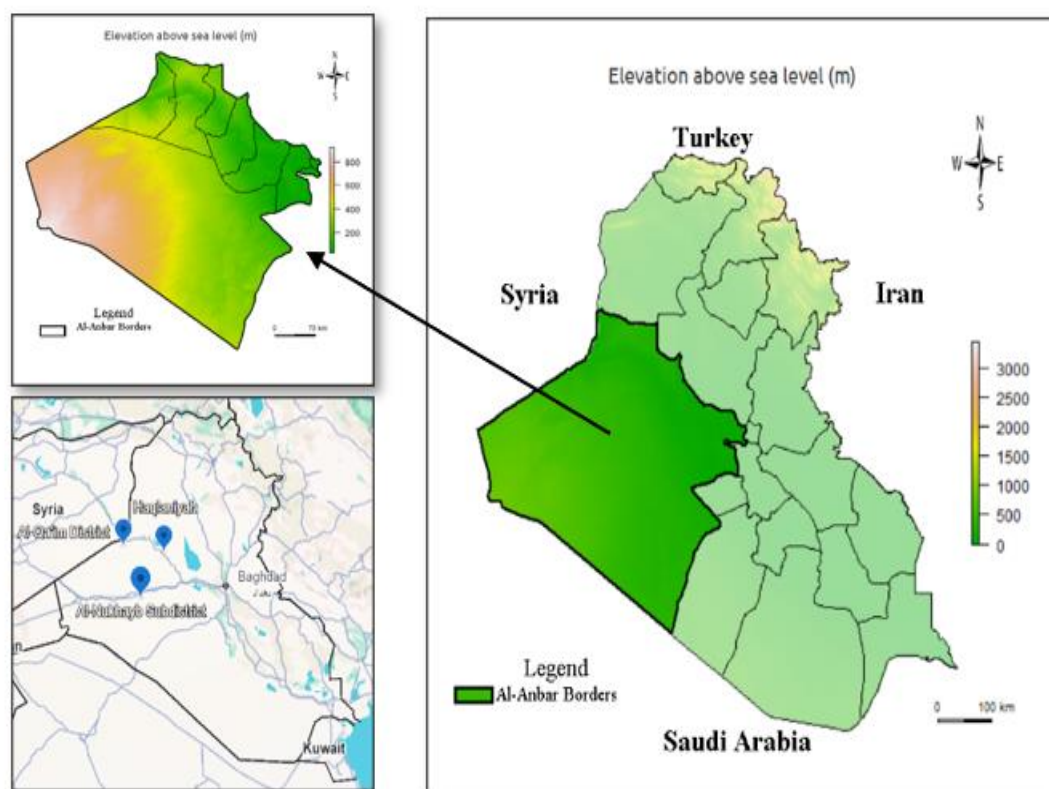


Fig.1. Map of the study area

Three geographically close sites that differ in surface roughness were selected to study the effect of varying surface roughness on evaluating wind energy potential, and consequently, wind power generation, as shown in Table 1.

The first site is located in the Al-Nukhayb Subdistrict of Al-Rutba District, at coordinates 32.971804°N, 41.616211°E, defined by a roughness length of $z_0 = 0.0050$ m. This site presents very smooth terrain typical of unvegetated desert surfaces with minimal surface obstacles. The second site is located in Al-Qa'im, specifically within the Al-Qa'im Central Subdistrict of Al-Qa'im District, at coordinates 34.402604°N, 41.02858°E, with a roughness length of $z_0 = 0.10$ m. This intermediate roughness classification applies to agricultural land with scattered windbreaks and dispersed built-up areas. The third site features located in the Al-Haqlaniyah Subdistrict of Haditha District at 34.197037°N, 42.046738°E, roughness length $z_0 = 0.03$ m (Davis et al., 2023). It is open terrain characterized by scattered grassland vegetation. There are marginal surface obstacles, and only a few isolated structures.

Table 1. Coordinates of study area sites

Site	coordinates	Name	Roughness length z_0 (m)
1	N:32.971804°, E:41.616211°	Al-Nukhayb Subdistrict, Al-Rutba District, Al-Anbar Governorate, Iraq	0.0050
2	N:34.402604°, E:41.02858°	Al-Qa'im, Al-Qa'im Central Subdistrict, Al-Qa'im District, Al-Anbar Governorat	0.10
3	N:34.197037°, E:42.046738°	Al-Haqlaniyah Subdistrict, Haditha District, Al-Anbar Governorate, Iraq	0.03

3. Data and Methodology

3.1. Data Acquisition and Processing

The assessment of wind resources in this work is based on the Global Wind Atlas GWA database. This data was then used as the basis for assessing the wind resource potential within sites under study. It combines multi-year data sets of atmospheric reanalysis (ERA) and satellite observation which provides long-term estimates for wind resources that are regarded as reliable. The wind resource data extracted from GWA and exported as WASP library file format (.lib).

3.2. Wind Resource Characterization

Mean wind speed (WS), power density and Weibull distribution parameters have been obtained at five height levels (10 m, 50 m, 100 m, 150 m, 200 m, and 250 m) and used to conduct a wide-ranging evaluation of available wind resources. The vertical resolution was selected to resolve unique wind profile development across the lower atmospheric boundary layer and span the current hub height of modern commercial wind turbines. A two-parameter Weibull probability distribution was fitted to each site's wind speed data. The Weibull distribution is expressed as (Shi et al., 2021):

$$f(x) = \frac{k}{A} \left(\frac{x}{A}\right)^{k-1} \exp\left[-\left(\frac{x}{A}\right)^k\right] \quad (1)$$

where: A is the scale parameter, and k is the shape parameter of the Weibull distribution. x represents the wind speed (m/s).

3.3. Terrain Surface Characteristics and Surface Roughness Classes in WASP

The classification ranges from perfectly smooth surfaces (roughness class 0), such as water bodies like seas, fjords and lakes to rougher terrain $z_0 = 0.40$ metres. Surface roughness length values applied in the Global Wind Atlas 4.0 (GWA 4.0) were derived systematically from a globally available high-resolution land cover product, specifically version 200 of European Space Agency's WorldCover dataset, which is one of the newest global products available for land cover classification and mapping based on satellite observations. The dataset combines remote sensing from different types, from optical sensors and synthetic aperture radar (SAR) data of the Sentinel-1 and Sentinel-2 missions to reach an overall classification accuracy level up to 76.7% for a version used in this application. WorldCover detects 11 different land cover classes at a native spatial resolution of around 10 metres (Davis et al., 2023).

To integrate it into the GWA framework, the original WorldCover data was resampled to a finer horizontal grid spacing of 1/2400 degrees (approximately 50 metres at the equator) using nearest neighbour interpolation techniques, while maintaining the WGS 1984 geographic coordinate system

(European Petroleum Survey Group, EPSG: 4326). Taking into account physical properties related with each surface type, the processed from explicit land cover classes to continuous roughness length values required precise study (Davis et al., 2023). The correlation between roughness length, terrain characteristics, and roughness class is described in Table 2 (Peña et al., 2016).

Table 2. Roughness length values (Peña et al., 2016)

Roughness length z_0 (m)	Terrain surface characteristics	Roughness class z_0	Specified in WAsP (m)
1.5			1.5
> 1	Tall forest	4(1.5) m	>1
1	city		1
0.80	forest		0.80
0.50	suburbs		0.50
0.40	Villages / suburban terrain	3(0.4) m	0.40
0.30	Shelter belts		0.30
0.20	Many trees and/or bushes		0.20
0.1	Farmland with a closed appearance	2(0.10) m	0.1
0.05	Farmland with an open appearance		0.05
0.03	Farmland with very few buildings/trees	1(0.03) m	0.03
0.02	Airport areas with buildings and trees		0.02
0.01	Airport runway areas		0.01
0.008	Mown grass		0.008
0.005	Bare soil(smooth)		0.005
0.001	Snow surfaces (smooth)		0.003
0.0003	sand surfaces (smooth)		0.003
0.0002	Used for the water surface in the Atlas	0(0.0002) m	0.0
0.0001	Water areas(lakes, fjords, open sea)		0.0

3.4. Wind Shear Coefficient

Wind shear, a quantitative indicator for describing how the speed of the wind changes with height in an atmospheric boundary layer, is also a key parameter in wind resource assessment and turbine performance evaluation. Wind shear is mainly influenced by surface roughness, atmospheric stability, and thermal stratification, with surface roughness often acting as the dominant factor under neutral atmospheric conditions (Emeis, 2013; Gualtieri, 2019).

Numerous empirical and theoretical studies have demonstrated a strong positive relationship between z_0 and the wind shear exponent α for neutral conditions as expressed by (Counihan, 1975; Wieringa, 1992).

$$\alpha = \frac{0.096 \log_{10}(z_0) + 0.016(\log_{10}(z_0))^2 + 0.24}{\ln\left(\frac{z}{z_0}\right)} \quad (2)$$

α is the wind shear exponent (dimensionless), z_0 is the surface roughness length (m), and z is height above ground level (m).

Other expressions for α in terms of roughness length have been suggested by several authors, demonstrating the local nature of the wind shear relationship and the intricate details of boundary layer physics (Hsu et al., 1994). Precise characterisation of wind shear is critical to many considerations of wind energy project development, since spatial variations in shear coefficients lead to uncertainty in wind resource mapping and require careful consideration in optimizing turbine siting (Wharton and Lundquist, 2012).

3.5. Turbine Selection Methodology

The Vensys V100-2.5 MW wind turbine was chosen since it has International Electrotechnical Commission IEC Class IIIA certification, which is suitable for the moderate wind regime observed at the study sites (average wind speed of 6.5 m/s at a height of 100 m). The turbine's relatively low start-up speed (3 m/s) also enables power generation under low wind speed conditions typical of the region. Fig. 2 shows the power curve for the Vensys V100-2.5 MW wind turbine.

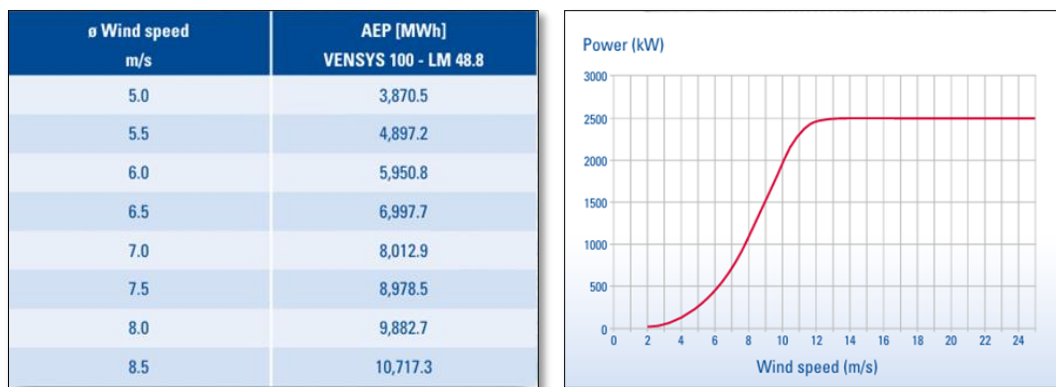


Fig. 2. Power curve of Vensys V100-2.5 MW wind turbine

3.6. Annual Energy Production Estimation

Annual energy production (AEP), usually expressed in MWh/year or GWh/year, is defined as the total electrical energy generated by wind turbines over a one-year operating period (Pryor et al., 2018).

$$AEP = 8760 \times \int P(v) \times f(v) dv \quad (3)$$

where 8760 represents the total number of hours in a standard year, v denotes wind speed, $f(v)$ is the probability density function (PDF) of wind speed, and $P(v)$ is the turbine power output at wind speed v (kW).

3.7. Capacity Factor Determination

The wind turbine capacity factor shows the ratio of actual energy output to maximum possible energy output. This parameter is mathematically defined as (Jung & Schindler, 2023).

$$CF = AEP / (P_{\text{rated}} \times 8760) \quad (4)$$

where P-rated denotes the turbine's nameplate capacity in megawatts, and annual energy production AEP is expressed in MWh/year. The wind turbine capacity factor is a standard indicator of turbine performance efficiency.

4. Results and Discussion

4.1. Regional Wind Climate for Site 1: Extract energy

Fig. 3a illustrates the relationship between mean wind speed and height for different values of surface roughness length (z_0). It is revealed that height-wise wind speed monotonically grows in all of the cases. The reasons for this behavior are the decrease of frictional actions right over the ground and obstacles like buildings or terrain features that influence lower at given levels.

The appearance also shows the large effect of surface roughness. This airflow resistance causes more drag, such that as the roughness length (z_0) rises, wind speed to ground drops. Fig. 3b reveals that wind power density shows a strong vertical gradient and reaches about 496 W/m^2 at 250 m above ground over a smooth landform, which represents a significant increase in wind power potential. Surface roughness has a wide-ranging effect on the distribution of power density; smooth surfaces (very low roughness) have much higher power densities than highly roughened terrains (z_0 equal to 3.00 m), especially in the region of the lower atmospheric boundary layer. Nevertheless, higher surface roughness increases turbulence and reduces wind speed near the surface, leading to lower power density; however, these effects progressively weaken with height, as is seen at 250 m above ground level. Concurrently, the Weibull shape parameter (k) increases both with elevation and with surface roughness magnitude as shown in Fig.4a, indicating a shift toward a more uniform and temporally consistent wind speed distribution at higher levels, where flow in the atmosphere is decoupled from surface drag effects. Mean wind speed is directly proportional to the height and inversely proportional to the roughness of the surface. Fig.4b illustrates the relationship between Weibull (k) and height for different surface roughness.

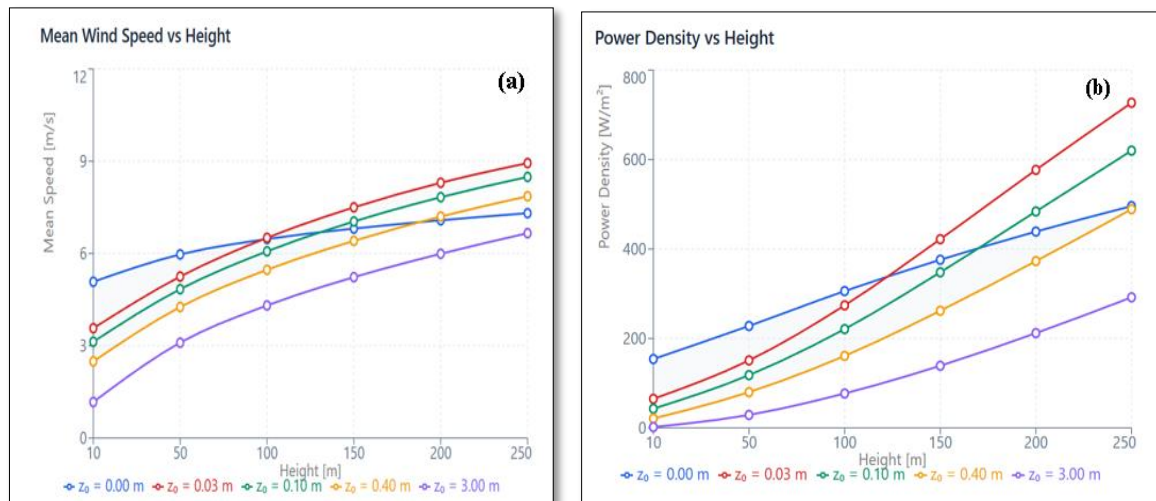


Fig. 3. a) The relationship between mean wind speed and height for different surface roughness across study site 1, Al-Nukhayb – Anbar Gov., western Iraq. b) The relationship between power density and height for different surface roughness across study site 1, Al-Nukhayb, Anbar, Iraq

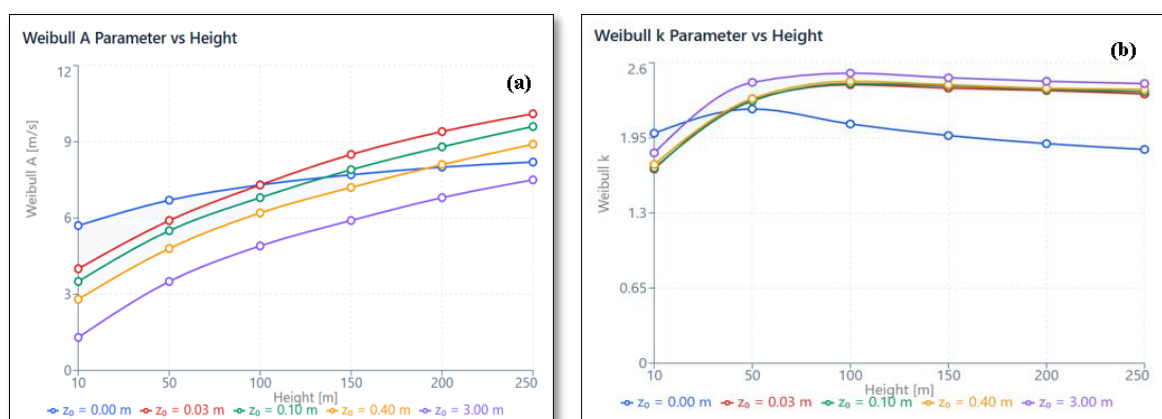


Fig. 4. a) The relationship between Weibull (A) and height for different surface roughness, b) The relationship between Weibull (k) and height for different surface roughness

The wind rose indicates that the prevailing wind direction is northwest (Fig. 5).

Fig. 6 reveals a strong relationship between the shear coefficient and surface roughness; The shear coefficient increases significantly with increasing surface roughness. For smooth terrain ($z_0 = 0.00$ m), the power law exponent has a minimal value of $\alpha = 0.1207$, indicating very low wind shear and consequently a relatively uniform vertical wind speed profile throughout the atmospheric boundary layer. In contrast, extremely rough terrain ($z_0 = 3.00$ m) generates a markedly elevated power law exponent of $\alpha = 0.4797$, representing the highest degree of wind shear, which increases significantly with increasing height above the surface.

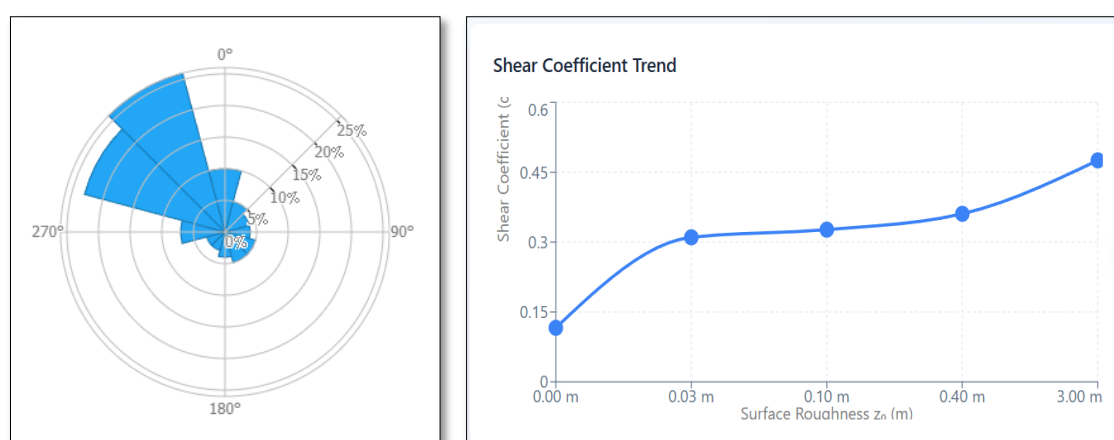


Fig. 5. Wind rose for site 1

Fig. 6. Relationship between the shear coefficient and surface roughness for site 1

4.2. Energy Production and Performance Analysis for Site 1

The selected Vensys V100–2.5 MW wind turbine is expected to generate 6.69 GWh/year (gross), with a capacity factor of 30.5%, placing it at the lower bound of the 'good' category and indicating moderate-to-good wind resource quality and commercial viability.

4.3. Regional Wind Climate for Site 2

Fig. 7a illustrates the relationship between mean wind speed and height for different surface roughness across study site 2. Fig. 7-b illustrates the relationship between power density and height for different surface roughness. Fig. 8 -a depicts the relationship between Weibull A and height for different

surface roughness across study site 2, while Fig.7-b reveals the relationship between Weibull K and height for different surface roughness.

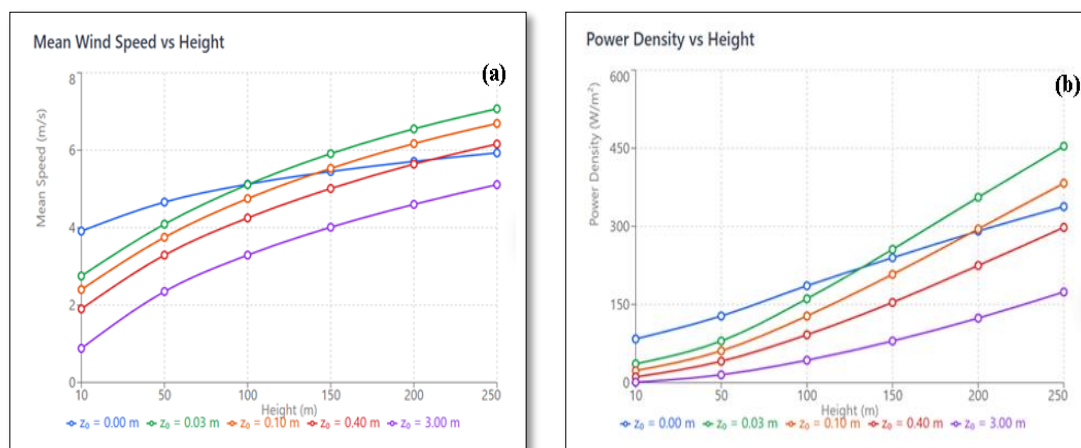


Fig. 7. a) Illustrates the relationship between mean wind speed and height for different surface roughness across study site 2, Al-Qa'im, Anbar, Iraq. b) illustrates the relationship between power density and height for different surface roughness across study site 2, Al-Qa'im, Anbar, Iraq.

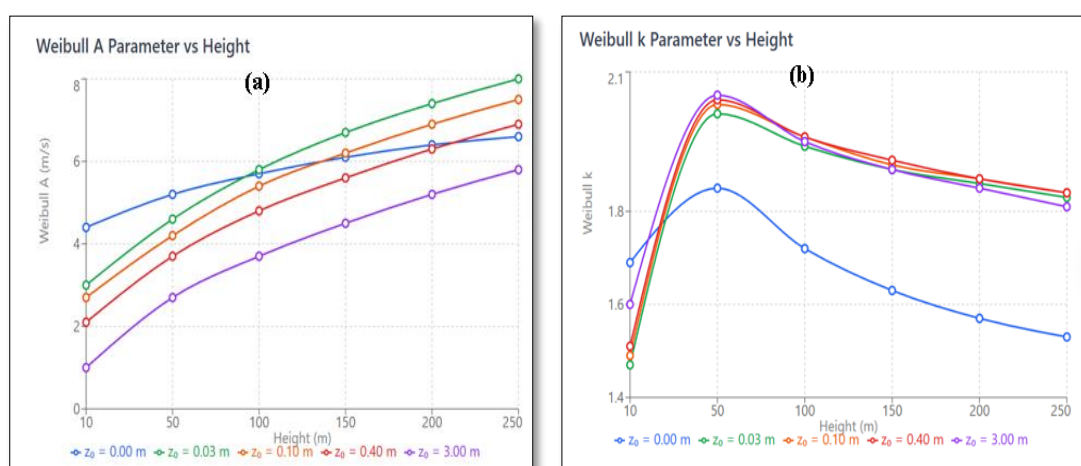


Fig. 8. a) The relationship between Weibull A and height for different surface roughness across study site 2, Al-Qa'im, Anbar, Iraq b) The relationship between Weibull K and height for different surface roughness across study site 2, Al-Qa'im, Anbar, Iraq

Both Weibull parameters and mean wind speed increase with height and decrease with surface roughness. Smoother surfaces show less variation with height. Weibull k peaks around 50 m height for all roughness values, then gradually decreases. Increased surface roughness is associated with a slight increase in the Weibull shape parameter (k), while smoother surfaces generally exhibit higher wind power density due to reduced frictional effects. The results clearly indicate that wind resource assessment is highly strongly influenced by surface roughness, with smoother surfaces generally supporting higher wind speeds, although they do not always yield the highest power density at all heights.

Fig. 9 illustrates the wind roses in site 2; there is a northwest direction of the prevailing wind. Fig. 10 represents the correlation between the shear coefficient and surface roughness.

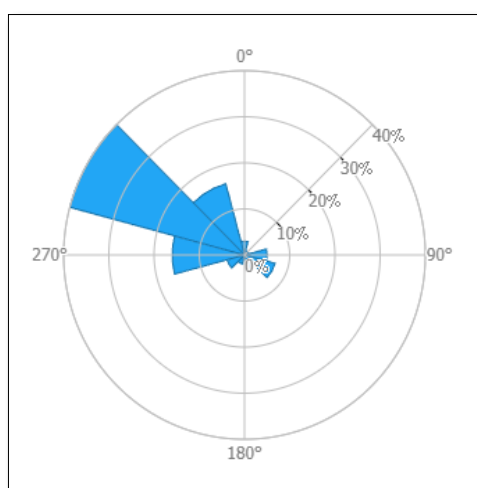


Fig. 9. Wind rose for site 2

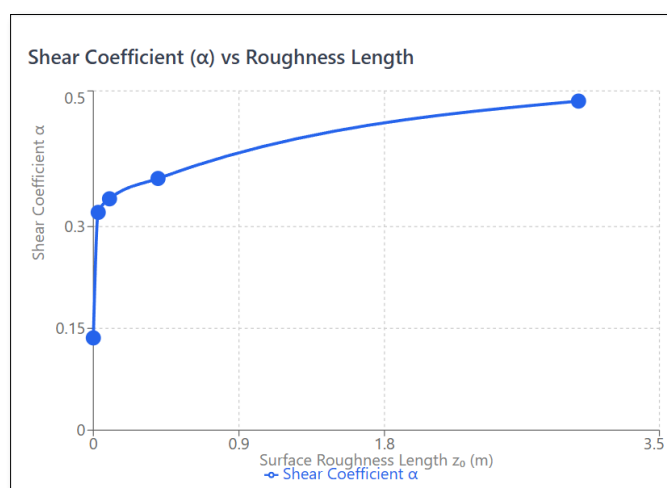


Fig. 10. Relationship between the shear coefficient and surface roughness for site 2

The shear coefficient rises from $\alpha=0.136$ for smooth surfaces to $\alpha=0.485$ for very rough terrain. This correlation is in line with physical principles, as small percentage of surface roughness states produce differences between shear coefficient α . The shear coefficient is log-dependent on surface roughness.

4.4. Energy Production and Performance Analysis for Site 2

The overall performance evaluation of the Vensys V100–2.5 MW wind turbine installation has shown that the anticipated rate of the generation of energy is about 4.22 GWh/year. The resulting capacity factor of 19.2% places the installation at the low range of the commercially viable range of wind energy projects, which indicates a mediocre quality of wind resource in the site under consideration.

4.5. Regional Wind Climate for Site 3

Fig. 11a illustrates the relationship between mean wind speed and height for different surface roughness across study site 3, Al-Haqlaniyah – Anbar Gov., western Iraq. Fig. 11b depicts the relationship between power density and height for different surface roughness. It seems that, in lower heights (less than 100 m), smooth surfaces have a greater wind speed and power density. However, beyond 150 m, a medium roughness ($z_0=0.03\text{m}$) is the best. The maximum power density of 717 W/m^2 at 250 m, out of all other roughness values, in this case of ($z_0=0.03\text{m}$). Fig. 12a illustrates the relationship between mean wind speed and height for different surface roughness. It is clear that the Weibull A parameter increases with height and decreases with surface roughness. Fig. 12-b depicts the relationship between Weibull K and height for different surface roughness across study site 3. It is evident that increasing surface roughness systematically elevates the Weibull shape parameter (k), reflecting a more uniform wind distribution, with k values spanning roughly 1.7 to 2.4 across the roughness range. In cases of hub height 150 m or greater, locations with z_0 of 0.03-0.10 (open grassland/farmland) have the best potential to exploit the wind resource. The ($z_0=0 \text{ m}$) case shows non-standard behaviour, and for the very smooth surface, the wind turbine shows improved performance at higher elevations. This is due to the increase in wind speed with height, as predicted by the wind shear profile. Local surface characteristics, such as smooth water bodies, can reduce near-surface turbulence and modify the wind velocity profile, which influences the turbine's energy output. Consequently,

turbines operating at higher hub heights over smooth terrain can achieve higher energy production compared to lower elevations.

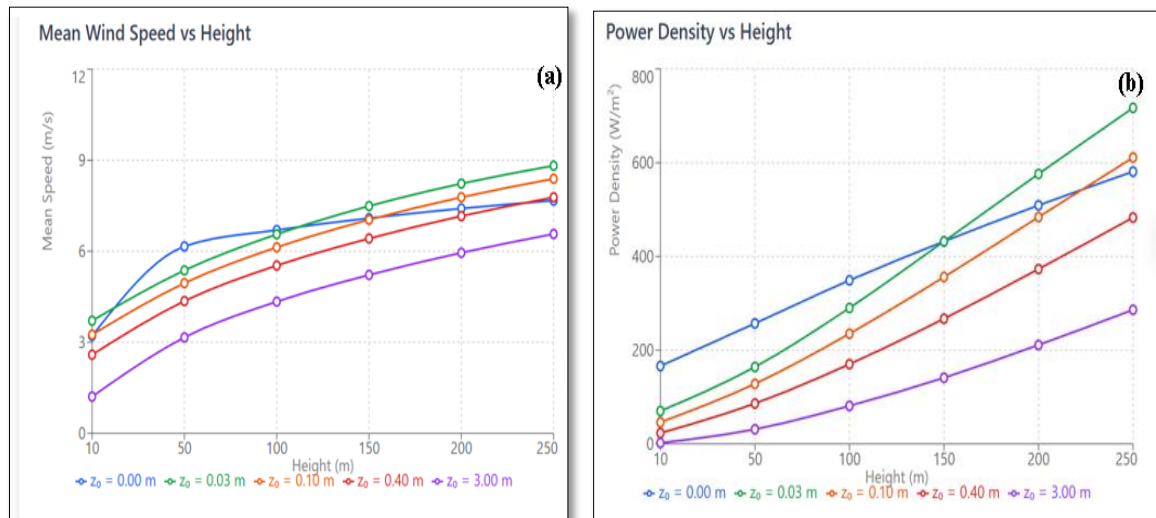


Fig. 11. a) The relationship between mean wind speed and height for different surface roughness across study site 3, Al-Haqlaniyah – Anbar Gov., western Iraq. b) The relationship between power density and height for different surface roughness across study site 3, Al-Haqlaniyah – Anbar Gov., western Iraq.

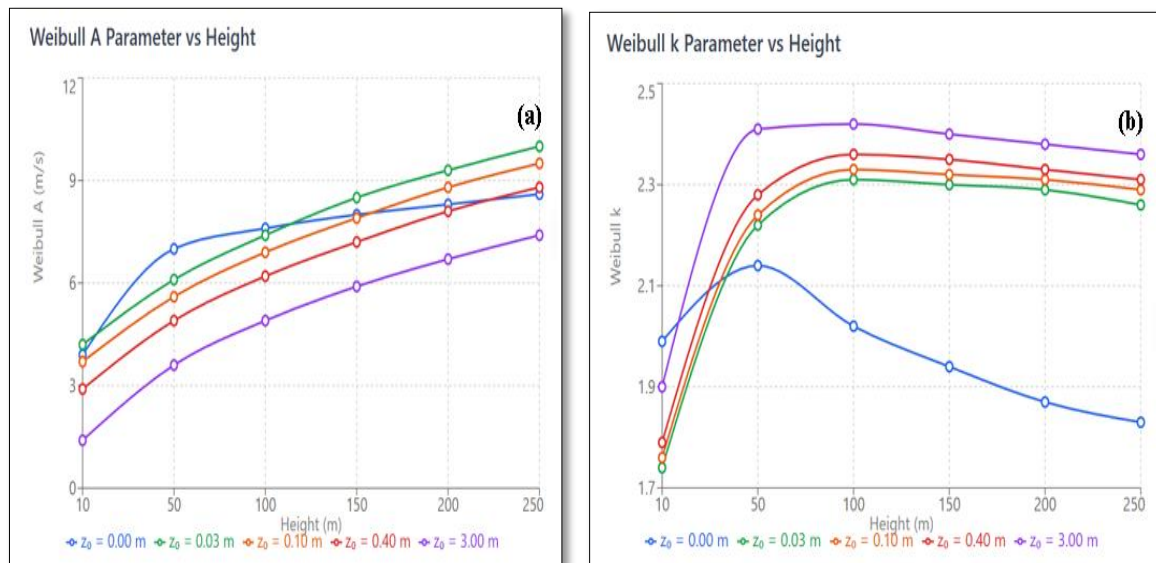


Fig. 12. a) Illustrates the relationship between Weibull A and height for different surface roughness across study site 2, Al-Haqlaniyah – Anbar Gov., western Iraq. b) Illustrates the relationship between Weibull K and height for different surface roughness across study site 3, Al-Haqlaniyah – Anbar Gov., western Iraq.

Fig. 13 shows that the dominant wind direction is northwestern. The results in Fig. 14 indicate a strong positive relationship between shear coefficient and surface roughness, whereby the former rises logarithmically with the latter (α : 0.121 $\rightarrow$ 0.457).

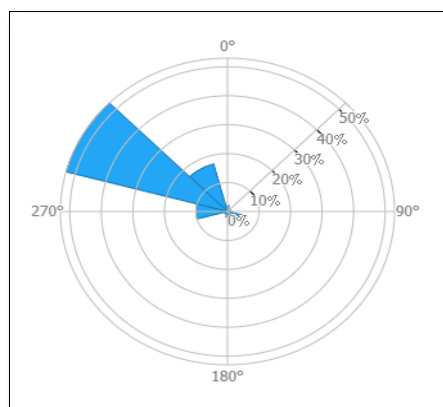


Fig. 13. Wind rose for site 3

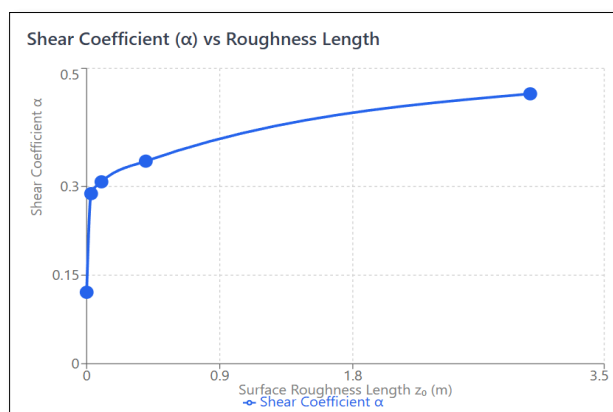


Fig. 14. Relationship between the shear coefficient and surface roughness for site 3

4.6. Energy Production and Performance Analysis for Site 3

Assessment of the wind turbine installation of Vensys V100-2.5 MW wind turbine reveals that the expected annual energy output of the installation is estimated to be around 6.94 GWh of energy. With a calculated capacity factor of 31.7%, it is possible to categorize this installation as a good performance segment of onshore wind energy developments.

5. Conclusions

This paper presents a detailed assessment of wind potential and the corresponding energy generation at three locations in Al Anbar Governorate, western Iraq: Al-Nukhayb, Al-Qa'im, and Al-Haqlaniyah. The study particularly focuses on analyzing the effect of surface roughness on wind patterns and turbine performance. The results of this study have conclusively shown that surface roughness has a significant effect on all the basic parameters of wind resources. Mean wind speed and Weibull scale parameter (A) have a systematic negative correlation with the roughness length. Wind speed on smooth terrain ($z_0 = 0.00\text{--}0.03\text{ m}$) is 15-30% above the wind speeds on very rough terrain ($z_0 = 3.00\text{ m}$) at typical turbine hub heights. The power density is more sensitive to the change in the surface roughness. The power density of smooth surfaces is two to three times that of very rough terrain at elevations less than 100 m. However, the effect of surface roughness weakens with height due to the decreasing influence of ground friction. A wind shear study shows that there is a high positive correlation between wind shear and surface roughness, which shows observed consistency and alignment of data points. Directional analysis indicates that the prevailing wind comes from the northwest (around 300°), with 33.6–38.9% of observed wind speeds occurring from this direction under the specified surface roughness conditions. Computations of energy yields at the Vensys V100-2.5 MW wind turbine show high variation across the tested locations; the value of capacity factors was within the range of 19.2-31.7%. The study confirms that the parameterization of surface roughness is one of the most important determinants for characterizing wind energy potential and assessing the future viability of wind energy projects.

Author contributions: CRediT

Ali K. Resen: Conceptualization, Formal analysis, Methodology, Software, Writing- review and editing.

Omar A. Abdulrazzaq: Conceptualization, Validation, Writing- original draft, Writing – review and editing.

Yasir A. Abood: Resources, Writing- original draft. Zina A. Khadim: Data curation, Investigation.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this study.

Acknowledgments

The authors are deeply grateful to the Scientific Research Commission for the availability of the Wind Atlas Analysis and Application Program (WAsP), whose functionality was essential in the tedious evaluation of the wind resources and the stringent data analyses reported herein.

Funding sources

The authors received no financial support for this research.

Data Availability

The data that support the findings of this study are openly available at [<https://globalwindatlas.info/en/>]

References

- Asif, M., 2022. Sustainable energy transition in the 21st century. Handbook of Energy and Environmental Security. Academic Press, London, 27–38. <https://doi.org/10.1016/B978-0-12-824084-7.00023-0>
- Ayik, N., Ijumba, N., Kabiri, C., Goffin, P., 2021. Preliminary wind resource assessment in South Sudan using reanalysis data and statistical methods. Renewable and Sustainable Energy Reviews, 138, 110621. <https://doi.org/10.1016/j.rser.2020.110621>
- Bandória, L.H.T., Silva, W.N., de Almeida, M.C., Dias, B.H., 2025. Enhancing electrical load profile segmentation for smart campus energy management. Energy and Buildings, 329, 115232. <https://doi.org/10.1016/j.enbuild.2024.115232>
- Coleman, L., 2024. This is how the MENA region can accelerate its renewable energy production. World Economic Forum. <https://www.weforum.org>
- Counihan, J., 1975. Adiabatic atmospheric boundary layers: A review and analysis of data from the period 1880–1972. Atmospheric Environment, 9(10), 871–905. [https://doi.org/10.1016/0004-6981\(75\)90088-8](https://doi.org/10.1016/0004-6981(75)90088-8)
- Darwish, A.S., Shaaban, S., Marsillac, E., Mahmood, N.M., 2019. A methodology for improving wind energy production in low wind speed regions, with a case study application in Iraq. Computers and Industrial Engineering, 127, 89–102. <https://doi.org/10.1016/j.cie.2018.11.049>
- Davis, N.N., Badger, J., Hahmann, A.N., Hansen, B.O., Mortensen, N.G., Kelly, M., Larsén, X.G., Olsen, B.T., Floors, R., Lizcano, G., Casso, P., Lacave, O., Bosch, A., Bauwens, I., Knight, O.J., Potter van Loon, A., Fox, R., Parvanyan, T., Hansen, S.B.K., Heathfield, D., Onninen, M., Drummond, R., 2023. The Global Wind Atlas: A high-resolution dataset of climatologies and associated web-based application. Bulletin of the American Meteorological Society, 104(8), E1507–E1525. <https://doi.org/10.1175/BAMS-D-21-0075.1>
- Dourian, K., 2023. Solar and wind energy are driving the Middle East's energy transition. The Arab Gulf States Institute in Washington. <https://agsi.org/analysis/solar-and-wind-energy-driving-the-middle-east-s-energy-transition/>
- Drobinski, P., 2026. Assessing renewable wind and solar energy yield with gridded climate datasets. npj Climate Action, 5(1), 17. <https://doi.org/10.1038/s44168-025-00332-4>
- Emeis, S., 2013. Wind Energy Meteorology: Atmospheric Physics for Wind Power Generation. Springer, Berlin, Heidelberg. <https://doi.org/10.1007/978-3-642-30523-8>
- Ezekiel, J., Vahrenkamp, V., Hoteit, H.A., Finkbeiner, T., Mai, P.M., 2024. Techno-economic assessment of large-scale sedimentary basin stored-CO₂ geothermal power generation. Applied Energy, 376(B), 124270. <https://doi.org/10.1016/j.apenergy.2024.124270>

- Gualtieri, G., 2019. Analysing the uncertainties of reanalysis data used for wind resource assessment: A critical review. *Renewable and Sustainable Energy Reviews*, 167, 112–133. <https://doi.org/10.1016/j.rser.2022.112741>
- Hasan, M.M., Genç, G., 2022. Techno-economic analysis of solar/wind power-based hydrogen production. *Fuel*, 324(A), 124564. <https://doi.org/10.1016/j.fuel.2022.124564>
- Hsu, S.A., Meindl, E.A., Gilhousen, D.B., 1994. Determining the power law wind profile exponent under near-neutral stability conditions at sea. *Journal of Applied Meteorology*, 33(6), 757–765. [https://doi.org/10.1175/1520-0450\(1994\)033%3C0757:dtplwp%3E2.0.co;2](https://doi.org/10.1175/1520-0450(1994)033%3C0757:dtplwp%3E2.0.co;2)
- Ibrahim, M.M., Suarez-Lopez, M.J., Hanafy, A.A., William, M.A., 2025. Optimizing NZEB performance: A review of design strategies and case studies. *Results in Engineering*, 25, 103950. <https://doi.org/10.1016/j.rineng.2025.103950>
- Jazeera, A., 2021. Saudi Arabia's first wind farm begins electricity production. *Al Jazeera*. <https://www.aljazeera.com>
- Jung, C., Schindler, D., 2023. Reasons for the recent onshore wind capacity factor increase. *Energies*, 16(14), 5390. <https://doi.org/10.3390/en16145390>
- Kadhim, H.T., Resen, A.K., Faraj, N.Q., 2022. Simulation and experimental study of micro wind turbine rotor blades using Q-blade software. *AIP Conference Proceedings*, 2394(1), 090017. <https://doi.org/10.1063/5.0121556>
- Kapoor, L., 2025. Iraq expands renewable energy with solar projects. *SAUR Energy*. <https://www.saurenergy.me>
- Kucukali, S., Dincal, Ç., 2014. Wind energy resource assessment of Izmit in the West Black Sea Coastal Region of Turkey. *Renewable and Sustainable Energy Reviews*, 30, 790–795. <https://doi.org/10.1016/j.rser.2013.11.018>
- Lee, B., Lim, D., Lee, H., Lim, H., 2021. Which water electrolysis technology is appropriate? Critical insights into potential water electrolysis for green ammonia production. *Renewable and Sustainable Energy Reviews*, 143, 110963. <https://doi.org/10.1016/j.rser.2021.110963>
- Li, L., Lin, J., Wu, N., Xie, S., Meng, C., Zheng, Y., Wang, X., Zhao, Y., 2022. Review and outlook on the international renewable energy development. *Energy and Built Environment*, 3(2), 139–157. <https://doi.org/10.1016/j.enbenv.2020.12.002>
- Muslih, K.D., Abbas, A.M., 2024. Climate of Iraq. In: *The Geography of Iraq*. Springer Nature Switzerland, Cham, 19–47. https://doi.org/10.1007/978-3-031-71356-9_2
- Nassif, W.G., Hashim, A.A., Muter, S.A., Al-Taai, O.T., 2024. Relationship between winds, surface roughness, and carbon dioxide concentrations over Iraq. *Asian Journal of Water, Environment and Pollution*, 21(1), 89–96. <https://doi.org/10.3233/AJW240012>
- Peña, A., Gryning, S.-E., Hasager, C.B., Hahmann, A.N., 2016. *New European Wind Atlas*. DTU Wind Energy, Roskilde, Denmark. <https://map.neweuropeanwindatlas.eu>
- Pryor, S.C., Shepherd, T.J., Barthelmie, R.J., 2018. Interannual variability of wind climates and wind turbine annual energy production. *Wind Energy Science*, 3(2), 651–665. <https://doi.org/10.5194/wes-3-651-2018>
- Rehman, S., El-Amin, I.M., Ahmad, F., Shaahid, S.M., Al-Shehri, A.M., Bakhashwain, J.M., 2007. Wind power resource assessment for Rafha, Saudi Arabia. *Renewable and Sustainable Energy Reviews*, 11(5), 937–950. <https://doi.org/10.1016/j.rser.2005.07.003>
- Resen, A.K., 2024. Feasibility study of wind farm using RETScreen model: A case study of Al-Razaza site, Iraq. *Iraqi Journal of Science*, 65(11), 6765–6780. <https://doi.org/10.24996/ijs.2024.65.11.45>
- Shi, H., Dong, Z., Xiao, N., Huang, Q., 2021. Wind speed distributions used in wind energy assessment: A review. *Frontiers in Energy Research*, 9, 769920. <https://doi.org/10.3389/fenrg.2021.769920>
- Ucar, A., Baló, F., 2010. Assessment of wind power potential for turbine installation in coastal areas of Turkey. *Renewable and Sustainable Energy Reviews*, 14(7), 1901–1912. <https://doi.org/10.1016/j.rser.2010.03.021>
- Wharton, S., Lundquist, J.K., 2012. Atmospheric stability affects wind turbine power collection. *Environmental Research Letters*, 7(1), 014005. <https://doi.org/10.1088/1748-9326/7/1/014005>
- Wieringa, J., 1992. Updating the Davenport roughness classification. *Journal of Wind Engineering and Industrial Aerodynamics*, 41(1–3), 357–368. [https://doi.org/10.1016/0167-6105\(92\)90434-c](https://doi.org/10.1016/0167-6105(92)90434-c)