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DATA-DRIVEN ASSESSMENTS OF CASPIAN SEA OFFSHORE WIND ENERGY: ERA5 – WEIBULL ANALYSIS

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ABSTRACT

This study presents the first comprehensive, basin-wide assessment of offshore wind energy potential in the Caspian Sea based on a unified and reproducible analytical framework. We process 85 years (1940–2024) of hourly ERA5 reanalysis at 0.25° resolution for 653 grid points, assigning each to the EEZ of Azerbaijan, Iran, Kazakhstan, Russia, or Turkmenistan. A two-stage 90th-percentile filter selects the windiest decile per EEZ; two-parameter Weibull distributions provide hub-height (100 m) wind-power density (WPD) statistics. High-potential zones cover ≈36,10 km^2 – 10 % of the sea yet about 70–85 % of its usable wind. Median 100 m wind speeds peak in Turkmenistan (7.52 m s^{-1}), however, the highest wind power density is found in Azerbaijan (613.48 W m^{-2}), followed by Russia (560.62 W m^{-2}), Kazakhstan (555.90 W m^{-2}), and Turkmenistan (477.62 W m^{-2}), while dropping significantly in Iran (168.50 W m^{-2}). Shallow depths, existing oil-and-gas logistics and proximity to load centers make ≥1 GW pilot projects viable in the northern shelf before 2030. A 15 GW build-out by 2040 could displace ≈40 TWh of gas-fired generation and avoid ≈25 Mt CO_2 annually. The reproducible Python pipeline forms an updatable evidence base that can be refined with LiDAR campaigns and mesoscale down-scaling to underpin bankable offshore-wind development.

Keywords: Caspian Sea; offshore wind resource; ERA5 reanalysis; Weibull distribution; wind-power density; renewable energy; data-driven analysis.

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1. Introduction

The accelerating transition toward low-carbon power systems has catapulted offshore wind energy from a niche technology into a cornerstone of global decarbonization strategies. Annual installations have doubled every three to four years since 2015, and the International Energy Agency projects worldwide offshore capacity to exceed 500 GW by 2050, surpassing today's entire on-shore wind fleet in yearly electricity generation [1]. While the North Sea and the Chinese littoral currently dominate deployment, enclosed and semi-enclosed waterbodies with moderate wave climates—such as the Baltic, Great Lakes and the Caspian—are increasingly recognized as the next frontier for fixed-bottom and, in the longer term, floating offshore wind technologies. These basins combine favorable bathymetry and proximity to coastal load centers with a geopolitical landscape that encourages regional cooperation on grid expansion and supply-chain localization.

Among them, the Caspian Sea is uniquely positioned. It is the world's largest inland body of water (≈371 000 km^2) and a historic energy province whose hydrocarbon infrastructure, heavy-lift ports and specialized vessel fleets offer a ready-made industrial backbone for renewable projects. Nevertheless, despite more than a century of intensive oil and gas development, the offshore wind resource of the Caspian Sea remains inadequately quantified at the basin scale to date. Assessments have been largely piecemeal, focusing on specific national waters or relying on limited coastal data, which prevents a consistent, basin-wide comparison. Consequently, policy makers lack a unified evidence base for setting national targets, and investors face considerable uncertainty when evaluating the bankability of prospective offshore wind farms.

This paper addresses that gap by presenting the first basin-wide, high-resolution assessment of the Caspian offshore wind resource grounded in a uniform analytical framework. Leveraging 85 years of hourly ERA5 reanalysis data (1940 – 2024) at 0.25° spatial resolution, we (i) assign every grid point to the Exclusive Economic Zone (EEZ) of Azerbaijan, Iran, Kazakhstan, Russia and Turkmenistan; (ii) apply a two-stage, 90th-percentile (P90) filtering technique to isolate the windiest decile of locations within each EEZ; and (iii) fit two-parameter Weibull distributions to derive hub-height wind-power-density (WPD) metrics. The workflow is fully automated in Python with Prefect, Xarray Dask and

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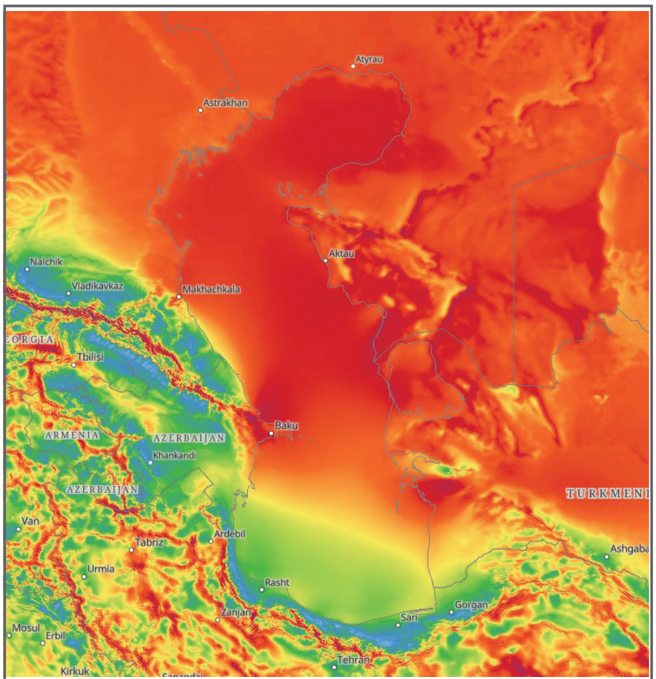

Fig. 1. Wind-speed map of the Caspian Sea (m s⁻¹) provided by the World Bank's Global Wind Atlas

GeoPandas, ensuring both reproducibility and seamless scalability to future reanalysis vintages.

The analysis yields three principal contributions. First, it delineates national high-potential zones totaling ≈36700 km² and quantifies their median 100 m wind speeds (4.61-7.52 m s⁻¹) and WPDs (168.50-613.48 W m⁻²), thereby establishing a comparative resource hierarchy across the five littoral states. Second, it demonstrates how leveraging P90 statistics captures energy-rich events more effectively than mean-speed filters, a critical consideration for capacity-factor forecasting and extreme-load design. Third, it lays the empirical groundwork for techno-economic scenarios that couple offshore wind development with the Caspian's existing oil-and-gas supply chain, hydrogen export ambitions and emerging regional electricity markets.

2. Literature review

To substantiate the need for a basin-wide assessment, this review synthesizes the existing literature on wind energy development for each of the five littoral states. The following country-by-country analysis highlights the current state of knowledge and the specific contexts that shape wind-power prospects across the region (see fig.1).

2.1. Azerbaijan: mature onshore development and emerging offshore potential

Early scholarly interest in Azerbaijan's wind resource concentrated on on-shore coastal sites around the Absheron Peninsula. The first GIS-based map of mean speeds was produced using sparse World Meteorological Organization gauges; this dataset subsequently underpinned a site-selection review which highlighted the «scarcity of comprehensive meteorological wind data» and urged expansion beyond Absheron toward mountainous western districts [2]. Government statistics compiled by the Renewable Energy Agency estimate 3 GW of technical on-shore wind capacity within a wider 26.9 GW renewable portfolio, yet detailed empirical confirmation remained limited until recently.

A new generation of data-driven studies now leverages long ERA5 reanalysis records [3]. One such study processed >70 million hourly observations spanning 1940–2023 and fitted two-parameter Weibull functions to 24 strategically chosen stations, determining hub-height wind power densities exceeding 600 W m⁻² in Baku–Sumgait–Gobustan while also quantifying the underestimation bias over complex topography [3]. Their findings corroborate earlier analyses that listed five Ministry-endorsed wind-energy projects (total 442.5 MW) and proposed two inland clusters in Kalbajar–Lachin and Ganja–Gazakh (207 MW) to diversify the national pipeline [4]. Nevertheless, the ERA5-based works uniformly recommend site-specific mast or floating-LiDAR campaigns in high-relief zones to capture sub-kilometer flow variability and refine Weibull fits.

Offshore literature is dominated by the World Bank/IFC Offshore Wind Roadmap for Azerbaijan [5]. Using a constraint-filtered resource model, the report downsized the technical potential to 35 GW in shallow (<40 m) waters and 122 GW for future floating concepts, with lowest projected LCOE north of the Absheron Peninsula [5]. The roadmap proposes a 210 MW «pathfinder» fixed-bottom project at Bilgah to be sanctioned in 2025 and commissioned by 2028; under its low-growth scenario this would initiate a 1.5 GW build-out by 2040, whereas a high-growth trajectory envisages 7.2 GW and 37% of national electricity demand. Subsequent academic assessments emphasise Azerbaijan's comparative advantage: a mature oil-and-gas supply chain capable of supporting European energy security needs [6], shallow 20–60 m bathymetry within 15–50 km of shore, and existing heavy-lift ports, all of which lower CAPEX benchmarks for first-of-a-kind farms.

Research gaps persist [4]. Offshore studies still rely exclusively on reanalysis products; no public met-ocean campaigns or long-term LiDAR buoys have yet been reported for the Caspian shelf. Integrated grid-integration modelling, cumulative environmental-impact baselines, and techno-economic coupling with hydrogen production remain nascent topics – as noted in the roadmap's recommended future work packages [5]. Addressing these gaps and challenges will be critical for translating Azerbaijan's documented on- and offshore resource endowment into bankable utility-scale projects aligned with its 30% renewable-energy target for 2030 [4].

2.2. Kazakhstan: continental wind corridors and cold-climate design challenges

Early investigations placed Kazakhstan at the core of Central Asia's wind resource: over 70% of the region's theoretical wind potential located within its national borders [7]. National-scale modelling estimated ≈760 GW of economically developable capacity, noting that half of the national territory experiences mean speeds of 4–6 m s⁻¹ and that the Caspian littoral, northern steppe and south-eastern mountain passes form the three foremost wind corridors [8]. Within the latter, the Djungar Gate exhibits power densities up to 525 W m⁻², while the Chu–Ili corridor attains ≈240 W m⁻² [8]. Contemporary ERA5-driven analyses corroborate these figures and provide refined capacity-factor and techno-economic estimates [9].

Site-specific mast campaigns supported by UNDP/GEF identify nine priority locations that satisfy IEC Class II–III criteria; Weibull fitting of 10-min records reveals mean hub-height speeds of 7–8 m s⁻¹ at steppe land stations and >9 m s⁻¹ in coastal Mangystau and mountain passes [8].

Policy momentum accelerated after the 2009 Renewable Energy Law, which obliges grid connection and introduces feed-in tariffs; however, analysts highlight obstacles such as the necessity of stronger tax incentives and investment-grade PPAs to unlock large-scale deployment [10]. Since competitive auctions began in 2018, Kazakhstan has awarded 6.8 GW of renewable capacity to be commissioned by 2027, positioning wind as the dominant tranche. Operational progress is tangible: by 2022, 44 utility-scale wind farms (957 MW) delivered 2.41 TWh—4.5% of national electricity output [11]. Government roadmaps envisage trebling this fleet within five years while prioritizing grid reinforcement along the Astana–Aktau corridor and hybrid storage solutions to mitigate the weak 220 kV backbone.

Research gaps persist in three domains. Cold-climate engineering challenges – particularly blade icing a and sub-zero gearbox lubrication – remains under-examined despite recurrent outages in Akmola and Kostanay. Dynamic grid-integration modelling is still limited to static N-1 criteria, leaving transient stability under high wind penetration uncertain. Finally, socio-economic co-benefits (rural employment, pastoral land-lease revenues) are seldom quantified, even though wind development is expected to shift investment toward sparsely populated western oblasts [9]. Addressing these lacunae, including the potential for small-scale installations [12], will be critical for translating Kazakhstan's 920 billion kWh yr⁻¹ gross wind potential into a bankable pipeline aligned with the national carbon-neutrality pathway.

2.3. Russian Federation: localization - driven expansion across diverse climatic zones

Scholarly work and reviews on wind energy in the Russian Federation have evolved from early Soviet-era engineering trials to today's multi-scalar analyses that couple resource assessment with policy and techno-economic inquiry [13]. Initial experiments with small and medium turbines in the 1950s-1960s were curtailed by the centralized electrification strategy of the USSR, which prioritized diesel-backed rural supply; nevertheless, this historical strand confirms a long-standing technical know-how base.

Modern cartographic studies and national cadastres indicate that annual 100 m wind speeds exceed the 5 m s⁻¹ development threshold across most of the Federation, with pronounced ridges along the Arctic seaboard, the Lower Volga steppes and southern Siberia [14]. Conservative estimates place the technical wind potential at ≈17100 TWh yr⁻¹ – about seventeen times current electricity consumption [15].

Commercial take-off has been recent but rapid, though market analyses point to ongoing problems and prospects for development [16, 17]. Installed wind capacity rose from 134 MW in 2018 to 2.17 GW by January 2023, despite pandemic-related supply shocks; 75 turbines (230 MW) were added in 2022 alone, raising wind's share to 0.93% of national generation [11].

The growth is underpinned by the capacity-based support mechanism introduced in 2013 [18]. Unlike feed-in or premium tariffs, the Russian scheme remunerates available capacity via long-term «Agreements for the Supply of RES Capacity,» selected through two-stage auctions that rank projects primarily on specific CAPEX while guaranteeing developers a 12% internal rate of return for 15 years. Annual caps and strict localization rules aim to limit tariff impacts and foster domestic manufacturing of components like rare-earth permanent magnets [18, 19]. The design, however, excludes isolated grids and thus leaves northern diesel communities to bespoke hybrid solutions.

Dedicated offshore analyses remain sparse. An expert review for the Friedrich-Ebert-Stiftung argues that large-scale offshore deployment is «premature» given Russia's still-untapped on-shore potential yet highlights export-oriented pilot projects as a means of leveraging shipbuilding and oil-and-gas competencies [20]. Research on wind–diesel hybrids underscore fuel-savings up to 50% for Arctic settlements but also highlights harsh-climate O&M constraints and human-capital shortages [13]. Public acceptance surveys reveal persistent skepticism, which presents a challenge to development [21]. Recent techno-economic modelling, in line with the national hydrogen energy concept [22], extends the discourse to green hydrogen exports from Far-Eastern ports, using capacity-factor-weighted ERA5 series for 20 coastal meteorological stations [23].

2.4. Turkmenistan: cadastre-based resource assessment and pilot deployment pathways

Early empirical appraisals of Turkmenistan's wind regime relied on sparse meteorological-station records. Sariyev (2020) processed data from 72 gauges covering the 2004–2018 period and concluded that ≈40% of the national territory surpasses the 4 m s⁻¹ development threshold, with the highest specific power (110–150 W m⁻²) concentrated along the Balkan-Köpetdag corridor and the northern Caspian shoreline [24]. These findings were later formalized into a draft wind cadaster that underpins current renewable-energy planning and strategic development roadmaps [25].

Offshore resource mapping advanced markedly when the World Bank's ESMAP programme applied its constraint-filtered GIS model to the Turkmen Exclusive Economic Zone (EEZ) [26]. The study identified 46 GW of fixed-bottom and a further 27 GW of floating technical potential (total = 73 GW) within 200 km of shore, flagging the Garabogazköl basin and the Cheleken sand-spit as priority lease areas [26].

Regional techno-economic case studies remain scarce but illuminating. Kochayeva et al. (2025) simulated hybrid supply options for the Atamyrat and Köýtendag load centres: a pair of 1.5 MW turbines could already satisfy 49–134 % of monthly demand, thanks to spring gusts that exceed 15 m s⁻¹ [27]. Such decentralized generation schemes, potentially using combined solar and wind technologies [28], are particularly relevant given that 80% of the population lives outside the main grid corridors and endures frequent diesel shortages, a factor in regional energy insecurity [29].

Despite the sizeable resource, hardware deployment is still at the demonstration stage. The only documented utility-scale installation is a 5 kW Soviet-era turbine on Gyzylsu Island, which powered a coastal school and research outpost [27]. Several micro-grids (<100 kW) using Chinese turbines have been reported anecdotally in desert farms, yet peer-reviewed performance data are lacking. Policy has begun to evolve, albeit cautiously. The State State Energy-Saving Programme 2018-2024 introduced a 10 MW wind-solar target for the Altyn Asyr Lake ecological zone and tasked the Ministry of Energy with publishing a national wind cadastre by 2025. Draft amendments to the Electricity Law envisage long-term power-purchase agreements and land-lease incentives, but tariff design, grid-code revisions and bankable guarantee mechanisms remain unresolved.

To transition from theoretical potential to bankable projects Turkmenistan must (i) install IEC-compliant 100 m met-masts or floating LiDARs in both desert and near-shore zones to validate hub-height climatology; (ii) undertake dynamic grid-integration studies for penetrations up to 30%, including reactive-power and storage requirements; (iii) launch a ≥50 MW pilot farm on the Cheleken sand-spit to test monopile corrosion mitigation and logistics using the existing oil-and-gas supply chain; and (iv) embed quantified wind deployment pathways into the forthcoming 2025–2040 Low-Carbon Development Strategy.

2.5. Iran: revitalizing wind deployment after an early pioneering phase

Systematic appraisal and overviews of Iran's wind resource began in the mid-1990s, when the Renewable Energy Organization (SUNA) deployed a national mast network [30, 31]. The first survey – covering 26 regions and 45 candidate sites – suggested a theoretical capacity of ≈6.5 GW, with the richest prospects in the eastern corridors of Sistan and Khorasan. These findings spurred construction of the Manjil (25 MW) and Binalud (60 MW) wind farms between 2003 and 2009, making Iran the first Middle-Eastern country to commission utility-scale wind power and demonstrating its manufacturing capabilities [32]. As measurement coverage expanded, the National Wind Atlas revised the technical potential upward to 15 GW – possibly 40 GW once ongoing analyses are completed – while confirming the superiority of the Sefid-Rood valley, Zagros and Alborz passes, and the Sistan Basin over the central plateau.

Despite substantial resource estimates, wind-energy deployment in Iran has progressed slowly [33]. Installed capacity reached only about 300 MW by 2021, all in private hands, after a sharp depreciation of the rial cut the feed-in tariff to roughly USD 0.03 kWh^{-1} [34]. Country-wide modelling nevertheless identifies an economic potential of 18 GW if tariffs return to at least USD 0.12 kWh^{-1}, and highlights six high-wind provinces – Qazvin, Razavi Khorasan, East Azerbaijan, Ardabil, South Khorasan and Sistan-Baluchestan – where summer gusts coincide with peak cooling demand [34]. Wind potential studies in specific regions like Kerman and eastern Iran confirm these rich resources [35, 36]. Mesoscale WRF reconstructions further show that the Levar wind accelerates to IEC class 7 (>8 m s^{-1}) over the Sistan Basin each July–August [37], yet no commercial project has been realized there to date despite studies showing its suitability for power generation [38].

Offshore investigations remain embryonic. Nationwide reviews also underline the scarcity of long-term met-ocean data, the absence of unified spatio-temporal datasets, and unresolved grid-code and PPA frameworks – factors that collectively obstruct large-scale investment [34, 39]. Realizing Iran's on- and offshore potential therefore hinges on restoring tariff credibility, extending the mast-LiDAR network to coastal and desert zones, and embedding wind-deployment pathways within the country's emerging hydrogen-export strategy [40]. Hybrid systems for applications like agriculture are also being explored [41, 42].

3. Methodology

This study implements a systematic, data-driven framework to assess the offshore wind energy potential within the Exclusive Economic Zones (EEZs) of the five Caspian Sea littoral states. The methodology is founded on the use of high-resolution reanalysis data, robust geospatial analysis, and established statistical modeling techniques for wind resource characterization. Each component of the methodology, from data sourcing to statistical fitting, was chosen to ensure scientific validity and reproducibility. The entire analytical pipeline was automated using a custom program developed in Python.

3.1. Data acquisition and preparation

3.1.1 Meteorological data

The primary meteorological data were sourced from the ERA5 reanalysis dataset, the fifth-generation atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) [43]. ERA5 is widely validated and utilized in wind energy research due to its high spatiotemporal resolution and consistency, proving to be a reliable proxy for direct measurements where they are unavailable [44]. The dataset utilized for this study spans from January 1, 1940, to December 31, 2024, inclusive. This 85-year period provides a recent and statistically significant sample of the regional wind climate. The dataset analyzed spans the period from 1 January 1940 to 31 December 2024, providing 85 years of continuous hourly data. This extended temporal coverage ensures a statistically robust characterization of the long-term wind climate of the Caspian Sea.

The data feature a spatial resolution of 0.25×0.25° (approximately 31×31 km at this latitude) and an hourly temporal resolution. The specific variables extracted were the zonal (u, eastward) and meridional (v, northward) wind components at two vertical levels: 10 meters and 100 meters above mean sea level. The 100-meter height serves as a proxy for the hub height of modern offshore wind turbines.

3.1.2. Geospatial data

To accurately delineate the maritime jurisdiction of each state, geospatial vector data for the Caspian Sea EEZs were obtained from the Flanders Marine Institute (VLIZ) Maritime Boundaries Geodatabase (version 12) [45]. These data define the official EEZ polygons for the five target nations: Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan. Figure 2 provides a map of the study area, illustrating these distinct maritime zones, which form the spatial basis for this assessment.

3.2. Computational framework and pre-processing

The analytical workflow was orchestrated using the Prefect dataflow automation framework to manage dependencies and ensure reliable execution. Large-scale data handling was optimized through the combined use ofthe Xarray and Dask libraries, enabling lazy, out-of-core computation on the multi-gigabyte NetCDF datasets. All geospatial operations were performed using the GeoPandas library.

For each grid point and time step, the instantaneous horizontal wind speed, V, was calculated from the zonal (u) and meridional (v) components using the Pythagorean theorem, as shown in Equation (1):

$$V = \sqrt{u^2 + v^2} \qquad (1)$$

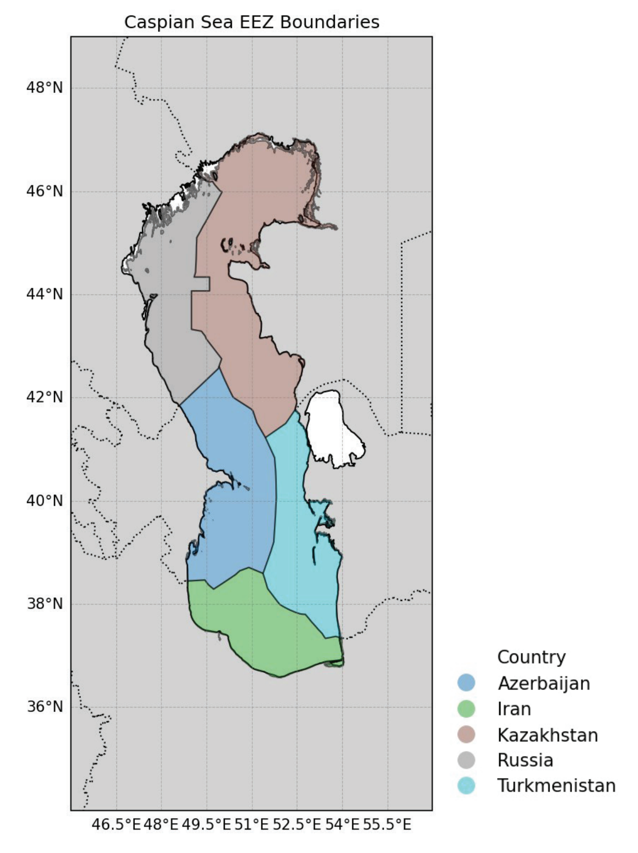

Fig. 2. The study area, showing the Exclusive Economic Zone (EEZ) boundaries of the five Caspian Sea littoral states as defined by the VLIZ Maritime Boundaries Geodatabase

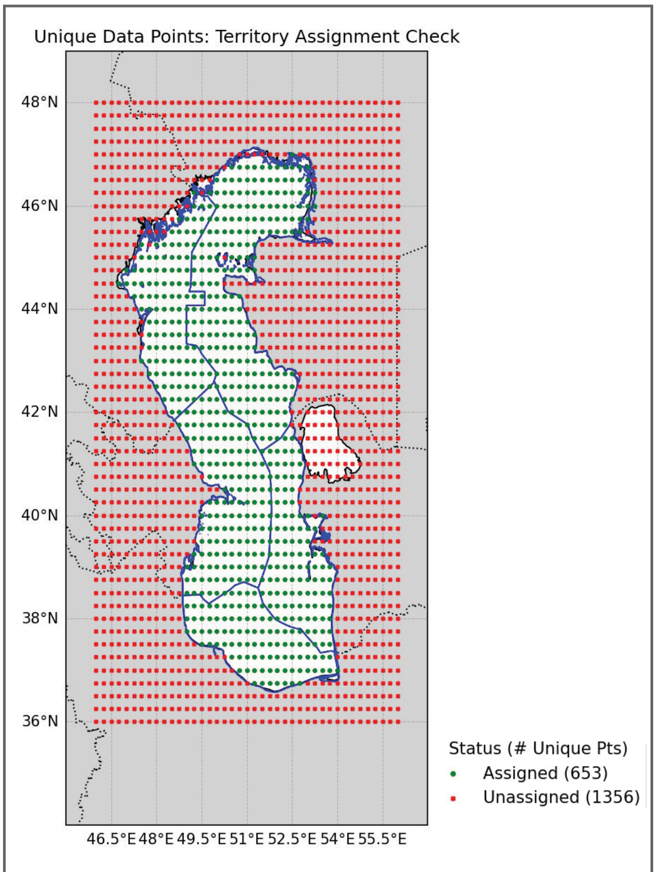

Fig. 3. Visual validation of the territory assignment process for ERA5 grid points: Green points indicate the 653 offshore locations successfully assigned to a national EEZ and used for analysis. Red points indicate locations outside the defined maritime bound

This calculation was performed for both the 10 and 100 m data layers, creating continuous time series of wind speed for the entire study area.

3.3. Spatial analysis and territory assignment

A critical preliminary step was to spatially constrain the gridded ERA5 meteorological data to the maritime jurisdictions of the five Caspian littoral states. This was achieved through a territory assignment process wherein all unique latitude and longitude coordinate pairs were extracted from the ERA5 data grid. Subsequently, a spatial join operation was performed between these unique grid points and the processed EEZ polygons (shown in fig. 3). Each grid point was tested for its location «within» a country's EEZ polygon, assigning each relevant offshore data point to a specific nation.

Figure 3 visually validates this territory assignment procedure. It displays the complete grid of unique ERA5 data points overlaid with the official EEZ boundaries. The points colored in green represent the 653 grid locations that fall within the maritime boundaries and were thus «Assigned» for inclusion in the wind resource assessment. Conversely, the points colored in red are «Unassigned» as they lie outside the EEZs (e.g., over land or in international waters) and were consequently excluded from subsequent analysis. This filtering step ensures that the study is strictly focused on the offshore wind potential within the national waters of the Caspian Sea.

3.4. Identification of high-potential wind energy zones

To objectively identify the most promising offshore zones, a two-stage percentile-based methodology was implemented.

Stage I: Grid-point potential characterization. For each grid point g in the dataset, its full hourly time series of wind speed $V_g(t)$ was used to compute the 90th percentile wind speed ($P_{90,\ g}$).

Stage II: National-level zone selection. Let G_c be the set of all grid points within the EEZ of a country c. A ranking threshold, T_c , was established by calculating the 90th percentile of the country-specific distribution of P_{90} values, $\{P_{90,\ g} | g \in G_c\}$. The final high-potential wind energy zone for country c, denoted as Z_c , is defined as the set of all grid points within its EEZ whose P90 value meets or exceeds this threshold:

$$Z_c = \{ g \in G_c \ | P_{90,g} \geq T_c \} \quad (2)$$

Methodological justification

The selection of this two-stage percentile-based methodology was a deliberate choice to overcome the limitations of traditional site-selection techniques that rely on mean wind speeds. While the mean provides a measure of central tendency, it is often insufficient for energy potential assessment due to the non-linear relationship between wind speed **and power**, where power is proportional to the cube of the wind speed ($P \propto V^3$). The use of the 90th percentile ($P90$) is specifically designed to characterize the upper tail of the wind speed distribution, identifying locations that consistently experience strong, energy-rich wind events, making it a more direct proxy for high energy yield [46]. Furthermore, the two-stage ranking process ensures that the identified zones represent the most promising regions relative to each nation's own maritime territory, facilitating country-specific development strategies rather than a simple basin-wide ranking.

3.5. Wind resource characterization and statistical modeling

For each identified zone Z_c, a comprehensive assessment was performed on the aggregated wind speed time series of all its constituent grid points.

3.5.1. Weibull distribution fitting

The statistical distribution of wind speeds was modeled using the two-parameter Weibull probability density function (PDF), which is widely accepted for wind energy applications [47]. The Weibull PDF is given by Equation (3):

$$f\left(v;k,c\right)=\left(\frac{k}{c}\right)\times\left(\frac{v}{c}\right)^{k-1}\exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (3)$$

where v is the wind speed, k is the dimensionless shape parameter, and c is the scale parameter in m/s.

Parameter estimation via maximum likelihood estimation (MLE)

The Weibull parameters (k and c) were estimated using the Maximum likelihood estimation (MLE) method. MLE is a standard statistical approach generally considered more accurate and possessing more desirable optimality properties than other methods like the Method of Moments (MoM), particularly for large datasets [47]. For a series of n independent wind speed observations $v_1, ..., v_n$, the likelihood function L is the product of the individual probability density functions:

$$L(k,c \mid v_1,\ldots,v_n)=\prod_{i=1}^{n}f\left(v_i;k,c\right) \quad (4)$$

The MLE method seeks the values of k and c that maximize this function, typically by numerically maximizing its logarithmic form. This approach, implemented via the scipy. stats library, ensures that the resulting Weibull distribution is the one that most closely represents the empirically observed wind speed data.

3.5.2. Wind power density (WPD)

The WPD represents the theoretical power available per unit of area swept by a turbine rotor. It was calculated from the fitted Weibull parameters using the formula in Equation (5):

$$WPD=\left(\frac{1}{2}\right)\cdot\rho\cdot c^{3}\cdot\Gamma\left(1+\frac{3}{k}\right) \quad (5)$$

where ρ is the standard air density (assumed to be 1.225 kg/m³) and Γ is the Euler-gamma function. This statistical method provides a more robust estimate than averaging cubed wind speeds as it leverages the full probability distribution [46].

3.5.3. Geographical area and directional analysis

The total geographical area of each zone Z_c was quantified by creating a polygon for each constituent grid cell, clipping the aggregated polygons to the precise EEZ boundary, and calculating the summed area after projecting the final geometries to an equal-area projection (Caspian LAEA). Finally, wind rose diagrams were generated from the u and v components to characterize the prevailing wind directions.

3.6. Derived potential and impact metrics

To translate the wind resource assessment into strategic insights, several key metrics were derived from the primary WPD results.

1. Technical capacity estimation: The technical potential for wind power generation (in gigawatts, GW) within the identified high-potential zones was estimated using a standard turbine power density assumption. Based on typical offshore wind farm layouts, we applied a conservative density of 5 MW/km² [48]. The total capacity for a given zone was calculated as:

$$Technical\,Capacity\left(GW\right)=\frac{Area\left(km^{2}\right)\times 5MW/km^{2}}{1000\,MW/GW}$$

2. Concentration of useful wind: To quantify the claim that the high-potential zones contain the majority of the «energetically useful wind,» we calculated a basin-wide energy index. This was done by summing the cube of the median wind speed (V^3_{med}) for all 653 offshore grid points to establish a total for the Caspian Sea $\left(E_{total}=\sum_{i=1}^{653}V_i^3\right)$.The same calculation was performed only for the grid points within the high-potential zones $\left(E_{zones}=\sum_{j=1}^{N_{zones}}V_j^3\right)$. The concentration percentage is the ratio of these two sums (E_{zones}/E_{total}).

3. Energy and emissions displacement: The potential displacement of fossil fuel generation was calculated based on a prospective 15–20 GW build-out. To derive the stated figures of ≈40 TWh of energy and ≈25 Mt of CO_2, the following assumptions were used: a blended net capacity factor of 30.4% for the Caspian wind fleet and an average carbon intensity of 625 gCO_2/kWh for the displaced gas-fired generation, reflecting the current regional grid mix.

4. Results

The analysis of 85 years of ERA5 reanalysis data yielded Weibull distribution parameters and wind power density (WPD) values for the five Caspian littoral states. For each country's Exclusive Economic Zone (EEZ), the top 10% of locations with the highest WPD were identified for detailed characterization (fig. 4). The number of selected grid points and their corresponding surface areas are:

- Azerbaijan — 8093.45 km²
- Kazakhstan — 10948.95 km²
- Russia — 6248.35 km²
- Turkmenistan — 5480.21 km²
- Iran — 5959.12 km²

Summary statistics, including median wind speeds, Weibull parameters, and WPD at 10 m and 100 m heights, are presented in table 1. For each country's high-potential zone, wind direction is characterized by wind roses, and wind speed distribution is modeled with Weibull fits.

4.1. Wind energy potential for the Caspian sector of Azerbaijan

The high-potential zone in the Azerbaijani EEZ (≈8093 km²) and is delineated by fourteen ERA5 grid-cell centroids located at (49.50 °E, 42.00 °N), (49.75, 42.00), (49.50, 41.75), (49.75, 41.75), (50.00, 41.75), (49.75, 41.50), (49.75, 41.25), (50.00, 41.25), (49.75, 41.00), (50.00, 41.00), (49.75, 40.75), (50.00, 40.75), (50.00, 40.25) and (50.00, 40.00) is located 15–50 km east of the Absheron Peninsula in waters 20–60 m deep. At 100 m hub height, the median wind speed is

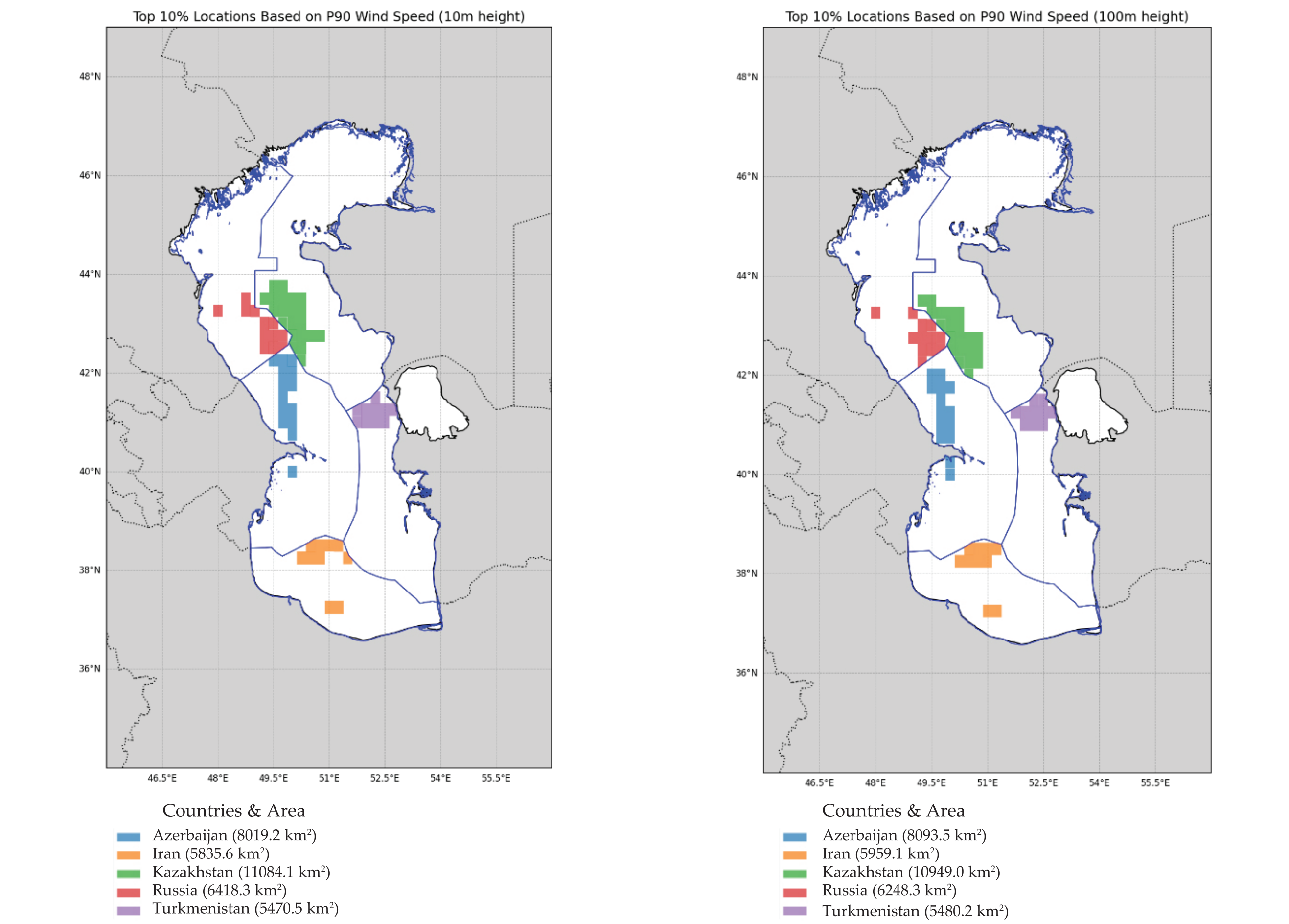

Fig. 4. The most promising locations of Caspian Sea (top 10%) with the highest wind power density (WPD) at 10m and 100m heights respectively

Table 1

Wind potential and Weibull parameters at 10 m and 100 m above sea level in the leading zones of the five Caspian littoral states

Country	Area, km²	Locations	Median Wind Speed: $\overline{v}$, m/s		WPD, W/m²		Weibull shape factor: k		Weibull scale parameter: c, m/s	
			100 m	10 m	100 m	10 m	100 m	10 m	100 m	10 m
Azerbaijan	8093.45	14	7.27	6.06	613.48	304.59	1.87	2.04	8.91	7.28
Kazakhstan	10948.95	21	7.40	6.10	555.90	291.47	2.03	2.13	8.88	7.27
Russia	6248.35	12	7.04	5.92	560.62	292.08	1.88	2.02	8.66	7.15
Turkmenistan	5480.21	10	7.52	6.10	477.62	244.19	2.26	2.37	8.71	7.05
Iran	5959.12	10	4.61	4.16	168.50	109.94	1.83	1.94	5.73	5.09

Note. The parameters k and c correspond to fitting the empirical data with the Weibull law; wind power density (WPD) was computed as the integral over the probability density function assuming standard air density (1.225 kg m⁻³). The listed values represent averages across the top 10% of locations with the highest wind energy potential in each country according to ERA5 data (resolution 31×31 km).

7.27 m s^{-1} with a corresponding WPD of 613.48 W m^{-2} (k=1.87, c=8.91 m s^{-1}). At 10 m, the median speed is 6.06 m s^{-1} with a WPD of 304.59 W m^{-2} (k=2.04, c=7.28 m s^{-1}). The wind speed frequency distributions are presented in figure 5. The dominant wind directions are from the north-west and south-east sectors at both heights, as shown in the wind roses (fig. 6).

4.2. Wind energy potential for the Caspian sector of Kazakhstan

In the Kazakh EEZ, the high-potential cluster covers ≈10949 km² comprising twenty-one ERA5 centroids at (49.25 °E, 43.50 °N), (49.50, 43.50), (49.50, 43.25), (49.75, 43.25), (50.00, 43.25), (50.25, 43.25), (49.75, 43.00), (50.00, 43.00), (50.25, 43.00), (50.00, 42.75), (50.25, 42.75), (50.50, 42.75), (50.75, 42.75), (50.00, 42.50), (50.25, 42.50), (50.50, 42.50), (50.75, 42.50), (50.25, 42.25), (50.50, 42.25), (50.75, 42.25) and (50.50, 42.00) in waters 10–25 m deep. At 100 m, the median wind speed is 7.40 m s^{-1} and the WPD is 555.90 W m^{-2} (k = 2.03, c = 8.88 m s^{-1}). At 10 m, the median speed is 6.10 m s^{-1} and the WPD is 291.47 W m^{-2} (k = 2.13, c = 7.27 m s^{-1}). The wind roses at both heights display a pronounced bimodality with dominant WNW (280–310°) and ESE (110–140 °) directions (fig. 7). Figure 8 shows the corresponding wind speed distributions.

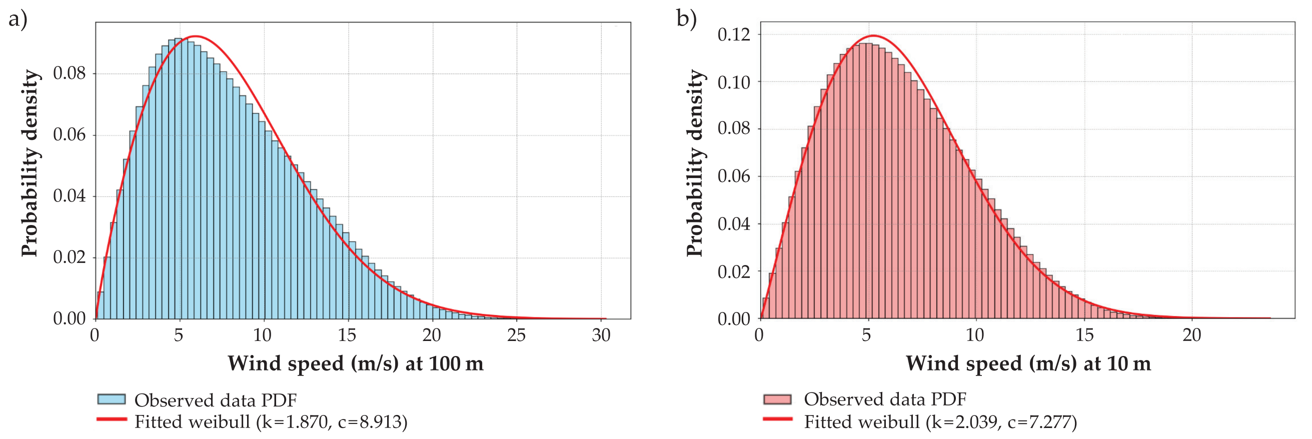

Fig. 5. Wind speed frequency distributions and Weibull fits for the windiest Azerbaijani sector of the Caspian Sea (top 10% WPD): 100 m and 10 m

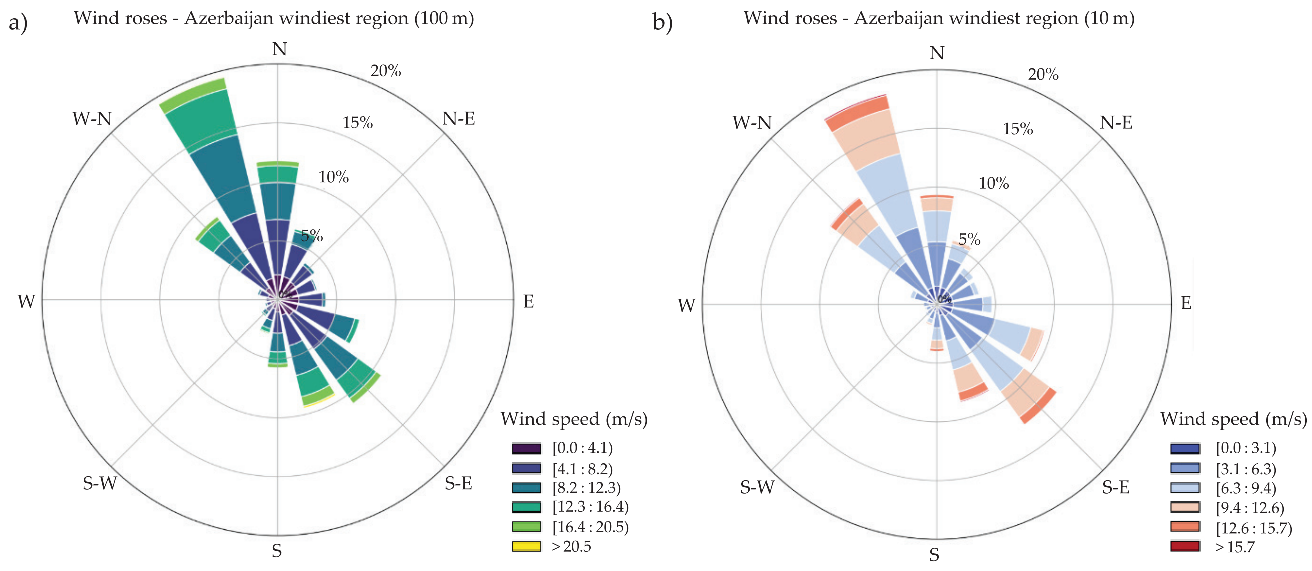

Fig. 6. Wind roses for the windiest Azerbaijani Caspian sector: 100 m hub-height proxy and 10 m near-surface

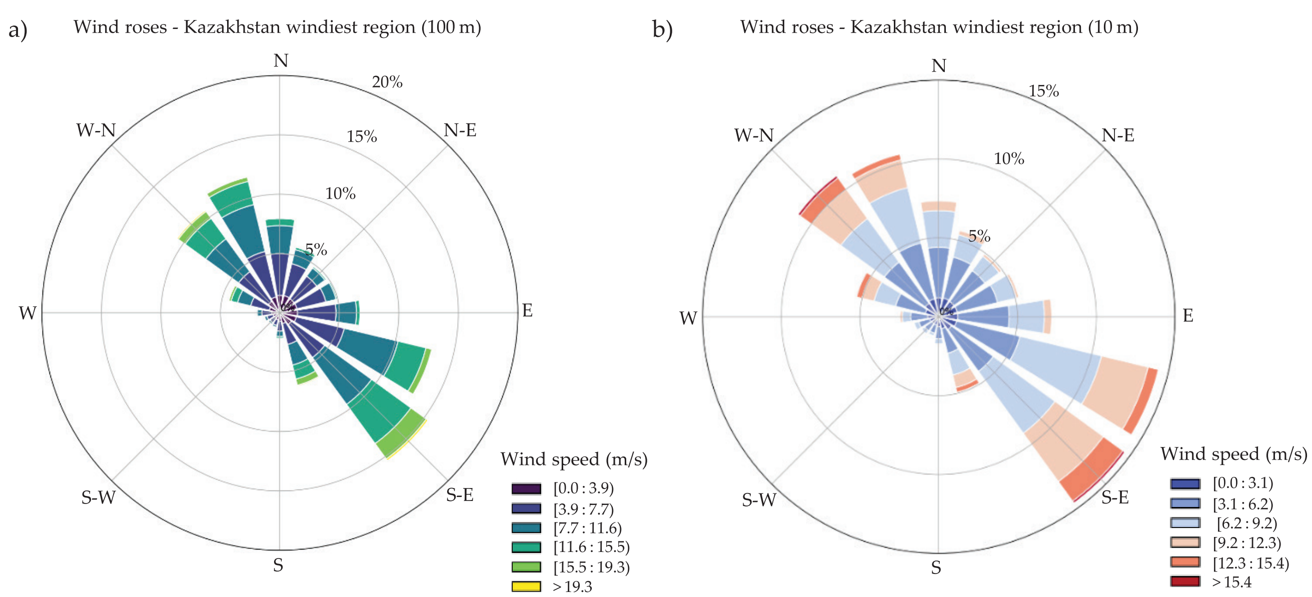

Fig. 7. Wind roses for the windiest Kazakh Caspian sector: 100 m hub-height proxy and 10 m near-surface

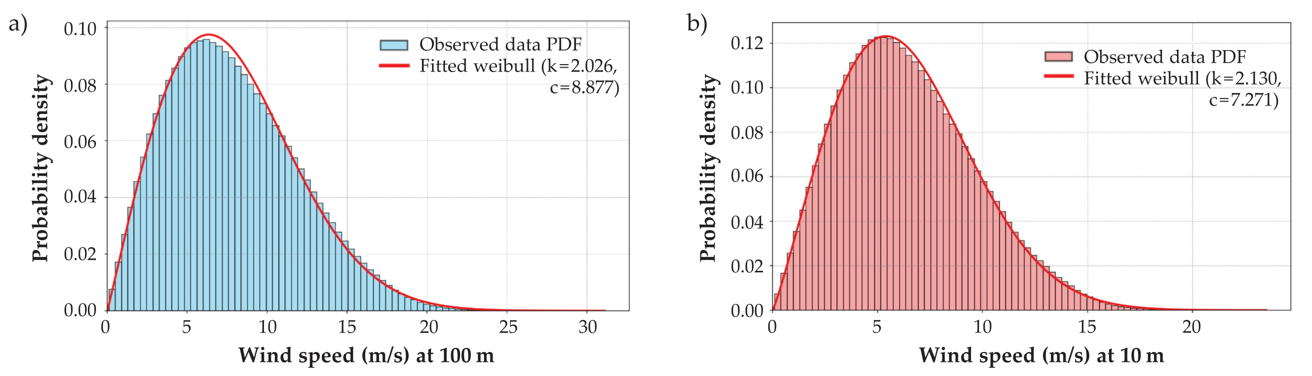

Fig. 8. Wind speed frequency distributions and Weibull fits for the windiest Kazakh sector of the Caspian Sea (top 10% WPD): 100 m and 10 m

4.3. Wind energy potential for the Caspian sector of Russia

The identified zone in the Russian EEZ covers ≈ 6,248 km² and is defined by twelve centroids located at (48.00 °E, 43.25 °N), (49.00, 43.25), (49.25, 43.00), (49.50, 43.00), (49.00, 42.75), (49.25, 42.75), (49.50, 42.75), (49.75, 42.75), (49.25, 42.50), (49.50, 42.50), (49.75, 42.50) and (49.25, 42.25) in the north-western Caspian in waters 5–15 m deep. The 100 m median wind speed is 7.04 m s^{-1} with a WPD of 560.62 W m^{-2} (k = 1.88, c = 8.66 m s^{-1}). The 10 m values are a median speed of 5.92 m s^{-1} and a WPD of 292.08 W m^{-2} (k = 2.02, c = 7.15 m s^{-1}). The wind speed distributions are shown in figure 10, and wind roses show a persistent bimodality with dominant WNW (280–305°) and ESE (115–145°) sectors (fig. 9).

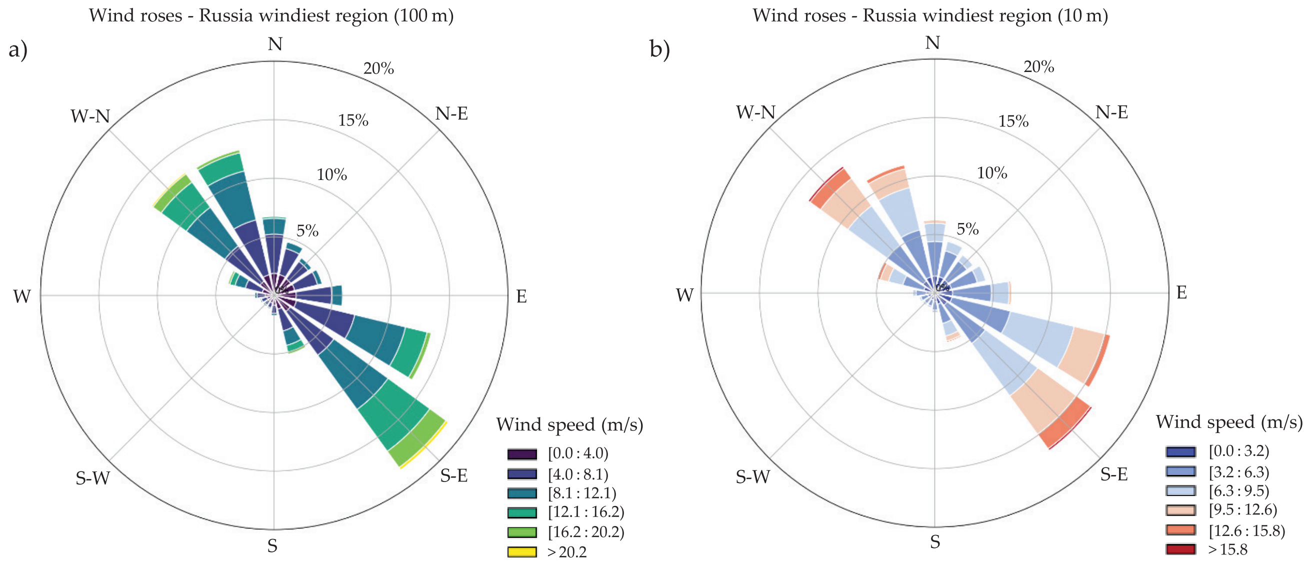

Fig. 9. Wind roses for the windiest Russian Caspian sector: 100 m hub-height proxy and 10 m near-surface

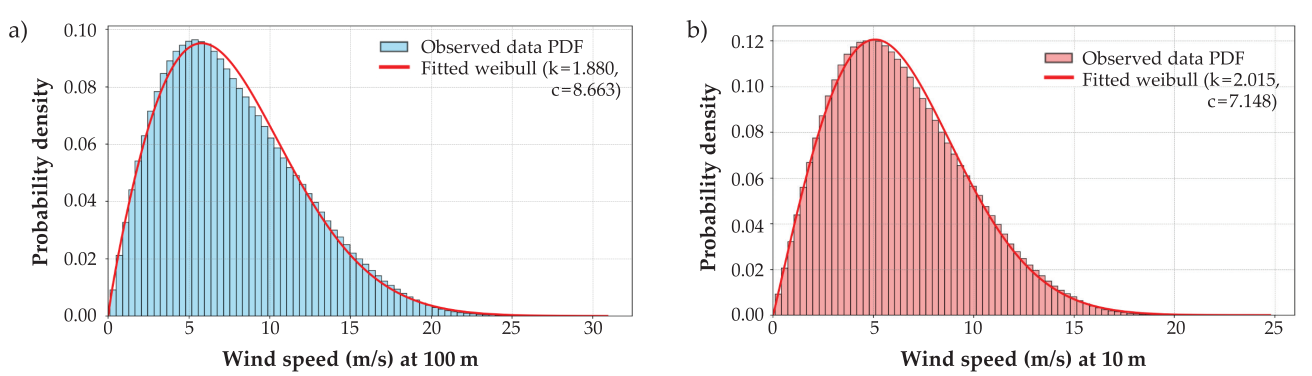

Fig. 10. Wind speed frequency distributions and Weibull fits for the windiest Russian sector of the Caspian Sea (top 10% WPD): 100 m and 10 m

4.4. Wind energy potential for the Caspian sector of Turkmenistan

On the Turkmen shelf, the high-potential cluster spans ≈5480 km² and is represented by ten centroids at (52.25 °E, 41.50 °N), (52.50, 41.50), (51.75, 41.25), (52.00, 41.25), (52.25, 41.25), (52.50, 41.25), (52.75, 41.25), (52.00, 41.00), (52.25, 41.00) and (52.50, 41.00) in waters 20–50 m deep. At 100 m, it shows a median wind speed of 7.52 m s^{-1} and a WPD of 477.62 W m^{-2} (k=2.26, c=8.71 m s^{-1}). At 10 m, the median speed is 6.10 m s^{-1} with a WPD of 244.19 W m^{-2} (k=2.37, c=7.05 m s^{-1}). Figure 11 presents the wind speed distributions. The wind roses register a persistent bimodality with dominant NNW (330–350 °) and E (85–115 °) sectors (fig. 12).

4.5. Wind energy potential for the Caspian sector of Iran

In the Iranian sector, the identified zone covers ≈5959 km² and is represented by ten ERA5 centroids positioned at (50.50° E, 38.50° N), (50.75, 38.50), (51.00, 38.50), (51.25, 38.50), (50.25, 38.25), (50.50, 38.25), (50.75, 38.25), (51.00, 38.25), (51.00, 37.25) and (51.25, 37.25) in waters 30–70 m deep. At 100 m, this area exhibits a median wind speed of 4.61 m s^{-1} and a WPD of 168.50 W m^{-2} (k=1.83, c=5.73 m s^{-1}). At 10 m, the values are a median speed of 4.16 m s^{-1} and a WPD of 109.94 W m^{-2} (k=1.94, c=5.09 m s^{-1}). The wind speed distributions are shown in figure 14, and the wind roses show predominately meridional directions, with N (345–015 °) and E (080–110 °) sectors being most frequent (fig. 13).

5. Discussion

The results of this basin-wide assessment provide a new, quantitative basis for evaluating offshore wind prospects across the Caspian Sea. The findings reveal a clear hierarchy of resource potential among the littoral states, highlight profound techno-economic implications stemming from the region's industrial heritage, and establish the engineering criteria for future development.

5.1. A clear hierarchy of national wind potential

Our analysis establishes a distinct ranking of wind resource quality across the Caspian EEZs. The sectors belonging to Turkmenistan, Kazakhstan, Russia, and Azerbaijan all demonstrate commercially attractive wind regimes, whereas the Iranian sector lags significantly.

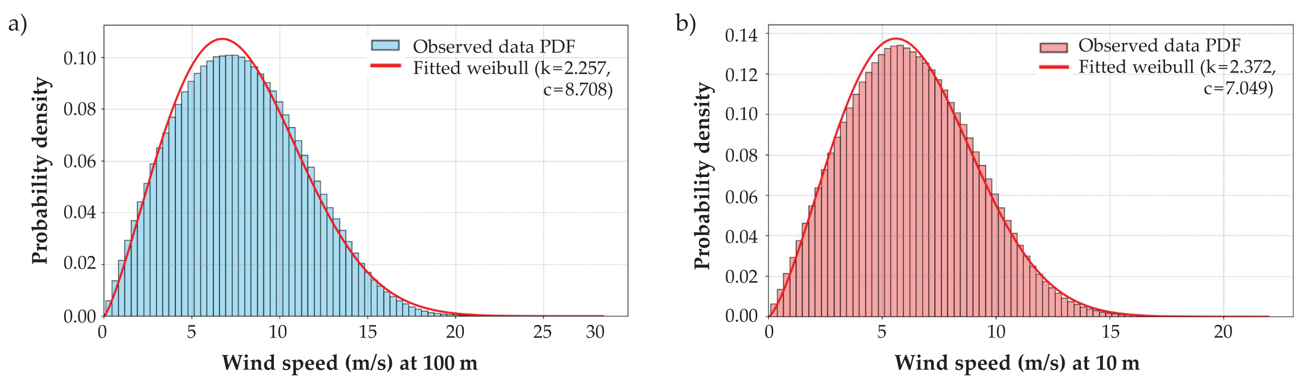

Fig. 11. Wind speed frequency distributions and Weibull fits for the windiest Turkmenistan sector of the Caspian Sea (top 10% WPD): 100 m and 10 m

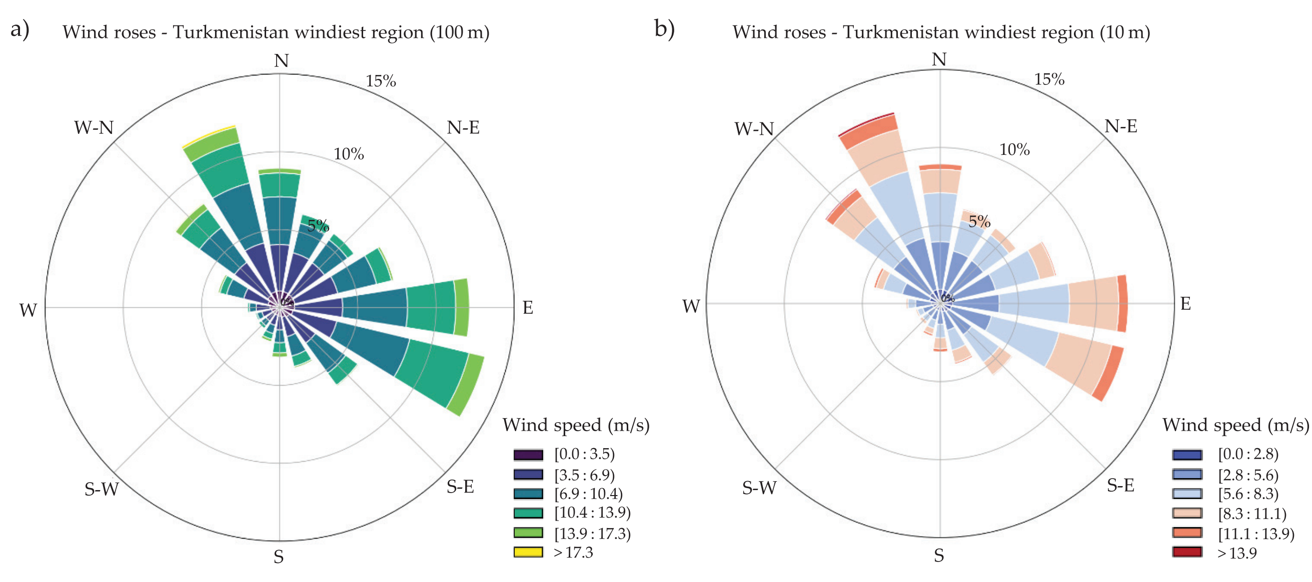

Fig. 12. Wind roses for the windiest Turkmenistan Caspian sector: 100 m hub-height proxy and 10 m near-surface

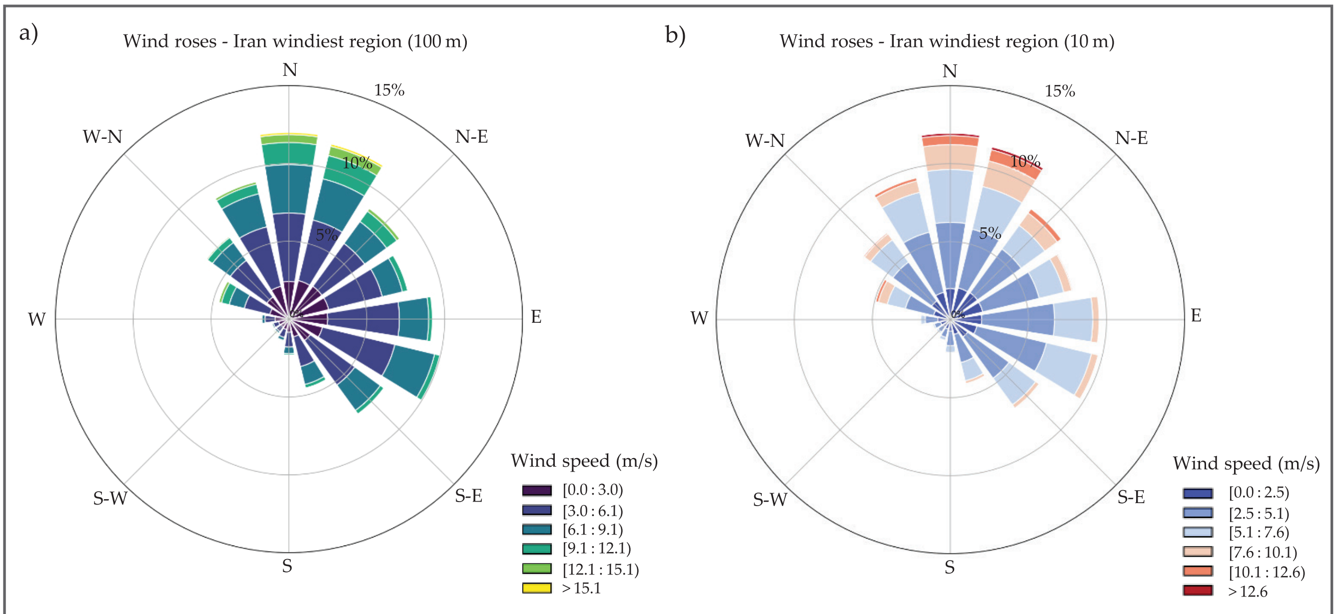

Fig. 13. Wind roses for the windiest Iranian Caspian sector: 100 m hub-height proxy and 10 m near-surface

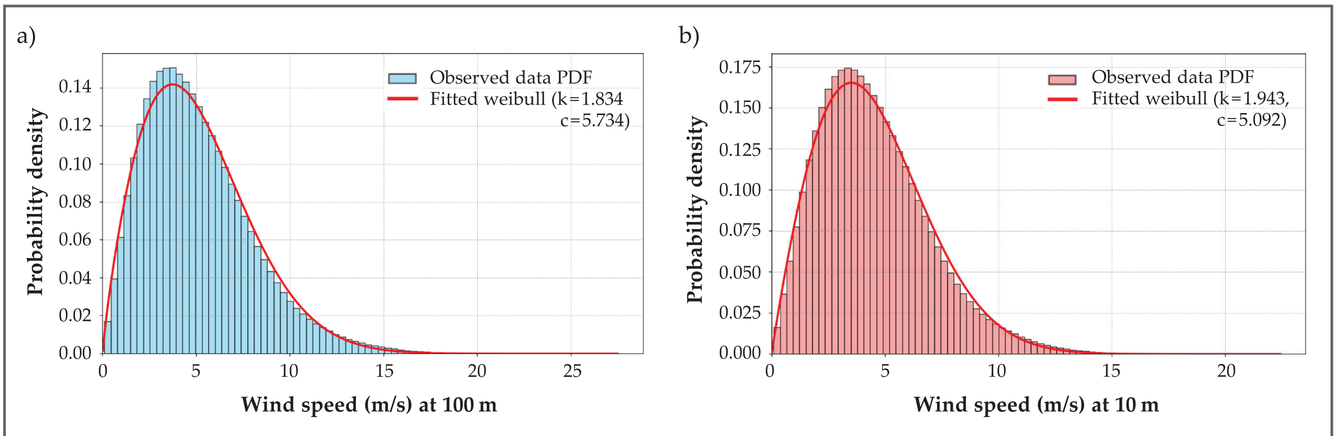

Fig. 14. Wind speed frequency distributions and Weibull fits for the windiest Iranian sector of the Caspian Sea (top 10% WPD): 100 m and 10 m

The results for Turkmenistan, which show a median hub-height speed of 7.52 m s^{-1} and a WPD of 477.62 W m^{-2}, corroborate earlier macro-scale estimates by the World Bank's ESMAP programme, confirming the high potential of the central Turkmen shelf. Similarly, the findings for Kazakhstan (7.40 m s^{-1}, WPD of 555.90 W m^{-2}) align well with prior UNDP/GEF-supported mast campaigns that identified the Caspian littoral as a premier wind corridor. These two nations possess the most extensive high-quality resource areas identified in this study.

The Russian sector, while smaller in area, exhibits an equally powerful resource (WPD of 560.62 W m^{-2}) in the shallow northern shelf. This study is among the first to systematically quantify this potential, confirming it as a viable development zone. Azerbaijan combines a strong resource (WPD of 613.48 W m^{-2}) with exceptional logistical advantages, as discussed below. In stark contrast, the Iranian sector's median hub-height speed of 4.61 m s^{-1} and WPD of only 168.50 W m^{-2} present a significant barrier to conventional development, distinguishing it from its Caspian neighbours-region countries.

5.2. Techno-economic implications and synergies with oil & gas

Perhaps the most critical finding beyond the raw resource numbers is the immense potential for synergy with the Caspian's century-old oil and gas industry. This existing ecosystem provides a unique opportunity to lower capital expenditures (CAPEX) and accelerate project timelines, particularly in Azerbaijan, Kazakhstan, and Russia.

The Azerbaijani sector is a prime case study. The proximity of high-potential sites (15–50 km) to the Absheron Peninsula, a hub of offshore hydrocarbon production, offers a ready-made industrial backbone. Leveraging existing assets—such as heavy-lift ports, assembly yards, and specialized vessel fleets – obviates the need for massive greenfield investment in new coastal infrastructure. Furthermore, the moderate water depths (20–60 m) are ideal for proven, lower-cost fixed-bottom foundations like monopiles and jackets. This combination of factors allows projects in Azerbaijan to target a unit CAPEX far below the global average for offshore wind.

This principle extends to other nations. In Kazakhstan, the Port of Aktau and its associated oil and gas logistics can serve as a staging ground for developing the 55 GW of technical potential. In Russia, the proximity of the resource to Astrakhan's ports and refineries offers similar advantages. Tapping into this existing supply chain is the key that unlocks near-term bankability for Caspian offshore wind.

5.3. Engineering considerations for Caspian development

The calculated wind conditions directly inform turbine selection and foundation design. The resources in Azerbaijan, Kazakhstan, Russia, and Turkmenistan predominantly fall within IEC Wind Class III (average speed up to 7.5 m/s) and border on Class II (up to 8.5 m/s). This makes them suitable for a wide range of modern, high-efficiency offshore turbines. In contrast, the Iranian sector's low wind speeds would necessitate specialized IEC Class IV turbines (low-wind models) or hybrid concepts like power-to-hydrogen, which can tolerate lower capacity factors.

Site-specific engineering challenges must also be considered. The shallow northern Caspian, particularly the Russian sector, experiences seasonal ice formation. This requires the use of reinforced foundations and may impact winter-time operation and maintenance schedules. The more southerly locations in Turkmenistan and Azerbaijan are not exposed to this risk. The directional coherence of the wind, particularly the persistent bimodality seen in the Kazakh and Russian sectors, is a significant advantage, as it simplifies turbine row orientation and minimizes energy losses from wake effects.

5.4. Limitations of the study

While this study provides a robust, basin-wide framework, its findings are subject to three main limitations. First, the spatial resolution of the ERA5 dataset (≈31 km) cannot resolve localized, sub-grid scale effects like coastal breezes or flow acceleration over complex bathymetry. Second, this assessment is based entirely on reanalysis data and lacks in-situ validation. Long-term, bankable resource assessments require site-specific measurement campaigns using IEC-compliant met masts or floating LiDAR. Third, the WPD estimates are theoretical and do not account for array losses from turbine wakes, availability losses due to maintenance or icing, or the potential impacts of long-term climate change on regional wind patterns.

5.5. Future research and strategic outlook

The limitations highlighted above define a clear pathway for future research. The immediate priority should be the deployment of measurement campaigns in the high-potential zones identified in this paper. Subsequent work must involve high-resolution mesoscale modeling to downscale the climatology and refine resource maps for specific project areas.

Strategically, the results confirm that the Caspian Sea is a highly promising new frontier for offshore wind. A coordinated 15–20 GW build-out by 2040, centered on the Azerbaijan-Kazakhstan-Russia nexus, could generate up to 40 TWh of clean electricity annually. This would not only displace approximately 25 Mt of CO_2 emissions from gas-fired power plants but also free up valuable natural gas resources for export or for use as a feedstock in the petrochemical industry, supporting both regional decarbonization and economic diversification.

Conclusions

This study delivers the first reproducible, basin-wide appraisal of the Caspian Sea's offshore wind resource based on 85 years (1940 – 2024) of hourly ERA5 reanalysis data, systematically filtered and analyzed with a percentile-ranking workflow and two-parameter Weibull fits. By assigning every one of the 653 marine grid points to the appropriate Exclusive Economic Zone and then isolating the windiest decile within each jurisdiction, we delineate high-potential zones that together span ≈36700 km² – about 10 % of the Caspian's surface but 70–85 % of its energetically useful wind.

The comparative results establish a clear resource hierarchy, with Azerbaijan as the leader in resource quality with the highest WPD (≈613 W m^{-2}), followed closely by Russia (≈561 W m^{-2}) and Kazakhstan (≈556 W m^{-2}). In terms of total energy potential in the windiest zones, the technical capacity is highest in Kazakhstan (≈55 GW), followed by Azerbaijan (≈41 GW), Russia (≈31 GW), Iran (≈30 GW), and Turkmenistan (≈27 GW). While Azerbaijan's near-shore shelf combines the most potent wind resource with exceptional logistical advantages, the vast high-potential areas in Kazakhstan present the largest overall capacity for development.

Beyond ranking, the analysis demonstrates the value of P90 filtering: focusing on the upper tail of the wind-speed distribution captures the episodes that dominate annual energy yield and extreme structural loading, thereby providing a more relevant basis for capacity-factor forecasting, turbine-class selection and fatigue design than mean-speed maps alone. The automated Python workflow (Prefect + Xarray/Dask + GeoPandas) also creates an audit trail that can be refreshed with new reanalysis vintages or coupled to mesoscale/CFD down-scaling without manual intervention.

The findings carry three strategic implications for Caspian-rim energy policy and investment:

1. Near-term bankability – Shallow waters (15–60 m), proximity to shore and a mature oil-and-gas supply chain in Azerbaijan, Kazakhstan and Russia collectively shorten project timelines and depress CAPEX, making ≥1 GW pathfinder projects technically and financially feasible before 2030.
2. Regional Grid Integration – The magnitude and spatial clustering of the wind resource argue for coordinated grid reinforcement and cross-border power-exchange corridors, especially along the Aktau–Baku–Astrakhan axis, to smooth variability and unlock economies of scale.

3. Decarbonisation Potential – Even moderate build-out scenarios (15–20 GW by 2040) would displace up to 40 TWh yr^{-1} of gas-fired generation – equivalent to roughly 25 Mt CO_2 annually – while freeing natural gas for export or domestic petrochemical use.

Notwithstanding its scope, the study is constrained by ERA5's 31×31 km native grid, the absence of long-term LiDAR or met-mast measurements over the shelf and the omission of wake-interaction, icing and climate-change effects in the power-density estimates. Future research should therefore: (i) deploy IEC-compliant measurement campaigns in the identified hotspots; (ii) down-scale the climatology with mesoscale–microscale nesting to resolve sub-kilometre flow features and shear; (iii) integrate dynamic grid-stability, storage and hydrogen-supply-chain models; and (iv) extend the environmental baseline to cumulative impacts on bird migration, fisheries and sediment dynamics.

Taken together, the results provide the empirical foundation and open-source tooling needed to progress from concept studies to bankable projects, positioning the Caspian Sea as a credible new theatre in the global expansion of offshore wind.

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