

Article

Spatiotemporal Analysis of Wind Characteristics in Saudi Arabia Using GEFSv12 Reforecast Data for High-Wind-Sites Identification

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Abstract

Wind energy is a cornerstone of Saudi Arabia's renewable energy transition under Vision 2030, yet national-scale wind resource assessment remains constrained by sparse and unevenly distributed ground observations. This study evaluates the spatiotemporal variability of near-surface wind speed and direction across Saudi Arabia using Global Ensemble Forecast System Reforecast (GEFSv12 Reforecast) wind fields integrated with a GIS 10.8-based processing workflow. Wind vectors (U and V) were extracted from NetCDF files, converted to wind speed and meteorological wind direction, and analyzed at 183 grid-cell "virtual stations" covering the Kingdom for a five-year period (2018–2022) at four synoptic time steps (6-hourly). The resulting database comprises approximately 1,336,632 records. A practical verification using five airport stations matched to nearest virtual stations shows strong agreement between GEFS-derived and observed wind speeds (RMSE = 1.823; $R^2 = 0.879$), supporting the dataset's suitability for regional screening. Results reveal pronounced spatial heterogeneity and diurnal structure: northern, northeastern, central, and eastern Saudi Arabia consistently exhibit moderate-to-high winds (often >5.5 m/s) with persistent northwesterly–westerly flow, while western and southwestern coastal zones show stronger diurnal variability associated with thermal and sea-breeze influences. Peak, spatially coherent winds occur during the late-day synoptic period, forming a broad high-wind corridor across central and eastern regions. Given the $\sim 1^\circ$ (~ 110 km) resolution, findings are intended to be used for macro-scale wind-resource screening and the prioritization of high-wind zones for follow-up assessment.

Keywords: GEFSv12 Reforecast; GIS; spatiotemporal; wind energy; Saudi Arabia



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1. Introduction

The increasing environmental impacts of fossil fuel consumption, including climate change and severe air pollution, have intensified global interest in alternative and sustainable energy sources. Rapid urbanization and growing energy demand over recent decades have contributed significantly to rising greenhouse gas emissions, particularly carbon dioxide, prompting an urgent transition toward renewable energy systems [1,2]. In this context, renewable energy development plays a crucial role not only in environmental protection but also in long-term economic growth [3].

Among renewable energy resources, wind energy has emerged as one of the most promising options due to its sustainability, wide availability, and relatively low installation, operation, and maintenance costs [4,5]. Globally, wind power capacity has expanded

rapidly, increasing more than thirtyfold to approximately 435 GW, with a cumulative growth rate of around 17% in recent years [6]. These trends highlight the growing importance of wind energy in the global energy mix and its potential to support cleaner and more reliable power generation.

Saudi Arabia, despite its historical reliance on fossil fuels, has begun to actively pursue renewable energy as part of its national energy transition strategy. Under Vision 2030, Saudi Arabia aims to generate 9.5 GW of renewable energy, including wind power, to diversify its energy portfolio and reduce dependence on oil-based electricity generation [7]. According to Saudi Aramco, national electricity demand is projected to more than double from 58 GW in 2015 to approximately 121 GW by 2030, further emphasizing the urgency of developing alternative energy sources. Wind energy, alongside solar photovoltaic (PV) and concentrated solar power (CSP), is considered a key contributor to bridging this anticipated energy gap [8,9].

The successful deployment of wind energy systems is highly dependent on wind characteristics, particularly wind speed and direction, which exhibit significant spatial and temporal variability. Consequently, accurate wind resource assessment is a critical prerequisite for identifying suitable locations for wind farm development. Traditionally, wind regime characterization relies on data from ground-based meteorological stations; however, this approach presents substantial limitations in regions with sparse observational networks. In Saudi Arabia, the distribution of weather stations is uneven and largely concentrated in major urban centers, with fewer than 30 stations covering a vast and geographically diverse territory. This scarcity of observational data poses a major challenge for comprehensive wind energy assessment across Saudi Arabia.

To address this limitation, the present study adopts a model-based approach using wind data from global atmospheric reanalysis and forecast systems. Specifically, this research utilizes data from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis, and the Global Ensemble Forecast System Reforecast (GEFSv12 Reforecast) which integrate satellite observations and advanced numerical weather prediction models developed by the NCEP. Unlike studies that rely solely on surface measurements, these datasets provide spatially continuous, temporally consistent wind information, enabling a more robust assessment of wind characteristics over large regions.

In the GEFSv12 Reforecast dataset, Saudi Arabia is represented by grid cells, each functioning as a virtual wind station. Wind speed and direction data from these locations are analyzed using 6-hourly forecasts, allowing for detailed examination of spatiotemporal wind variability. This approach enables the identification of persistent wind patterns, diurnal cycles, and regional wind corridors that are critical for wind energy planning.

Furthermore, this study employs Geographic Information System (GIS) to process and analyze wind data extracted from NetCDF files. GIS-based methods are widely recognized as effective tools for high wind-resource potential sites, as they facilitate the integration of spatially referenced wind data with geographic and environmental factors [5]. By combining model-based wind datasets with GIS techniques, this research provides a comprehensive framework for evaluating wind energy potential across Saudi Arabia.

The primary objective of this study is to investigate the spatiotemporal variability of wind speed and direction across Saudi Arabia and to identify regions with high wind-resource potential for wind farm development. By addressing the limitations of observational data scarcity and leveraging advanced reforecast datasets, this work contributes to the growing body of research supporting wind energy deployment in arid and data-sparse regions. The findings are expected to support strategic planning efforts aligned with Saudi Arabia's renewable energy targets and long-term sustainability goals.

2. Related Works

Saudi Arabia's transformation of its energy sector is fundamentally guided by the Vision 2030 strategic framework, which emphasizes economic diversification and environmental sustainability through the expansion of renewable energy sources. Wind energy is highlighted as a key pillar within this framework due to its potential to reduce reliance on hydrocarbons and mitigate greenhouse gas emissions. Saudi Arabia's geographic characteristics—such as vast desert expanses, favorable wind regimes, and low population density in many regions—provide strong natural advantages for large-scale wind energy deployment. Vision 2030 further promotes policy reforms that encourage private investment, international collaboration, and regulatory environments supportive of renewable energy infrastructure, reinforcing Saudi Arabia's growing integration into the global renewable energy landscape [10].

The academic literature consistently frames wind energy as a driver of sustainable economic development in Saudi Arabia. Studies link renewable energy adoption to multiple socio-economic benefits, including improved environmental performance, economic growth, and job creation. However, these benefits are not automatic; rather, they depend on the presence of enabling policies, suitable financial mechanisms, and technological innovation tailored to Saudi Arabia's socio-economic context [11]. Complementary research documents Saudi Arabia's gradual transition away from fossil fuels toward a renewable-energy-oriented future, highlighting the role of supportive technologies such as energy storage systems and smart grids in facilitating the integration of variable wind power into the national electricity system [12].

These projects demonstrate that wind energy can contribute measurable capacity to the national grid, supported by empirical evidence of favorable wind speeds and energy densities suitable for commercial turbine deployment. Nevertheless, the literature also identifies significant barriers to expansion, including limitations in grid connectivity, transmission infrastructure, and environmental challenges such as habitat disruption and dust-related maintenance issues. These constraints underscore the importance of rigorous site identification studies and techno-economic assessments to ensure viable project scaling [13].

Wind energy is also widely recognized as a critical component of Saudi Arabia's decarbonization strategy. Empirical analyses report positive trends in wind power density and generation potential across Saudi Arabia, suggesting that wind energy can make substantial contributions to future power capacity while supporting greenhouse gas emission reductions [6,14]. Broader renewable energy assessments reinforce this view, noting that wind power plays a central role in achieving Vision 2030 targets, including increasing the share of renewables to at least 10% of the national energy mix, with further acceleration anticipated beyond 2030 [12].

Accurate spatiotemporal analysis of wind resources emerges as a recurring theme in the literature, reflecting Saudi Arabia's pronounced geographic and climatic heterogeneity. Traditional ground-based measurements, such as meteorological towers and anemometers, are limited by sparse spatial coverage and temporal discontinuities, often failing to capture mesoscale atmospheric processes and seasonal variability essential for wind farm feasibility assessment [10]. To address these limitations, researchers advocate the integration of high-resolution climate datasets derived from global reanalysis products and mesoscale numerical models, which provide consistent multi-decadal coverage and improved spatial detail.

Among global reanalysis datasets, the GEFS Reforecast has gained prominence due to its extensive temporal coverage and standardized gridded format [15]. Reforecast models, such as those derived from the GEFS offer valuable long-term, high-resolution wind speed data that can serve as key elements for wind integration studies [16]. These datasets can be

processed using techniques like noise addition and error reduction to produce synthetic power forecasts with characteristics similar to actual forecasts, enabling robust analysis over extended periods [16]. The use of such models provides detailed insights into long-term wind speed variability and trends, which are crucial for identifying optimal locations for wind farms [17].

GEFS enables long-term climatological analysis and trend detection of wind speed and direction, making it particularly valuable for preliminary wind resource screening and investment risk assessment in data-sparse regions of Saudi Arabia [18]. Although its coarse spatial resolution limits the representation of complex terrain and microscale wind features, validation studies demonstrate that GEFS performs reliably when combined with ground observations and mesoscale model outputs [19]. Ensemble-mean approaches further enhance forecast accuracy and reduce uncertainty, increasing the dataset's utility for wind power forecasting and scenario analysis [20].

To overcome the spatial limitations of global reanalysis products, mesoscale numerical models—especially the Weather Research and Forecasting (WRF) model—are extensively applied in Saudi wind energy studies. Configured with fine horizontal grid spacing (typically 3–5 km) and advanced planetary boundary layer parameterization schemes, WRF captures terrain-induced wind patterns, local circulations, and atmospheric stability effects critical for turbine micro-siting [21,22]. Model evaluation studies comparing WRF simulations with surface stations and tall-mast observations confirm its reliability when appropriately calibrated and supported by accurate topographic data [23]. Sensitivity analyses further indicate that model performance depends strongly on planetary boundary layer schemes, nesting strategies, and boundary condition selection, though WRF remains indispensable for resolving mesoscale wind features in complex terrain and coastal environments [24].

Recent advances in wind energy modeling increasingly integrate physics-based approaches with data-driven techniques. Hybrid models combining wavelet transforms with deep learning architectures, such as long short-term memory networks, have demonstrated improved day-ahead wind power forecasting accuracy, which is crucial for grid management and renewable energy integration. These models show strong performance even in data-scarce regions by transferring learned representations from data-rich sites [25]. Additionally, spatiotemporal correlation frameworks reveal delayed relationships between wind farms, enabling more realistic scenario-based power generation modeling and cost-effective system operation under uncertainty [26]. Ensemble forecasting and analog methods further contribute to uncertainty quantification and bias correction, enhancing operational reliability [27].

Beyond numerical modeling, the literature highlights the importance of Geographic Information System (GIS) in wind farm site selection. These methods integrate wind characteristics with land use, infrastructure proximity, and environmental constraints to classify land suitability [28,29]. Statistical approaches, including Weibull distribution analysis and copula-based methods, are also widely applied to characterize wind speed distributions and joint wind speed–direction behavior, supporting turbine selection and energy yield estimation [30,31] this is outside the scope of the study.

Despite these methodological advances, challenges persist related to optimal model resolution, representation of complex terrain, and limited availability of high-quality observational data for validation. Studies indicate that grid spacing exceeding 3 km can reduce accuracy in complex terrains, while finer resolutions significantly increase computational costs and may introduce numerical artifacts [20]. Mesoscale models also exhibit systematic biases associated with surface characteristics and atmospheric stability, emphasizing the need for robust validation frameworks and expanded measurement

campaigns using both in situ and remote sensing technologies [24,32]. Overall, the literature underscores the necessity of integrated spatiotemporal analysis—combining reanalysis datasets, mesoscale modeling, GIS-based decision tools, and advanced machine learning—to support the sustainable expansion of wind energy in Saudi Arabia in alignment with Vision 2030 objectives [7].

3. Materials and Methods

This study adopts a novel approach by utilizing wind fields from global forecast and reanalysis products. Instead of describing the wind regime using observations from local meteorological stations, the analysis is based on the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis (NCEP/NCAR Reanalysis) and the GEFSv12 Reforecast dataset. To improve understanding of Saudi Arabia's wind regime, we quantify the spatial and temporal variability of four daily time wind speed across the country and compute relevant indices describing wind resource variability. The wind data, provided in NetCDF format, are processed in ArcGIS 10.8 (Esri) by converting the fields to raster grids and applying standard geoprocessing and spatial analysis tools.

3.1. Study Area

Saudi Arabia is located in the central part of the Arabian Peninsula and covers an area of approximately 2.15 million km², making it the largest country in the Middle East. It is bordered by Jordan, Iraq, and Kuwait to the north, the Arabian Gulf, the United Arab Emirates, and Oman to the east, Yemen to the south, and the Red Sea to the west. The country's geographic position places it within the arid and semi-arid climatic zones, which strongly influence its atmospheric circulation and wind regimes. The Rub' al Khali to the south, and the Great Nafud desert to the north and Dahna Desert to the east as shown in Figure 1. There are 30 weather stations in Saudi Arabia, most of them exist in big cities, the distribution of meteorological stations is uneven across the country. In this study, the entire territory of Saudi Arabia is considered as the study area. Wind characteristics are analyzed using GEFSv12 Reforecast grid cells, each representing a virtual wind station, to ensure spatially continuous coverage across regions where ground-based meteorological observations are sparse or unevenly distributed.

3.2. Data Source

The GEFSv12 generates forecasts using 21 ensemble members, producing predictions for a range of atmospheric variables four times per day. NOAA's Earth System Research Laboratory (ESRL), through its Physical Science Division (PSFD), has used the GEFSv12 to develop a historical archive of model forecasts based on a reduced 11-member ensemble [19,33,34]. Spanning from December 1984 to the present, this reforecast archive provides outputs at 3 h intervals for forecast lead times of 0–72 h, followed by 6 h intervals extending to 16 days. These products were generated to construct a long-term historical reforecast dataset [35]. In this study, the required datasets were extracted for the Saudi Arabia domain at 6 h intervals:

21Z → 00:00 local time (midnight);

03Z → 06:00 local time;

09Z → 12:00 local time (noon);

15Z → 18:00 local time;

("Z" = Zulu time = UTC. Saudi Arabia is UTC + 3.)

The analysis covers a five-year period (1 January 2018–31 December 2022). The required datasets were obtained from the NOAA ESRL/PSD portal (<http://www.esrl.noaa.gov/psd/forecasts/reforecast2/>) (18 April 2024).

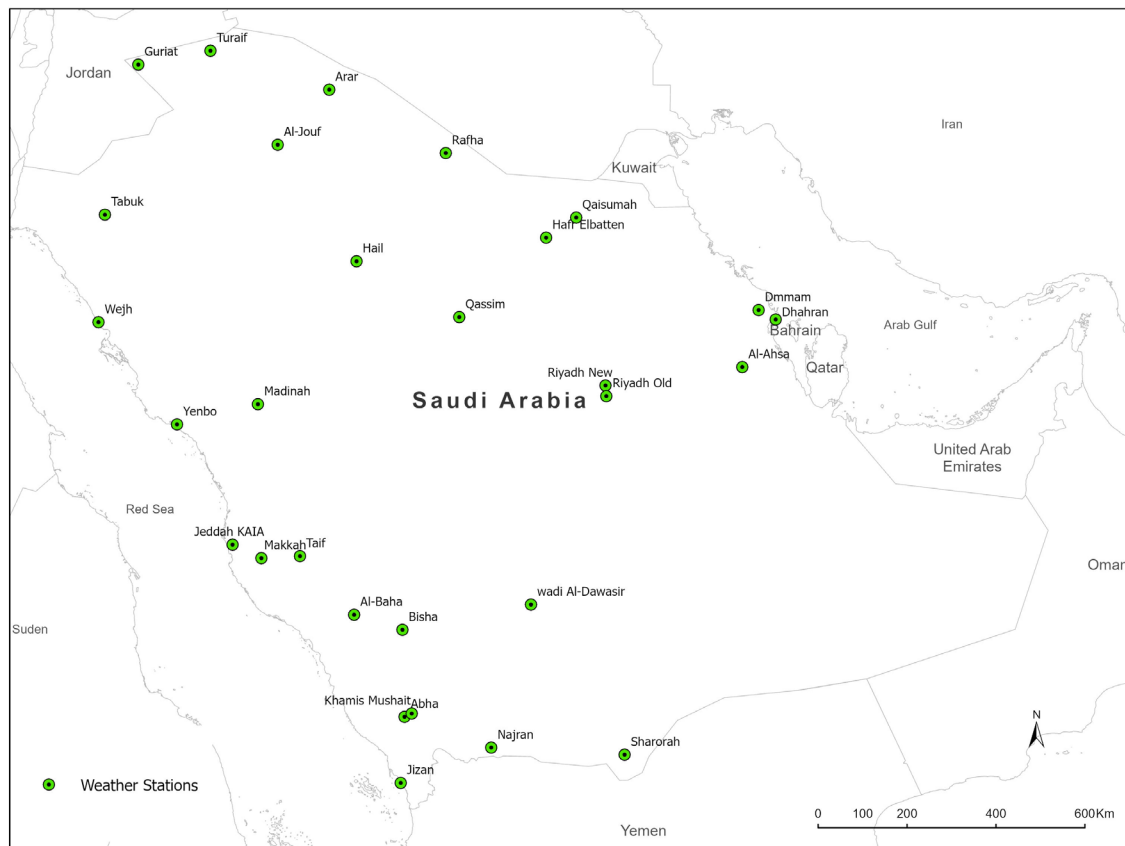


Figure 1. Map of Saudi Arabia with weather station locations.

3.3. Geo-Processing

To improve understanding of the wind regime, GEFSv12 data were used to assess the spatial and temporal variability of wind speed. After downloading the datasets, the zonal (U) and meridional (V) components were used to derive wind speed and wind direction at each grid cell [34]. The workflow begins by converting the NetCDF files into raster layers using the GIS “Make NetCDF Raster Layer” tool.

The second step involves extracting the U and V wind components from the grid cells covering Saudi Arabia and compiling them into a single tabular dataset. The spatial distribution of the 183 grid cells used in this study, with labeled points representing the corresponding virtual weather stations. Across the full analysis period, the database contains approximately 1,336,632 records, derived from four-time steps per day over five years for all 183 stations ((1826 days $\times$ 4 time) 7304 $\times$ 183 grid cells $\times$ 5 years).

The GEFSv12 Reforecast products provided via the NOAA ESRL/PSD portal have a spatial resolution of 1° (~ 110 km) and are distributed in NetCDF format. Wind fields are supplied in two separate datasets: one for the zonal (U) component and another for the meridional (V) component. Once organized in tabular form, the third step is to transform the U and V vectors into wind speed and wind direction. This conversion was implemented using Python 3.10 and VB scripts, applying the standard vector-based equations as follows:

$$\text{Wind Speed} = \sqrt{U^2 + V^2}$$

$$\text{Wind Direction} = 180/\pi \times \text{Atan } 2(V, U)$$

The processes used to: (1) convert wind data from netCDF into a raster layer, (2) extract U and V wind data from raster grid cells, (3) calculate wind speed and direction, and

(4) create maps of wind speed and direction. The raster layer was then clipped to the boundary of Saudi Arabia.

4. Results

The KSA is taken as a case study for selecting the wind-resource potential sites that have been collected from 183 grids. The datasets are collected from GEFSv12 Reforecast divided into 183 grid cells. To examine the spatial variability of wind speed and wind direction across Saudi Arabia, this study utilizes wind fields from the Global Ensemble Forecast System, version 12 (GEFSv12). Wind conditions were evaluated at 183 locations using a five-year archive of 6-hourly forecasts. In the GEFSv12 Reforecast framework, Saudi Arabia is represented by 183 grid cells, each of which serves as a virtual weather station for extracting wind information.

To increase confidence in the GEFSv12 Reforecast wind fields used in this study, a practical verification was conducted using wind observations from five Saudi Arabian stations representing different regions of the Kingdom: Prince Abdulmajeed bin Abdulaziz Airport, King Fahd International, King Abdulaziz International, King Khaled AB, and King Khaled International. Each station was matched to the nearest GEFSv12 virtual station (grid cell) among the 183 locations analyzed in this study. The corresponding virtual-station identifiers were 112, 161, 18, 71, and 128, respectively (Figure 2). The five verification stations were chosen based on the availability of high-quality, complete records and to achieve the widest feasible geographic coverage across Saudi Arabia (including coastal, inland, and eastern settings). Although this limited set strengthens confidence in the GEFS-based screening results, it cannot fully represent the Kingdom's spatial wind variability. Therefore, the validation is presented as a screening-level consistency check rather than a comprehensive nationwide assessment.

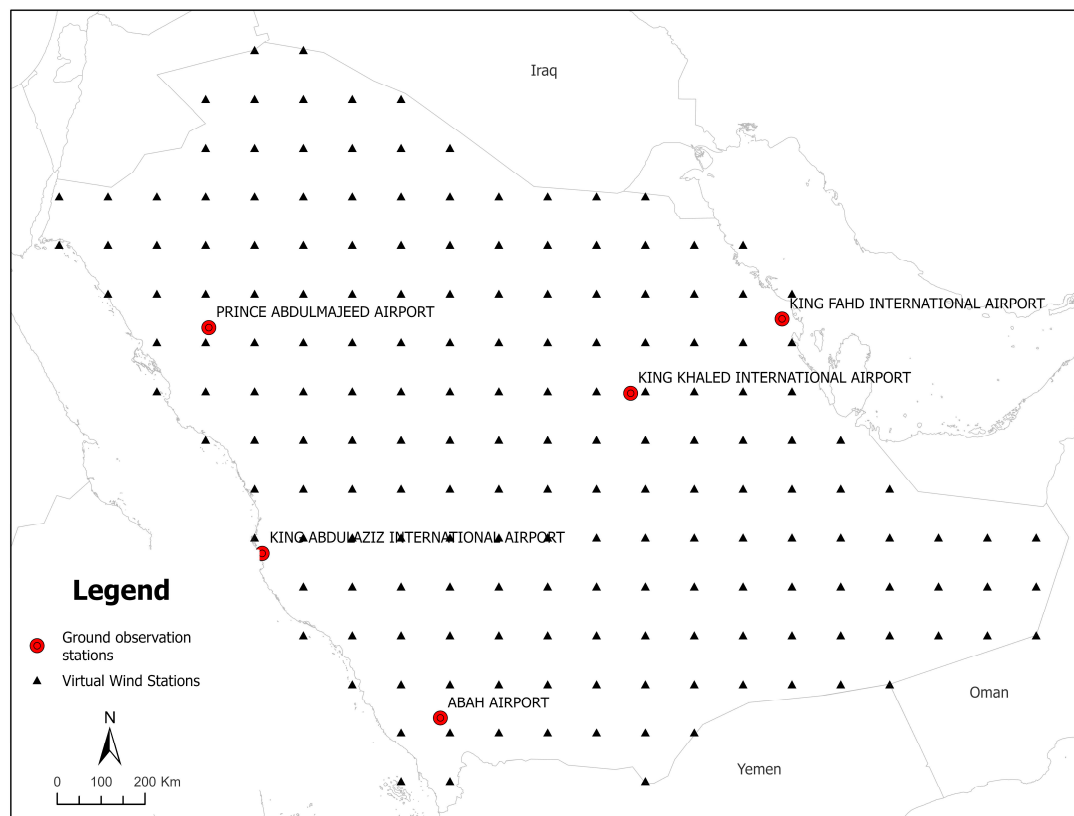


Figure 2. Location of the 183 virtual wind stations with ground observation stations covering Saudi Arabia.

For each matched pair, GEFSv12-derived wind speed time series were extracted at the corresponding synoptic time steps (00, 06, 12, and 18 UTC) over the study period and compared against the station wind speed observations. Model performance was quantified using standard error metrics, including the root mean square error (RMSE) and the coefficient of determination (R^2). The comparison produced an overall RMSE of 1.82318402 and $R^2 = 0.879$, indicating strong agreement between GEFSv12-based estimates and station observations. These results support the suitability of GEFSv12 Reforecast data for regional-scale wind-resource screening in Saudi Arabia, while acknowledging that site-level micro-siting and complex-terrain assessments require higher-resolution modeling and additional validation.

Overall, the results indicate that central–western interior and northeastern Saudi Arabia represent the most promising regions for large-scale wind energy development. These zones combine favorable wind speed thresholds, consistent wind directions, and geographic conditions conducive to infrastructure deployment. The spatial patterns identified in this study provide a robust empirical basis for prioritizing wind energy investments and support strategic planning aligned with Saudi Arabia’s renewable energy and decarbonization objectives under Vision 2030.

4.1. Spatial Variability of Wind Speed and Direction at 00:00

The spatial distribution of mean wind speed and prevailing wind direction across Saudi Arabia at 00:00 reveals clear regional contrasts in wind intensity and directional coherence (Figure 3). Wind speeds across the study domain generally range from approximately (2.0 to 7.5 m/s), indicating substantial spatial variability during nocturnal conditions.

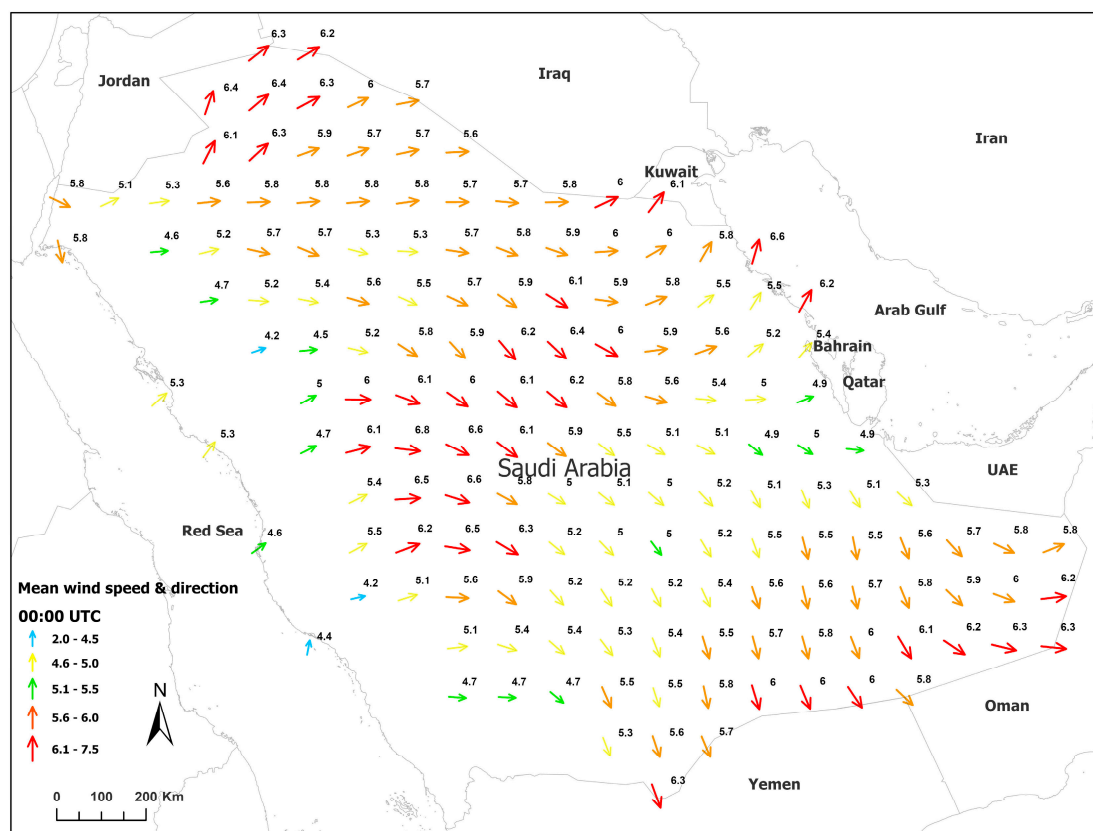


Figure 3. Spatial Variability of Mean Wind Speed and Direction at 00:00 in Saudi Arabia.

The northern and northeastern regions exhibit relatively high wind speeds (5.6–7.5 m/s), with wind vectors predominantly aligned in a northwesterly to westerly direction. This

strong directional consistency reflects the influence of large-scale synoptic circulation, particularly the Shamal wind system, which remains active during nighttime hours.

In the central region, wind speeds are mostly moderate (4.6–5.5 m/s), with localized areas reaching (5.6–6.5 m/s). Wind directions remain fairly uniform, dominated by west-northwesterly flow, suggesting stable atmospheric conditions over the interior plateau during the night.

The eastern region, including the Arabian Gulf coast, experiences moderate to high wind speeds (5.1–6.5 m/s). Wind vectors in this area are largely oriented from the northwest, with minor directional variations near the coastline, likely influenced by land–sea thermal contrasts that persist into the nighttime period.

In contrast, the western coastal zone along the Red Sea and parts of the southwestern region display lower wind speeds (2.0–4.5 m/s) and greater directional variability. The scattered wind directions in these areas indicate the influence of local topography and weakened coastal circulations under nocturnal stability.

Overall, the 00:00 wind field highlights a pronounced north–south gradient in wind speed, with stronger and more directionally consistent winds over northern, northeastern, and central Saudi Arabia, and weaker, more variable winds in the western and southwestern regions. These spatial patterns suggest that nocturnal wind conditions remain favorable for wind energy generation in northern and eastern parts of Saudi Arabia, while southwestern areas exhibit comparatively limited wind potential during nighttime hours.

4.2. Spatial Variability of Wind Speed and Direction at 06:00

The spatial distribution of mean wind speed and prevailing wind direction across Saudi Arabia at 06:00 reveals distinct regional patterns in both wind magnitude and flow orientation (Figure 4). Wind speeds across the study area range from approximately (2.0 to 7.5 m/s), indicating substantial spatial variability during the early morning period.

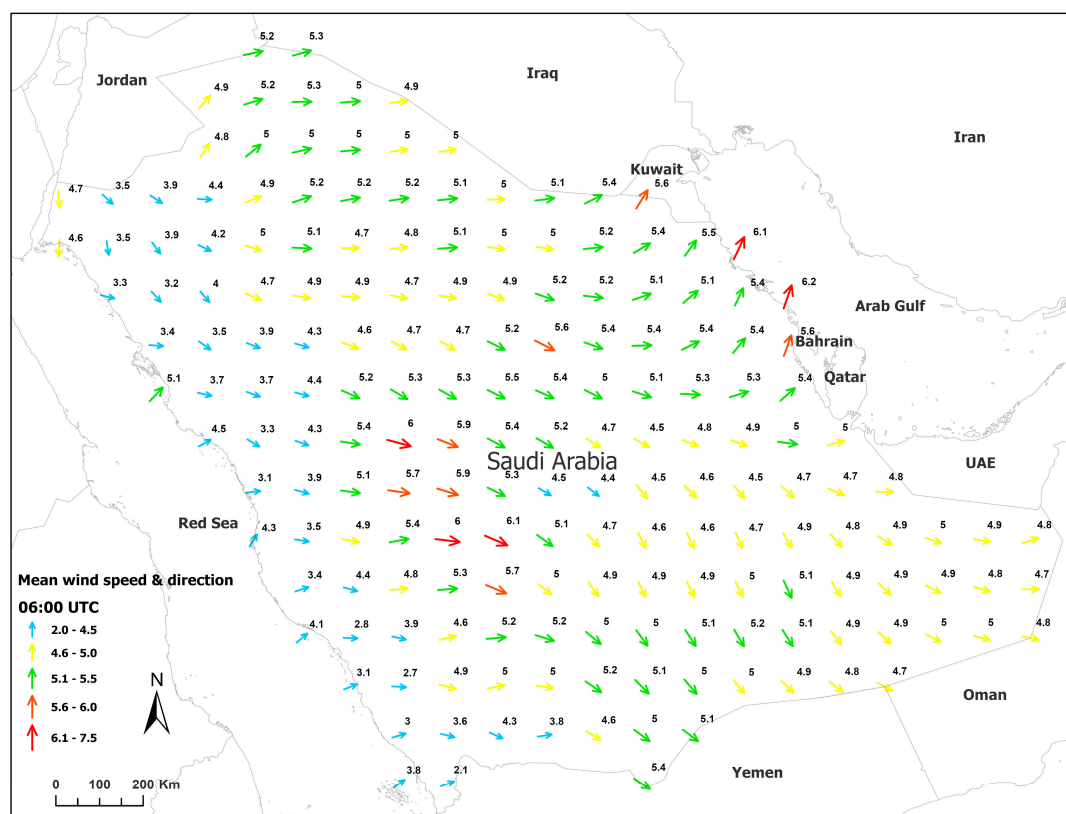


Figure 4. Spatial Variability of Mean Wind Speed and Direction at 06:00 in Saudi Arabia.

The northern region exhibits predominantly moderate wind speeds (4.6–5.5 m/s), with wind vectors largely aligned in a west-northwesterly to northwesterly direction. This consistent directional pattern suggests the dominance of synoptic-scale circulation influencing the northern Arabian Peninsula.

In the central interior, wind speeds generally fall within the (4.6–5.5 m/s) category, with localized enhancements reaching (5.6–6.0 m/s). Wind directions remain relatively uniform, primarily from the west and northwest, indicating stable atmospheric conditions and limited directional variability over the plateau region.

The eastern region, including the Arabian Gulf coastal zone, shows slightly higher wind speeds (5.1–6.1 m/s) compared to inland areas. Wind vectors in this region are mainly oriented from the northwest, with minor directional deviations near the coast that may be attributed to land–sea interactions.

In contrast, the western and southwestern regions, particularly along the Red Sea coast, experience lower wind speeds (2.0–4.5 m/s) and greater directional dispersion. The arrows in these areas indicate more variable wind directions, reflecting the influence of coastal processes, topographic complexity, and localized thermal circulation during early morning hours.

Overall, the arrow field illustrates a clear north-to-south gradient in wind speed, with stronger and more directionally consistent winds over northern, central, and eastern Saudi Arabia, and weaker, more variable winds toward the southwestern and western coastal regions. These spatial patterns highlight regions with persistent wind regimes that are potentially favorable for wind energy development, particularly in the northern and eastern parts of Saudi Arabia.

4.3. Spatial Variability of Wind Speed and Direction at 12:00

The spatial distribution of mean wind speed and prevailing wind direction over Saudi Arabia at 12:00 shows notable changes in both wind magnitude and directional patterns compared to the early morning period (Figure 5). Wind speeds across Saudi Arabia range from approximately 2.0 to 7.5 m/s, with clear regional contrasts emerging during midday conditions.

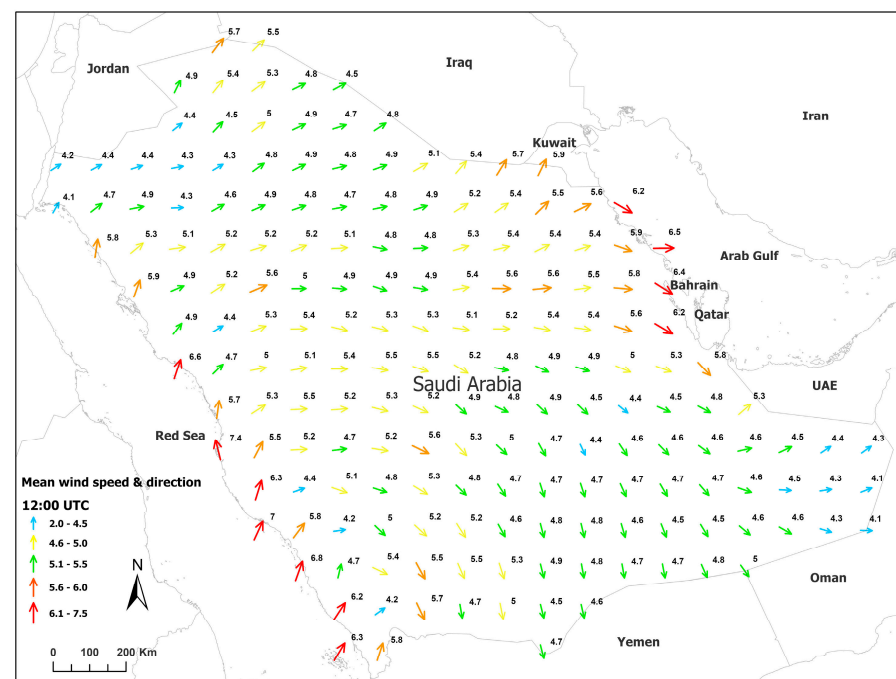


Figure 5. Spatial Variability of Mean Wind Speed and Direction at 12:00 in Saudi Arabia.

The western coastal region along the Red Sea exhibits some of the highest wind speeds (6.1–7.5 m/s) at this time, particularly along the southern and southwestern coastline. Wind vectors in this area are predominantly oriented northward and northwesterly, indicating the strengthening influence of sea-breeze circulation combined with regional pressure gradients during daytime heating. This enhancement contrasts with the weaker winds observed in the same region during nocturnal and early morning hours.

In the northern region, wind speeds are generally moderate (4.6–5.5 m/s), with relatively consistent wind directions from the west and northwest. Compared to earlier time steps, a slight reduction in wind intensity is evident, reflecting the temporal evolution of synoptic-scale forcing during midday.

The central interior of Saudi Arabia shows wind speeds mainly within the 4.6–5.5 m/s range, accompanied by more variable wind directions. The arrows indicate a gradual shift toward southerly and southwesterly components, suggesting the increasing role of thermal convection and surface heating over the interior plateau.

In the eastern region, including the Arabian Gulf coast, wind speeds range between 4.5 and 6.5 m/s, with localized maxima exceeding 6.0 m/s near the coastline. Wind directions here are more variable than during early morning hours, reflecting interactions between synoptic flow and coastal thermal effects.

Overall, the arrow field at 12:00 highlights a transition from predominantly synoptic-driven flow to a regime increasingly influenced by diurnal thermal processes, particularly along coastal and southern regions. The spatial pattern indicates enhanced wind energy potential along the Red Sea coast and parts of the eastern region during midday, while the central and northern areas maintain moderate but more directionally variable winds.

4.4. Spatial Variability of Wind Speed and Direction at 18:00

The spatial distribution of mean wind speed and prevailing wind direction over Saudi Arabia at 18:00 exhibits the strongest and most spatially coherent wind regime among the analyzed time steps (Figure 6). Wind speeds across Saudi Arabia range from approximately 4.5 to over 7.5 m/s, indicating a widespread intensification of winds during the late afternoon to early evening period.

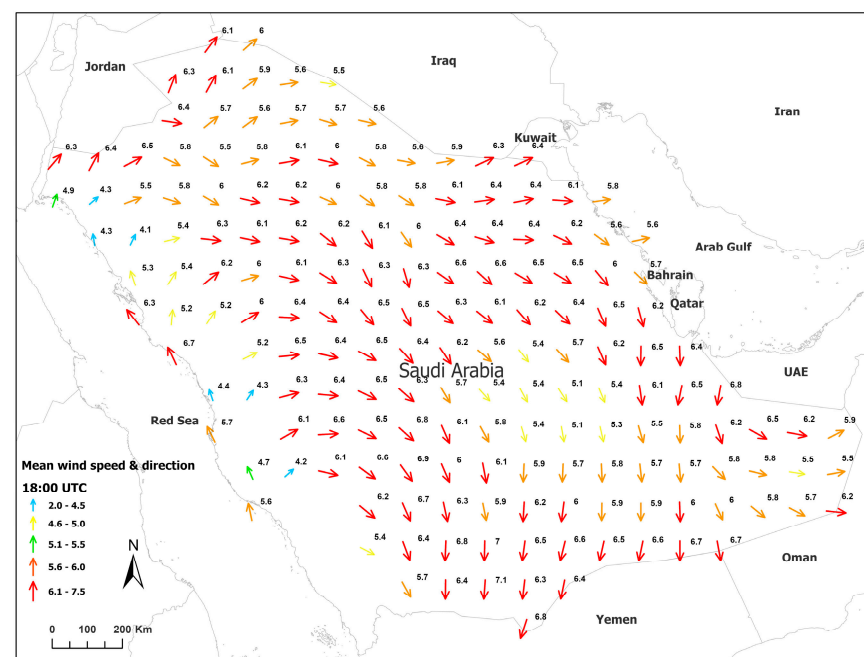


Figure 6. Spatial Variability of Mean Wind Speed and Direction at 18:00 in Saudi Arabia.

The central, eastern, and southern regions are dominated by high wind speeds (6.1–7.5 m/s), forming an extensive high-wind corridor across much of the country. Wind vectors in these areas are highly consistent in direction, predominantly oriented from the northwest and west, reflecting the strengthening influence of synoptic-scale pressure gradients combined with residual daytime thermal forcing.

In the northern region, wind speeds remain elevated (5.6–6.5 m/s), with well-aligned vectors indicating persistent northwesterly flow. Compared to earlier time steps, directional variability is minimal, suggesting a more organized atmospheric circulation during this period.

The eastern region, including the Arabian Gulf coast, exhibits sustained strong winds exceeding (6.0 m/s), with arrows consistently directed from the northwest toward the southeast. This pattern highlights the dominance of large-scale flow over localized coastal influences during the evening hours.

Along the western coastal zone of the Red Sea, wind speeds increase relative to morning conditions, generally ranging between 5.5 and 6.5 m/s. Wind directions here align more closely with the regional synoptic flow, indicating a reduced influence of localized sea-breeze circulations compared to midday conditions.

Overall, the arrow field at 18:00 demonstrates a nationwide enhancement in wind speed and a marked increase in directional uniformity across Saudi Arabia. This period represents the most favorable conditions for wind energy generation, with extensive areas experiencing strong and persistent winds. The pronounced spatial coherence suggests that late afternoon and early evening hours play a critical role in maximizing wind resource availability across Saudi Arabia.

4.5. High Wind-Resource Potential Across Saudi Arabia

The analysis of mean wind speed and prevailing wind direction across Saudi Arabia, based on four daily synoptic time steps (00:00, 06:00, 12:00, and 18:00), reveals clear spatial and temporal patterns that are highly relevant for wind energy development.

Overall, northern, northeastern, central, and eastern regions consistently exhibit moderate to high wind speeds, frequently exceeding (5.5 m/s) and reaching above (7.0 m/s) during peak periods. These regions also demonstrate strong directional consistency, predominantly characterized by northwesterly to westerly winds, which is a favorable condition for efficient wind turbine operation and reduced mechanical stress.

The late afternoon and early evening period (18:00) emerges as the most favorable time window for wind energy generation across much of Saudi Arabia. During this period, wind speeds intensify and become spatially extensive, forming a broad high-wind corridor across central, eastern, and southern Saudi Arabia. The high degree of directional uniformity observed at this time further enhances wind energy reliability.

The northern and northeastern regions show strong wind conditions throughout both nocturnal and daytime hours, indicating high temporal stability of the wind resource. This persistence makes these areas particularly suitable for large-scale wind farm deployment and long-term energy planning.

In contrast, the western and southwestern regions, especially along the Red Sea coast, exhibit greater diurnal variability. While wind speeds are relatively low during nighttime and early morning hours, they increase substantially during midday and afternoon due to sea-breeze and thermal effects. These areas may therefore be suitable for wind energy projects that benefit from diurnally enhanced winds, although careful site-specific assessment is required due to complex topography and directional variability.

Overall, the combined spatial and temporal analysis indicates that northern, northeastern, central, and eastern Saudi Arabia represent the highest wind energy potential

zones. Late afternoon to early evening hours provides peak wind conditions nationwide. Directional consistency, particularly under the influence of prevailing northwesterly winds, enhances the technical feasibility of wind energy systems. Southwestern coastal areas show moderate potential with strong diurnal dependence.

These findings highlight the strong potential of wind energy as a reliable renewable resource in Saudi Arabia and provide a robust scientific basis for prioritizing regions and time periods in future wind farm planning and energy policy development (Figure 7).

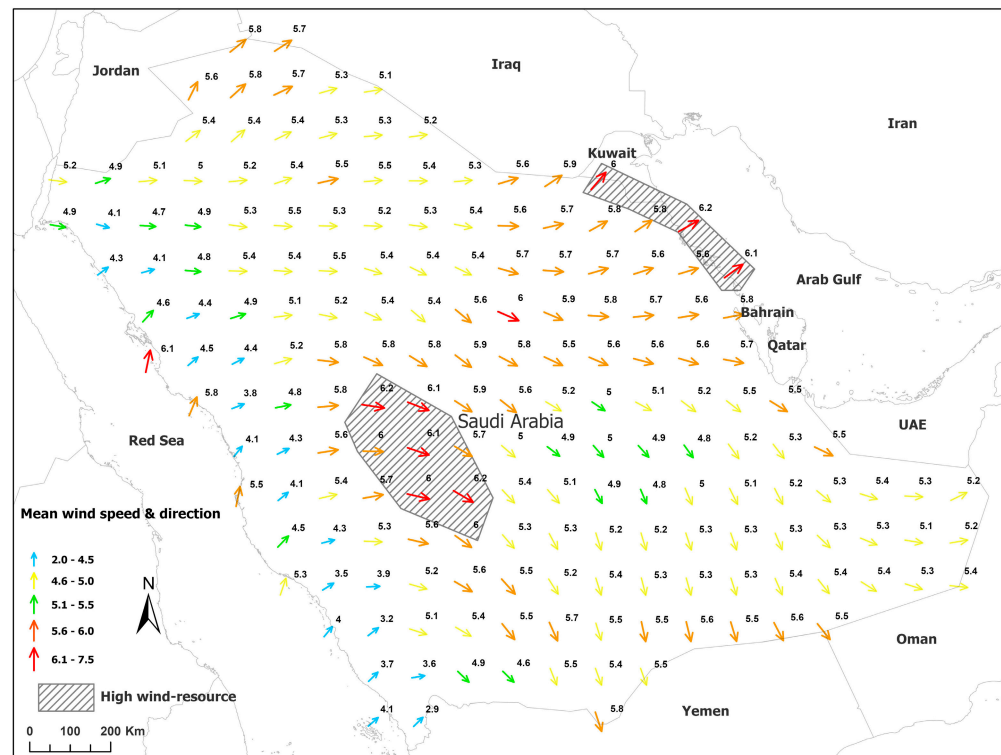


Figure 7. Mean Wind Speed and Direction in Saudi Arabia, regions indicate high wind-resource potential for wind farms.

5. Discussion

This study provides a comprehensive spatiotemporal assessment of wind speed and direction across Saudi Arabia using GEFSv12 Reforecast data, addressing a critical gap in wind resource evaluation for data-scarce regions. The results demonstrate pronounced spatial and diurnal variability in wind characteristics, confirming that wind energy potential in Saudi Arabia is both regionally heterogeneous and temporally structured. These findings are consistent with the broader literature emphasizing the necessity of detailed wind resource characterization prior to wind farm deployment [3,5].

The observed dominance of northwesterly to westerly winds, particularly across northern, northeastern, central, and eastern Saudi Arabia, aligns with the well-documented influence of large-scale synoptic systems such as the Shamal wind regime. Similar directional persistence and elevated wind speeds have been reported in previous regional and reanalysis-based studies, reinforcing the reliability of GEFSv12 Reforecast data for capturing mesoscale atmospheric behavior over the Arabian Peninsula [15,18,35].

The diurnal evolution identified in this study—characterized by weaker nocturnal winds, gradual morning intensification, midday coastal enhancement, and peak wind speeds during late afternoon and early evening—reflects the combined effects of synoptic forcing and diurnal thermal processes. The strengthening of winds along the Red Sea coast at 12:00 highlights the role of sea-breeze circulation driven by land–sea temperature

contrasts, a phenomenon widely observed in coastal wind energy assessments [21,24]. In contrast, the pronounced nationwide wind intensification at 18:00 suggests that residual daytime heating amplifies regional pressure gradients, resulting in the most favorable conditions for wind energy generation.

The spatial coherence and persistence of high wind speeds exceeding (5.5 m/s) across northern, northeastern, central, and eastern regions indicate high wind-resource potential for large-scale, utility-grade wind farm development. These results corroborate earlier assessments identifying northern regions such as Al-Jawf and Tabuk as potential wind resources for wind energy investment due to their favorable wind climatology and relatively low land-use conflicts [10,13]. The high directional consistency observed in these regions further enhances turbine efficiency and reduces operational stress, improving the long-term economic viability of wind projects [6].

Conversely, the western and southwestern regions exhibit stronger diurnal variability, with wind energy potential peaking during midday and afternoon hours. While this variability introduces operational complexity, it also presents opportunities for time-specific or hybrid energy systems, particularly when integrated with solar PV or CSP technologies. Such complementarities are increasingly recognized as effective strategies for balancing renewable energy output in arid regions [12].

The spatial patterns identified here are broadly consistent with wind-resource assessments in arid and semi-arid environments, where persistent synoptic regimes and desert-scale pressure gradients often produce coherent wind corridors across interior plains. The high-wind priority zones identified in our GEFS-based screening align with these reported patterns and with the known dominance of northwesterly flow regimes across the Arabian Peninsula. In contrast, the western coastal and mountainous regions exhibit stronger diurnal modulation and directional dispersion, which is consistent with coastal thermal circulations and complex-terrain influences observed in arid coastal settings [5,9,14].

A key contribution of this study lies in its reliance on GEFSv12 Reforecast virtual wind stations, which overcome the limitations imposed by the sparse and uneven distribution of ground-based meteorological observations in Saudi Arabia. The use of 183 grid cells provides spatial continuity and enables the identification of regional wind corridors that would otherwise remain undetected using traditional station-based approaches. This finding supports previous assertions that global reanalysis datasets offer a robust foundation for preliminary wind energy screening in data-limited environments [19,20].

Nevertheless, while GEFSv12 Reforecast performs well at the regional scale, its coarse spatial resolution limits its ability to capture microscale effects related to complex terrain, surface roughness, and localized circulations. The literature strongly recommends coupling reanalysis data with mesoscale models such as WRF for refined site-level assessments, particularly in coastal and mountainous areas [21,23]. Future work should also incorporate validation using tall-mast measurements and remote sensing technologies, such as LiDAR, to reduce uncertainty and improve model calibration [32].

From a policy and planning perspective, the results directly support Saudi Arabia's Vision 2030 objectives, which emphasize renewable energy expansion as a pathway to economic diversification and emissions reduction. The identification of high-potential wind zones and optimal time windows for energy generation provides actionable insights for grid planning, investment prioritization, and infrastructure development. By enabling more informed decision-making, this study contributes to reducing investment risk and accelerating the deployment of wind energy capacity needed to meet Saudi Arabia's projected energy demand growth [8,11].

Despite its contributions, this study is subject to several limitations. The five-year analysis period, while sufficient for identifying dominant wind patterns, may not fully capture

long-term climate variability and extreme wind events. Additionally, the exclusive focus on wind speed and direction does not account for other critical factors influencing wind farm feasibility, such as grid proximity, land-use constraints, environmental impacts, and socio-economic considerations. Future research should integrate GIS-based multi-criteria decision-making frameworks and advanced statistical methods, including Weibull and copula-based analyses, to enhance energy yield estimation and site classification [28,30,31].

6. Conclusions

This study presents a comprehensive spatiotemporal assessment of wind speed and direction across Saudi Arabia using GEFSv12 Reforecast data integrated with GIS-based analysis. By employing 6-hourly wind data over a five-year period and representing Saudi Arabia through 183 virtual wind stations, the research addresses a critical limitation associated with the sparse and uneven distribution of ground-based meteorological observations. The adopted approach provides a robust and spatially continuous framework for wind resource evaluation in data-scarce regions.

The results reveal pronounced spatial and diurnal variability in wind characteristics across Saudi Arabia. Northern, northeastern, central, and eastern regions consistently exhibit moderate to high wind speeds, frequently exceeding 5.5 m/s, with strong directional consistency dominated by northwesterly to westerly winds. These regions demonstrate high temporal stability and emerge as the most suitable zones for large-scale wind farm development. In contrast, western and southwestern regions, particularly along the Red Sea coast, show greater diurnal variability, with wind energy potential enhanced during midday and afternoon hours due to thermal and sea-breeze effects.

The late afternoon and early evening period (18:00) is identified as the most favorable time window for wind energy generation nationwide, characterized by peak wind speeds and high spatial coherence. These findings underscore the importance of incorporating diurnal variability into wind energy planning and operational strategies.

Overall, the study confirms that model-based reforecast datasets, when combined with GIS tools, provide an effective alternative to traditional station-based wind assessments. The identified high-potential wind zones and temporal patterns offer valuable insights for strategic planning, investment prioritization, and infrastructure development in support of Saudi Arabia's Vision 2030 renewable energy targets.

Future research should focus on extending the temporal analysis to longer climatological periods, integrating downscale models (e.g., WRF) for site-level refinement, and incorporating additional environmental, technical, and socio-economic criteria through multi-criteria decision-making frameworks. Such efforts will further enhance the accuracy and applicability of wind energy assessments and support the sustainable expansion of wind power across Saudi Arabia.

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