Energy for Sustainable Development 80 (2024) 101439

Contents lists available at ScienceDirect

Energy for Sustainable Development

journal homepage: www.journals.elsevier.com/energy-for-sustainable-development

GIS-based suitability mapping for offshore and onshore wind energy in the United Arab Emirates

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ARTICLE INFO

Keywords:
Renewable energy
Wind
Suitability assessment
Offshore
Onshore

ABSTRACT

The study provides a geospatial assessment of the suitability of sites for onshore and offshore wind projects in the United Arab Emirates (UAE), where traditionally, wind energy has not been a focus. This assessment demonstrates how wind projects in the country could be developed using improved technology that produces power from lower wind speeds. The suitability mapping used the GIS-based multi-criteria decision-making analysis, which consists of combining: (i) long-term annual average wind speed at 120 m (m) height and 500 m spatial resolution, (ii) technical and financial constraints that take into account the site characteristics (slope and elevation/bathymetry) and the proximity to the country's infrastructure (roads/shore, and power transmission lines networks), and (iii) environmental and legal constraints that represent restricted zones (populated, protected, heritage, etc.). The trade-off between the constraints listed is crucial for identifying efficient, reliable, and economic locations. The results confirm that onshore wind project deployment is limited in the UAE, with the suitable areas concentrated in the country's central and northwestern regions along the road and power transmission lines and spread intermittently in the eastern part of the country facing the Gulf of Oman, representing ~11 % of the country's total land area. These results are in accordance with the government's efforts that led to the commissioning of the 103.5 MW landmark wind project late 2023 and the planning of the 28 MW wind project in the western region near Hatta. As for suitable areas for offshore wind projects deployment, these are concentrated in the western part of the exclusive economic zone (EEZ), representing 32 % of the country's area.

Introduction

The United Arab Emirates (UAE) is aiming to diversify its energy sources by the middle of this century as society's energy demands increase and the reserves of the primary energy source (coal, natural gas, and oil) decrease (Karlsson et al., 2015; Masdar Institute/IRENA, 2015). The exploitation of renewables can help the country reach many of its energy and environmental policy targets, including its aim to reduce carbon dioxide emissions by 70 % and boost clean energy use by ~44 %.

The current share of renewable energy in the UAE's power generation mix is 7 %, mainly from solar photovoltaic (PV) systems (Masdar City - 2006, Sheikh Zayed solar park and Shams solar power plant - 2013, and Sweihan solar plant - 2019) and to less extent from waste-to-energy (Sharjah power plant - 2022) and onshore wind systems (103.5-megawatt (MW) landmark project - 2023) (Masdar, n.d.). Wind energy has not been a focus in the region because of constraints related to: (i) low wind resources that have not been suitable for establishing commercially viable utility-scale wind farms, where the estimated annual average wind power density based on historical wind measurements ranged between 44 W/m^2 and 122 W/m^2 (Janajreh et al., 2013; Yagoub, 2010; Zafar & Gadalla, 2013), and (ii) low competitiveness of wind in the electricity market, which is estimated to 10–15 US cents per kilowatt-hour (US₵/kWh) (Al-Salem et al., 2018), compared to solar energy, which has achieved 2.42 US₵/kWh at the Sweihan's solar plant (Giacomo, 2016). However, advances in material science and aerodynamics have enabled technology to evolve s through more reliable turbines that operate efficiently in low wind regimes (Masdar, n.d.; Li & Yu, 2017; Mathew et al., 2016).

Indeed, leading wind turbine manufacturers have directed their efforts to low (annual average wind speeds <7.5 m per second (ms^{-1})) and ultra-low (annual average wind speeds <6.5 ms^{-1}) wind-speed energy capture, to: (i) continue supporting the industry growth in regions previously classified as having less-energetic wind regimes (class 2: marginal average wind speed <6.4 ms^{-1}, and class 3: marginal average wind speed <7 ms^{-1}) (AWS Scientific, 1997); and (ii) restructure the planned energy consumption by combining the available energy sources (wind,

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https://doi.org/10.1016/j.esd.2024.101439
Received 29 November 2023; Received in revised form 13 February 2024; Accepted 21 March 2024
Available online 8 April 2024

solar, fossil fuels, etc.) (Wiser & Bolinger, 2012). The requirements for turbines to perform better under low and ultra-low wind speed spectra consist of: (i) lowering the cut-in (3–5 ms^{-1}) and rated (11–14 ms^{-1}) wind speeds, (ii) incorporating technological innovations in blade design (larger and slender blade of ~100 m diameter, and taller hub height of ~100 m and higher) and materials (carbon fibre) (Mathew et al., 2016; Wiser et al., 2012), and (iii) integrating a direct-drive permanent magnet synchronous generators that have lower weight, improved thermal performance, as well as higher efficiency and energy yield. The designed turbines considering this concept (Vestas: V116–2.0 MW, V120–2.0/2.2 MW, V136–3.3 MW; Goldwind: GW93/1500, GW115/2000, GW155–3.3 MW, GW168–6.45 MW; and Siemens: SG2.1–122) have become cost-effective and are being deployed in many countries, such as Chile (Comuna de Renaico, Araucania), China, Cyprus, India, Thailand, UAE, and the United States (US) (Masdar, n.d.; Flin, 2011; Goldwind, 2016; Hellberg & Snickare, 2011; Jianxiang, 2012; Tordesillas, 2012). However, although these substantial advances allow an optimal design of wind projects (turbines, connection to the grid, storage, etc.) to maximise the power output and balance fluctuations in power demand (Molly, 2011), transportation and logistics challenges still hamper their deployment (Adeyeye et al., 2022).

The process to develop wind power projects requires several considerations, regardless of its location (onshore or offshore). It generally starts with a site selection (or siting), which depends on the site-specific characteristics and environmental conditions. Wind resource, which is defined as the available amount of energy in wind, is one of the main factors to consider because the power carried in wind is proportional to the cube of its speed at any given moment. It varies with time of day, season, geographic location, local weather, elevation above the surface, and form of terrain. For onshore site selection, slope and elevation variables are also factors to consider, for example, steep slopes can adversely affect the resulting wind flow separation around the turbine blades (Hyvarinen, 2018; Lubitz & White, 2007), and an increase in altitude can lower air density and air temperature (Hyvarinen, 2018; Lubitz & White, 2007). To make a wind project feasible from a technical and financial standpoint, the potential sites should have, in addition to site-specific characteristics and environmental conditions, fewer obstacles, relatively easy access, proximity to power transmission lines, and regulatory compliance.

Offshore wind presents a significant opportunity to produce more energy compared to onshore wind (Enevoldsen & Jacobson, 2021). This technology makes economic sense as larger installations can be built near major coastal cities where the wind tends to blow even stronger and more uniformly (i.e. lower turbulence) than on land (Ellabban et al., 2014). However, despite recent substantial decline of offshore wind costs, it is still greater than onshore wind (Ellabban et al., 2014; Hevia-Koch & Klinge Jacobsen, 2019). Further, the offshore industry is an emerging sector that faces several issues related to (i) technical-financial constraints imposed by the site characteristics, i.e. water depth, remoteness from the shore, and seabed conditions, such as the limiting conditions for the foundation mounting and undersea cable (EEA, 2009; Higgins & Foley, 2014), and (ii) environmental-legal constraints imposed for the economic development, environmental-ecological protection, and social preferences, such as the exclusionary zones, i.e. shipping routes, oil and gas exploitations, touristic zones, aircraft navigation routes, preserved and heritage restriction areas, visual and aural impacts limits (Mahdy & Bahaj, 2018; Sourianos et al., 2017).

However, an optimal siting of wind farms can boost power production and minimise both total investment cost and the impact of the turbines on the environment (Pookpunt & Ongsakul, 2013). The commonly used approach for choosing a site is a trade-off between the renewable resources and the technological, financial, environmental, and legal factors (Chaouachi et al., 2016; Díaz et al., 2022; Gherboudj & Ghedira, 2016; Latinopoulos & Kechagia, 2015; Mahdy & Bahaj, 2018; Noorollahi et al., 2016; Shao et al., 2020). A Geographic Information System (GIS) approach can play a significant role as a decision support tool to identify and map suitable areas for hosting wind farms (von Krauland et al., 2021). It combines the relevant spatial parameters using multi-criteria decision-making (MCDM) analysis to score each area on a scale of 0 (least suitable) to 1 (most suitable) (Latinopoulos & Kechagia, 2015; Mahdy & Bahaj, 2018). Weighted linear combination and analytical hierarchy process are the most frequently applied MCDM methods respectively, for ranking and weighting the constraints to build suitability map. Alternative approaches to improve the decision-making process for sites identification include artificial intelligence-based methods, such as machine learning, deep learning, and neural networks (Asadi & Pourhossein, 2021; Petrov & Wessling, 2015; Sachit et al., 2022; Shahab & Singh, 2019; Sun et al., 2023). Even though these other approaches overcome the limitations of the MCDM (subjective weighting process), they are perceived as black-box models that rely on the availability of ground truth samples to be trained successfully (Chakraborty et al., 2021). The MCDM methods are both popular and practical at solving highly complex problems with multiple conflicting constraints to obtain an integrated decision-making result (Latinopoulos & Kechagia, 2015; Shao et al., 2020). But assessment of wind resources and generic site characteristics using advance techniques (weather forecasting models, remote sensing technique, and geospatial information system) is required at a high degree of accuracy and adequate spatiotemporal resolutions.

This study aims to assess the capability of the UAE to deploy onshore and offshore wind farms operating in low wind conditions (without identifying investment-grade locations) considering technical, financial, environmental, and legal constraints imposed by the site characteristics and infrastructure. A GIS-based multi criteria method can support the suitability mapping for wind energy development. Such mapping would provide policy makers and stakeholders insights on the country's wind potential to ensure the sustainable development of wind farms. To reach this goal, the following objectives are set: (1) present an overview of the constraints affecting the wind turbine siting and operation, (2) generate the suitability map measuring the aptitude of areas to host onshore and offshore wind projects using GIS-based MCDM analysis that combines the relevant geospatial parameters (wind resources, slope, elevation/bathymetry, distance to road/shore, and distance to power transmission lines), and (3) present analysis results.

Siting wind farm

An effective and multi-objective decision-making framework is necessary for identifying optimal locations for wind energy development. Such a framework will: (i) ensure an optimal production, lower socio-economic costs, reduced negative environmental impacts, and progress in targeted regions, and (ii) guarantee sustainable wind energy growth while preventing conflicts on land use and avoiding delays in approval and licensing processes. A managed wind farm growth will therefore require considering above mentioned factors that can be categorised under wind resources assessment, technical-financial constraints, and environment-legal constraints.

Wind resources assessment

Long-term hourly assessment of the wind resources at the area under examination is required, as this allows the initial selection of the most favourable sites for the siting of wind turbines. Usually, these sites are discerned by considering long-term annual average wind speed, preferably at altitudes comparable to the turbine's hub height, over at least a decade without worrying about variability (Mahdy & Bahaj, 2018). As a general rule, the optimal performance of the utility-scale wind turbines is assured when the annual wind speed exceeds a threshold of ~7 ms^{-1} (class 4 or greater) without reaching extreme values that would lead to the destruction of the turbine or prohibitive maintenance cost, and the plane of rotation of the turbine is perpendicular to the prevailing wind direction most of the time (Rodman & Meentemeyer, 2006). These conditions are mainly found on rounded hills, or on top of smooth mountain gaps that funnel wind, wide-open plains, and open waters (sea or freshwater) (Casper, 2007). Open waters are usually the most suitable locations for wind power development as wind resources are abundant, steadier, and blow more consistently than on land (Ellabban et al., 2014).

However, given the prospects for innovations that continuously improve the efficiency of turbines and reduce their cost of production, studies on wind power suitability are now considering average wind speed values as low as 5–6 ms^{-1} for onshore wind energy development (Baban & Parry, 2001; Bili & Vagiona, 2018; He & Kammen, 2016; Latinopoulos & Kechagia, 2015; Noorollahi et al., 2016) and 5.5–6 ms^{-1} for offshore wind energy development (He & Kammen, 2016; Sourianos et al., 2017; Vasileiou et al., 2016; Waewsak et al., 2015). Essentially turbine technology has substantially evolved to allow sites with lower wind resources to become economically viable for utility-scale applications through innovative design involving oversized rotors, which have higher aerodynamic efficiency and taller towers that raise the rotor above the air turbulences often created by obstacles (hills, buildings, and trees) (DOE, 2015; Mathew et al., 2016; Wichser & Klink, 2008). Currently, commercial large-scale wind turbines directed at low wind markets require an annual average wind speed ranging from ~5.5–6.5 ms^{-1} onshore and ~ 6.5 ms^{-1} offshore. But, onshore wind turbines could be designed for regions with annual winds as low as ~5–5.2 ms^{-1}, such as found at Long Ganhu wind farm (Vestas: V100–1.8 MW) and Zhangbei wind power test (Goldwind: GW115/2000), Hubei province, China. There could be a similar opportunity for offshore wind development in the future, especially for deep-water and low-wind-speed offshore turbines that could have a significant positive impact on the global energy transition (Langer et al., 2022).

Several techniques exist to estimate winds over an area being considered for a wind farm: (i) in-situ measurements from nearby weather stations (e.g. anemometers), which have a high temporal resolution (~few minutes) but are very limited in space to adequately represent the spatial variability, (ii) satellite-based measurements (SSMI: Special Sensor Microwave Imager, QuikSCAT: Quick Scatterometer satellite, TMI: TRMM Microwave Imager, and ERS-2: European Remote Sensing satellite 2), which only cover large water bodies but at a low spatial (ranging from few hundred meters to few kilometres) and temporal (~few hours to daily) resolutions, and (iii) mesoscale numerical weather prediction (NWP) models data, which cover large areas (land and water) at reasonable temporal resolution (i.e. hourly) but at low spatial resolution (~few kilometres) due to limited computational resources. However, large-scale mesoscale NWP model data are usually downscaled to a finer-scale using statistical post-processing techniques, such as microscale diagnostic model (MDM), quantile regression (QR), multinomial logistic regression (MnLR), and Bayesian model averaging (BMA) (Mendoza et al., 2015). For instance, the non-linear microscale diagnostic model has been applied to develop the UAE wind atlas of 500 m × 500 m spatial resolution and 1-h interval temporal resolution from 2002 to 2012 (Renewable Energy Assessment and Forecasting (3TIER), n.d.; UAE Wind Atlas, n.d.). This advanced model uses high-resolution land surface data to calculate the effects of microscale terrain features (hills, coastline, inland, etc.), near-surface roughness features, and other terrain blocking effects left unresolved by coarser mesoscale NWP model. Efficient use of the downscaled data will fulfil the requirements of several specific studies, including renewable energy resource assessment.

Technical and financial constraints

The total investment cost for siting a typical wind farm is shared mainly between the turbine (rotor, blades, generator, power converter, nacelle, tower and transformer), foundation, grid connection, and installation.

The total cost for siting an onshore wind farm is dominated by the turbine's share (~74–82 %) against a minor share for the remaining components (EEA, 2009). Specifically, the foundation accounts for ~1–6 % of the total costs as the turbines are generally constructed on land with (i) a slope lower than ~15 % because of the difficulty associated with building on steep slopes (Noorollahi et al., 2016; Satkin et al., 2014) and (ii) elevation lower than 2000 m because of the negative impact of the higher altitude on the turbines' output due to the decrease of the air density and air temperature (Noorollahi et al., 2016; Satkin et al., 2014). The grid connection accounts for ~2–9 % of the total costs as turbines are generally installed not very far from the power transmission lines within a distance ranging between 0.25 km (km) to 10 km (Baban & Parry, 2001; Noorollahi et al., 2016; Satkin et al., 2014). Finally, the installation accounts for ~1–9 % since the farms are generally built near highways and roads for easy access and transportation (around 0.25 km to 10 km) (Baban & Parry, 2001; Satkin et al., 2014).

The costs involved for offshore wind farms are much greater than for onshore farms for all components. Generally, offshore turbines are ~20 % more expensive than onshore turbines, while the foundation, grid connection, and installation costs are >2.5 times the price of onshore projects. Specifically, the offshore turbine's share of the total cost accounts for 30–50 %, while foundation, grid connection, and installation account respectively for ~15–25 %, 15–30 %, and 0–30 % (EEA, 2009). The foundation and grid connection costs depend on the water body characteristics, namely bathymetry and distance to the shore (but still within the country's exclusive economic zone (EEZ)) (Higgins & Foley, 2014). Cost estimations are usually provided for different offshore areas according to water depth for the foundations technology (0–30 m for monopiles, 25–50 m for multi-leg, and >50 m for floating) and distance to the shore (areas <10 km from the coast, areas 10–30 km away from the coast, areas 30–50 km away from the coast, and areas >50 km away from the coast) the latter is also related to social preferences (see Section 2.3) (EEA, 2009; EWEA, 2013; Higgins & Foley, 2014). These costs increase as the wind farm site moves: (i) into deep water, where it may increase from 1800 EUR/kW in areas of 10–20 m in depth to 2514 EUR/kW in areas of 40–50 m in depth, and (ii) far from coastline where it may increase from 1800 EUR/kW at 0–10 km distance to shore to 2131 EUR/kW at 50–100 km away from the coast (EEA, 2009). Although research is involved with developing innovative, cost-effective floating offshore wind platforms (spar-buoy, tension leg platform, and semi-submersible) for use in deep waters, the areas with a water depth of <60 m and distance to shore of fewer than 200 km remain the best locations for installing offshore wind farms as they generally allow low costs of construction (transmission line for grid interconnect), operations, and maintenance (Adedipe et al., 2016; Chaouachi et al., 2016; Higgins & Foley, 2014).

Legal and environmental constraints

Large-scale onshore and offshore wind energy developments can occur within the country's mainland and the EEZ (i.e. the area beyond and adjacent to a given country's territorial seas that extends no >200 nautical miles from the coastline). However, the exploration and exploitation of wind resources are generally restricted by governmental laws and regulations that ensure economic development, environmental and ecological protections, and social preferences. These restricting regulations are designed to: (i) protect exclusionary zones, such as preserved areas, animal habitats conservation, archaeological and cultural sites, touristic zones, shipping routes, military, oil and gas exploitation, aircraft navigation routes, dredged channels, and waste disposal, where a buffer zone is generally considered for each sector (Baban & Parry, 2001; Latinopoulos & Kechagia, 2015; Noorollahi et al., 2016) (Table 1), and (ii) accommodate visual and aural impacts, which decrease with distance and contrast (Bishop & Miller, 2007). Indeed, because of the aforementioned legal limitations, wind turbines in the UAE are generally restricted to farms, deserts, and offshore areas (water

Table 1
Description of the considered datasets with the upper and lower bounds to define the suitable/unsuitable areas for onshore and offshore wind energy development.

Constraints	Variables	Thresholds to define suitable areas			Source	Resolution
		Units	Onshore	Offshore		
Wind resources	Wind speed at 120 m heights	ms^{-1}	5.2≥	5.5≥	Khalifa Univ.	500 m
Technical/Financial	Elevation/bathymetry	km	2 <	0.05–0.6	ADSDI/ NOAA	30 m
	Slope	%	15<	–		
	Distance to the ssroad/shoreline	km	0.25–10	2–200	OSM	–
	Distance to the electrical grid	km	0.25–10	–		
Environmental/Legal	Residential areas	km	2>	–	UNEP	–
	Airports/military	km	2.5>	–		
	Environmental/ecological sites	km	1>	–		
	Cultural/historical Archaeological sites	km	1>	–		
	rotected areas (land and marine)	km	2	2		

depth and distance to shore in the ranges of 5–60 m and ~23–200 km, respectively) (Adedipe et al., 2016; Casper, 2007; Chaouachi et al., 2016; Higgins & Foley, 2014; Mahdy & Bahaj, 2018; Sourianos et al., 2017) thereby making it is possible to mitigate the impacts on human health (visual blurring, headache, dizziness, nausea, fast heart rate, sleep disturbance, and depression), landscape, and benthic ecology (Mee, 2006). But, although large modern wind turbines are better perceived by observers than numerous smaller turbines because of the large spacing between the individual turbines and lower rotational speeds of the blades, all wind farms should be included as a new function of the land and sea, and integrated into the spatial planning policies to increase wind energy development.

Study site and dataset description

Study site description

The UAE is in the southeastern part of the Arabian Peninsula where its land area covers ~83,600 km^2, and consists of abrupt topography, including inland desert areas, coastal areas facing the Arabian (also known as the Persian) Gulf, and mountainous areas facing Gulf of Oman. The country has an arid climate characterised by low rainfall, high temperatures and humidity, and frequent dust storms (Beegum et al., 2018). The country's exclusive economic zone (EEZ) covers ~58,218 km^2, spans over 1318 km of coastlines (~800 km on the southern shore of the Arabian/Persian Gulf, and 90 km on the shore of the Gulf of Oman) and extends to a depth of no >50 m in the Arabian Gulf and 1000 m in the Gulf of Oman (Fig. 1). The main land and the Arabian/Persian gulf is exposed to an extra-tropical weather system (Richter & Abuhilal, 2006), where the monsoon circulation produces a northerly and north-westerly wind (Shamal; 'north' in Arabic) that blows continuously but low (average of ~3 ms-1) during summer (summer Shamal) and

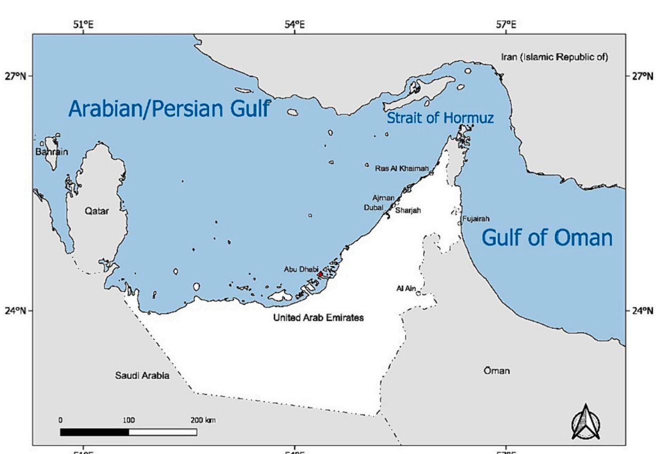

Fig. 1. The United Arab Emirates (UAE) location map.

intermittently but stronger (average of ~5 ms^{-1} and may reach 10 ms^{-1}) during winter (winter Shamal) (Kämpf & Sadrinasab, 2006). The Gulf of Oman is situated at the northern edge of the tropical weather system in the Arabian Sea and the Indian Ocean, where the monsoon circulation produces southerly winds in summer and strong northerly winds in winter (Rezai et al., 2008; Richter & Abuhilal, 2006).

Dataset description

Given the importance of wind data in identifying potential areas for implementing a wind energy system in the UAE, this study has considered high-resolution long-term annual average wind speed at 120 m height (WS_{120m}). The theory for using 120 m height follows the anticipated typical hub height of ~115 m for onshore wind projects and 125 m for offshore wind projects by 2030 (Beiter et al., 2022; Wiser et al., 2016).

The long-term annual average wind speed is calculated based on the high-resolution hourly wind data between 2002 and 2012 at a spatial resolution of ~500 m (UAE Wind Atlas, n.d.). These estimates were calculated using the mesoscale Weather Research and Forecasting (WRF) model and calibrated using advanced ensemble statistical post-processing approach (UAE Wind Atlas, n.d.). This later approach uses the available observations from the National Center of Meteorology and Seismology (NCMS), Abu Dhabi, UAE, to correct the systematic errors of the WRF model and account for the country's unique local environment (NCMS, n.d.).

Additional supporting information describing the site characteristics, infrastructure, and environmental conditions has been taken into account to refine the identification of suitable locations for wind project development (Table 1). This information includes: (i) a digital elevation model (DEM) at 30 m resolution from Abu Dhabi Spatial Data Infrastructure (AD-SDI, n.d.), which shows a general low elevation that increases in the mountains of the eastern region (~1900 m); (ii) a bathymetry vector of the seas from National Oceanographic and Atmospheric Administration (NOAA) (NOAA, n.d.), finds that the Arabian Gulf is shallow along the coastline of the UAE (up to 50 m water depth) and both broader and deeper in the Gulf of Oman (up to 1000 m in depth); (iii) roads and power transmission line networks from OpenStreetMap (OpenStreetMap, n.d.), showing that they are concentrated around the main cities; (iv) geographical exclusionary zones vectors (W. and I. UNEP, 2019), which comprises of populated areas (residential, commercial, industrial, military, touristic, etc.), environmental zones (protected and recreative), and heritage sites (archaeological and cultural); and (v) maritime EEZ boundaries from the Flanders maritime Institute (Flanders maritime Institute, n.d.).

Methodology

This study used a GIS-based multi-criteria decision-making analysis that was undertaken in multiple steps as follows (Fig. 2),

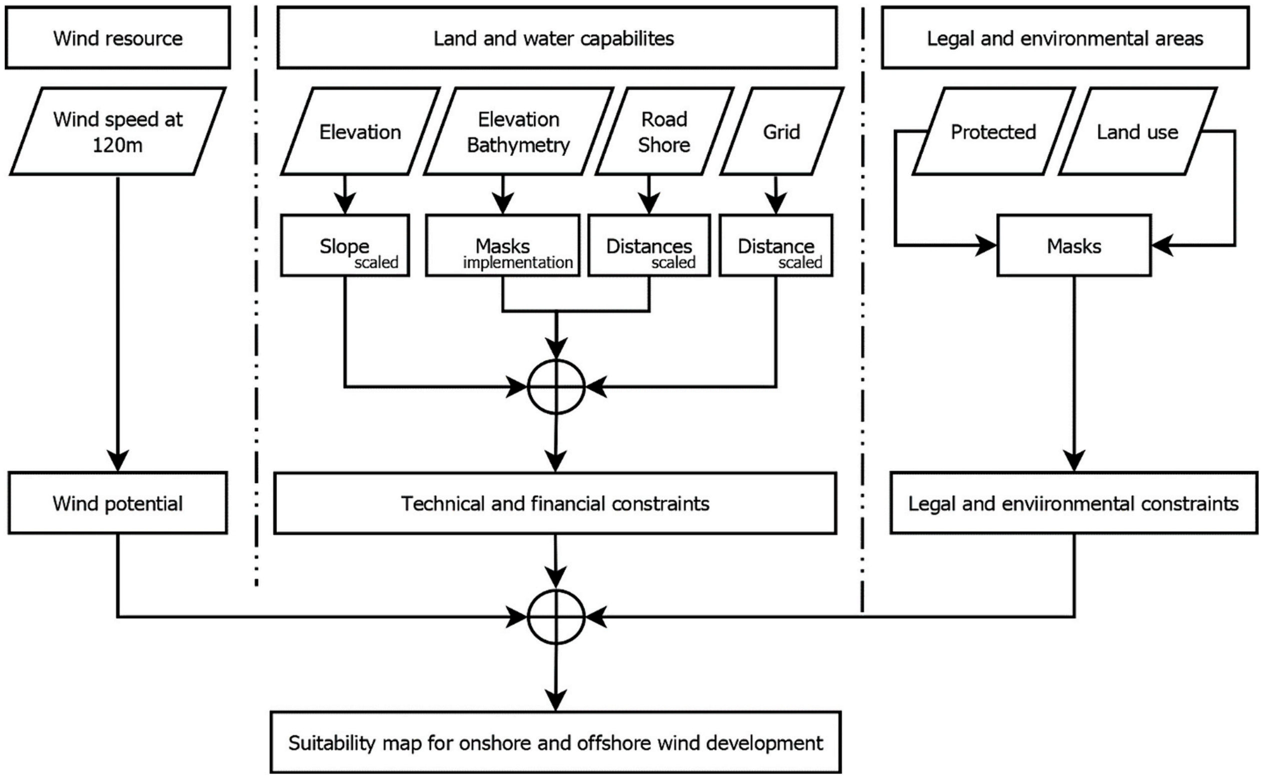

Fig. 2. The methodology flowchart for the suitability mapping of the onshore and offshore wind power plant in the UAE.

1. Identification of the **potential areas for wind energy applications** based on the long-term annual average wind speed at 120 m height,
2. Identification of the technical and financial restriction map **according to the factors characterising the sites and infrastructure**, such as slope, elevation/bathymetry, distance-to-road/distance-to-shore, and distance to the power transmission lines,
3. Identification of the **environmental and legal restriction map** resulting from the overlaying of the protected areas with the land use map (residential areas and military areas), and
4. Finally, the aggregation of the outcome from steps 1, 2, and 3 to generate a **suitability map** for onshore and offshore wind energy development in the UAE.

Wind potential map

The annual average wind speed over the UAE, as displayed in Fig. 3-a1, ranges mainly between 0.9 ms^{-1} and 6.5 ms^{-1} onshore and between 2.27 ms^{-1} and 6.1 ms^{-1} offshore, which confirms the low wind potential (Janajreh et al., 2013; Zafar & Gadalla, 2013). The figure also shows that the wind speed is higher in the western region, where it ranges between 6 ms^{-1} and 6.5 ms^{-1} onshore and 5.5 ms^{-1} and 6.1 ms^{-1} offshore, but gradually decreases toward the eastern part, the exception being over the mountainous region, where it reaches ~9.1 ms^{-1}. According to previous studies considering model-derived and ground data (Gherboudj & Ghedira, 2016; Naizghi & Ouarda, 2017), the wind speeds values and variation are high during spring and summer monsoons, and low during autumn and winter monsoons.

In this study, we have considered lower threshold values to identify the potential areas for low wind energy development – 5.2 ms^{-1} for onshore areas and 5.5 ms^{-1} for offshore areas, a common practice in other studies that expect further technological progress (Baban & Parry, 2001; Bili & Vagiona, 2018; He & Kammen, 2016; Latinopoulos & Kechagia, 2015; Noorollahi et al., 2016; Sourianos et al., 2017; Vasileiou et al., 2016; Waewsak et al., 2015). Therefore, locations (onshore/

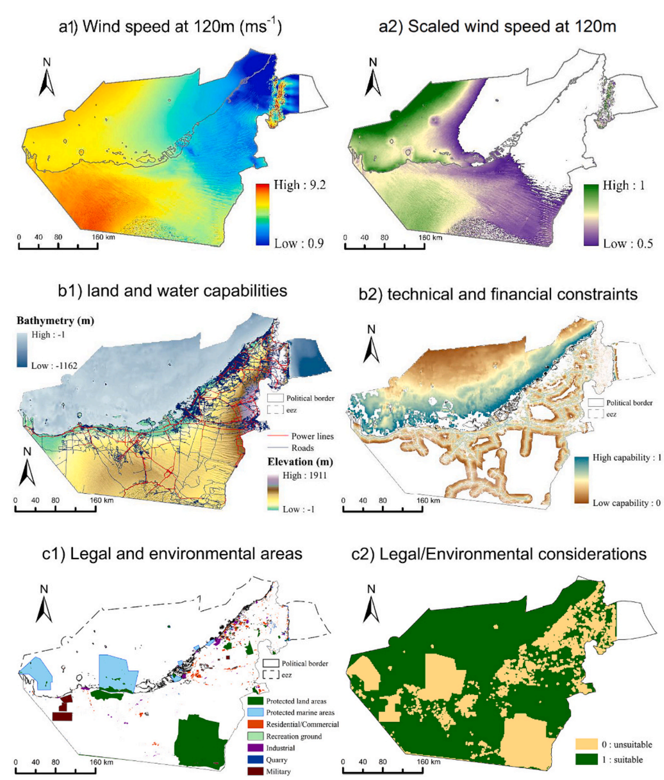

Fig. 3. The UAE wind resource, site characteristics, and infrastructure with the associated scored maps: (a1) long-term annual average wind speed, a2) scaled wind speed between 0 and 1, b1) site characteristics and infrastructure, b2) technical and financial constraints, c1) environmental and legal areas, and c2) environmental and legal constraints.

offshore) with an annual average speed: (i) <5.2/5.5 ms^{-1} (unsuitable areas) are set to zero, (ii) ranging between 5.2/5.5 ms^{-1} and 8 ms^{-1} (suitable areas) are scaled between 0.5 and 1, and (iii) >8 ms^{-1} are given the maximum boundary value of 1. The best locations are still those with higher wind speed values, mainly in the western areas and over the mountains (Fig. 3-a2).

Technical and financial restriction map

The technical and financial restriction map for onshore and offshore wind projects is generated by combining the following site characteristics and infrastructure constraints maps:

- The **slope constraint mask**, derived from the digital elevation model (DEM) at 30 m resolution (Fig. 3-b1). Several studies have demonstrated that land with a <15 % slope is required to implement onshore wind facilities (Table 1). Therefore, the locations with a slope greater or equal to 15 % were set as unsuitable with a value of 0, and all the other locations were selected as suitable with a value of 1.
- The **elevation and bathymetry constraint map**, derived from the DEM and bathymetry data (Fig. 3-b1), respectively. The implementation of onshore wind facilities requires areas with an elevation of <2000 m, while the implementation of offshore wind facilities requires areas with bathymetry values ranging between 5 m and 60 m (Table 1). Therefore, the onshore locations with an elevation greater or equal to 2000 m were set as unsuitable with a value of 0. All the other locations were selected as suitable with a value of 1. In contrast, offshore locations with bathymetry >60 m and below 5 m were set as unsuitable with a value of 0. All other areas were set as suitable and scaled between 0 and 1.
- The **roads and shoreline accessibility map,** extracted from the road and shoreline vectors (Fig. 3-b1) using the calculated Euclidian distance. These vectors generated continuous grid surfaces where each pixel value represents the distance to the nearest roads and shoreline. The implementation of onshore wind facilities requires locations with distance to the road ranging between 0.25 km and 10 km, while the implementation of offshore wind facilities requires locations with distance to the shore ranging between 2 km and 200 km (Table 1). Therefore, the onshore (offshore) locations with a distance to the roads (shore) below 0.25 km (2 km) and greater or equal to 10 km (200 km) were set as unsuitable with a value of 0. Otherwise, all the other locations were set as suitable and scaled between 0 and 1.
- The **transmission lines capability map**, extracted from the transmission lines vector (Fig. 3-b1) using the calculated Euclidian distance. As for the road vector, locations with a distance to transmission lines greater or equal to 10 km and below 0.25 km (far enough from the turbines) were set as unsuitable with a value of 0, and all the other locations were set as suitable and scaled between 0 and 1 (Table 1).

A weighted linear combination approach, in which equal weights are assigned to each criterion and weighted average is obtained by multiplying the weight assigned by the scaled value for that criterion and summing the products over all criteria, was applied. This approach combines the road accessibility map with the transmission lines capability map for the onshore areas, and the bathymetry constraint map with the shoreline accessibility map for offshore areas. The resulting map was multiplied by slope and elevation masks to exclude the restricted regions (Fig. 3-b2). The final locations with high scores have high capability levels, while areas with low scores have low capability levels for onshore and offshore wind systems.

Environmental and legal restriction map

A restriction mask (1: outside restricted areas, 0: within restricted areas) that remove regulatory areas (protected, recreative, residential, commercial, industrial, military, touristic, etc.) deemed not suitable for wind project developments because of environmental and societal impacts were derived from the ancillary datasets presented in Fig. 3-c1. As these restricted areas are designated for public safety or the protection of the environment, a buffer has been imposed to expand further the restricted regions (Table 1; Fig. 3-c2). Such measures further refined the potential locations considerably.

Suitability map

The suitability map for onshore and offshore wind energy development is generated by combining the scaled wind potential map (Fig. 3-a2) with the technical and financial restriction map (Fig. 3-b2) using the weighted linear combination approach. A weight of 50 % was considered for the scaled wind potential map, as a weight of 50 % was already considered to generate the technical and financial restriction map for onshore (equal weights of 25 % for road accessibility map with power transmission lines) and offshore (equal weights of 25 % for bathymetry with distance to shore) areas. The environmental and legal restriction mask (Fig. 3-c2) was overlaid on the resulting map to exclude the restricted areas (land and marine protected areas, residential, military, recreation, etc.) with a value of 0. Finally, the obtained map was scaled between 0 and 1, where a value of 1 is given to pixels with high wind resource and fair site capability (onshore: acceptable slope, and proximity to road and transmission lines; offshore: proximity to shore and acceptable water depth) and a value of 0 was given to pixels with low wind resources level and poor site capability. The generated map has a spatial resolution of 500 m, considered a high resolution for the siting of large wind farm systems.

Results and discussions

Fig. 4 represents the spatial distribution of the capability of the sites (suitability index) to host onshore and offshore wind facilities operating in low wind regimes in the UAE. This map was obtained by combining the high-resolution wind resource data with technical, financial, environmental, and legal constraints. Suitable areas that have a suitability index closer to 1 (green), and unsuitable areas have suitability index of 0 (blank/white).

Overall, the country has low wind potential. Areas with low suitability indices (<0.5) are not considered and represent ~89 % of the UAE's total land mass (Table 2). These areas are located in the eastern and southwestern parts of the country where the wind resource or

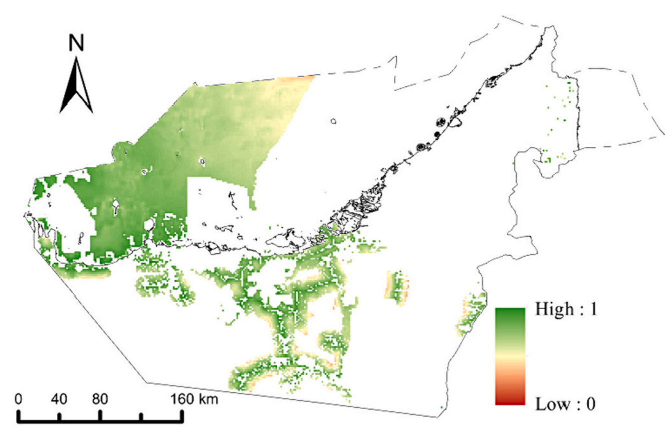

Fig. 4. The UAE suitability map for onshore and offshore wind energy development.

Table 2
Suitable and unsuitable areas for onshore and offshore wind energy development in the UAE.

Classes	Suitability Indices	Percentage areas (%)	
		Onshore	Offshore
High suitable	> 0.7	6.9	16.9
Moderate suitable	0.5–0.7	4.3	14.4
Less suitable	< 0.5	0.6	0.7
Unsuitable	0	88.2	68

accessibility to roads and power transmission lines networks are limited. The areas with moderate and high land suitability indices (>0.5), are concentrated in the central and northwestern regions of the country along the road and power transmission lines and spread intermittently in the eastern part facing the Gulf of Oman, where they represent ~11.2 % of the UAE's total land area. The results are in accordance with previous studies (Schult et al., 2023; Yagoub, 2010) and the government's efforts to exploit advances in wind turbine technology and the country's unique weather phenomenon that generates high winds at night to capture low wind speeds at utility scale. Late 2023, the government commissioned the 103.5 MW landmark wind project, which covers four sites located in Sir Bani Yas Island (45 MW; land suitability index of ~0.7), Delma Island (27 MW; land suitability index of ~0.7), Al Sila (27 MW; land suitability index of ~0.6), and Al Halah (4.5 MW; land suitability index of ~0.7), for powering >23,000 homes a year and reduce 120,000 t of carbon dioxide (i.e. equivalent of taking 26,000 cars off the road a year) (Masdar, n.d.; Asaba, 2023). A project under development is the 28 MW wind project in the western region near Hatta (land suitability index of ~0.8) (Energy and Utility, 2021).

Furthermore, this study suggests a maximum installable capacity of approximately 468 MW (234 MW, 702 MW, and 936 MW) for onshore wind farms assuming (i) an average installation density of 5 MW/km^2, depending on site conditions, local laws and technology (Eurek et al., 2017; Paul et al., 2009); and (ii) a conservative land utilisation factor of 1 % (0.5 %, 1.5 %, and 2 %) to limit the full utilisation of a land area for renewable development and allow other activities, including agriculture, mining, etc. A previous study has estimated a maximum installed capacity of 80 GW (Schult et al., 2023). But this estimation considers future extension and reinforcement of the road and transmission networks, which were not considered in the study.

Actually, the UAE seems to have better offshore wind potential. Areas with low suitability indices (<0.5) are located mainly in the eastern part of the EEZ, where the wind resource is low and represents ~68.7 % of the UAE's EEZ (Table 2). Areas with moderate suitability indices (0.5> and <0.7) are located at the central part of the EEZ and represent 14.4 % of the UAE's total EEZ (Table 2), while areas with high suitability indices (>0.7) are concentrated in the north-western part and represent 16.9 % from the country's EEZ (Table 2). A previous study concluded that the most appropriate potential locations for the offshore wind farms are located on the north-western coastal shores of the Emirate of Abu Dhabi (Dol et al., 2021; Yagoub, 2010). Other studies have reported that the offshore wind energy in the UAE is low for economic large-scale power production because of low wind speed and high technology costs (Al-Salem et al., 2018; Schult et al., 2023). But these studies didn't account for technology improvement opportunities for low wind speed turbines in their approaches. A continuous improvement in offshore wind turbines would further drive down costs and could lead to the deployment of the first offshore wind projects in the UAE.

This finding also suggests that the associated offshore wind development potential across the country EEZ is estimated at ~1330 MW (665 MW, 1995 MW, 2660 MW), assuming an average installation density of 7.3 MW/km^2 (Enevoldsen & Jacobson, 2021) and a conservative area utilisation factor of 1 % (0.5 %, 1.5 %, and 2 %) to limit the full utilisation of EEZ for wind development and allow future area plan build-out. But these results would need careful review before selecting a location for offshore wind project development to comply with local regulations on marine resources use, including marine life protection, navigation, fishing industry, and protection areas.

Conclusion

In this study, the mapping of the capability of a site to host an onshore or offshore low wind speed project in the UAE was conducted using the multi-criteria decision-making analysis. The methodology used is a trade-off between: (i) a high-resolution long-term annual average wind resource map at 120 m height and spatial resolution of 500 m, (ii) technical and financial constraints imposed by the site characteristics parameters (slope, elevation, and bathymetry) and the country's infrastructure (roads and power transmission line networks), and (iii) legal, environmental constraints (residential, commercial, industrial, military, touristic, protected, recreative, and heritage sites). Such considerations would significantly minimise the project's short- and long-term costs. The results show that the UAE has a lower onshore wind potential than offshore wind. Areas with moderate and high suitability indices (>0.4) are concentrated in: (i) the central and northwestern parts of the country's land along the road and transmission lines networks and the eastern region facing the Gulf of Oman, where they represent ~11 % of the UAE's total land, and (ii) central and western parts of the EEZ, specifically coastal shores of the Emirate of Abu Dhabi, where they represent ~32 % of the UAE total EEZ.

The results also suggest that the estimated onshore wind potential, assuming an average installation density of 5 MW/km^2, ranges between ~234 MW and ~ 936 MW when the land utilisation factor ranges between 0.5 % and 2 %. Whereas the estimated offshore wind potential assuming an average installation density of 7.3 MW/km^2, ranges between ~665 MW and ~ 2660 MW when the utilisation factor of the EEZ ranges between 0.5 % and 2 %. This estimate is in accordance with the government's efforts to further diversify the country's energy mix, which includes solar, nuclear, and waste-to-energy plants. Indeed, the country is developing a 28 MW wind project in the western region near Hatta and has commissioned the 103.5 MW landmark wind project in 2023 at four sites (45 MW in Sir Bani Yas Island, 27 MW in Delma Island, 27 MW in Al Sila, and 4.5 MW in Al Halah). This landmark wind project marks the first time that the UAE has added utility-scale wind power to its energy mix. Such a project was not viable before due to low wind speeds. But technological advancement of turbines, lower costs, and the understanding of a unique weather phenomenon that generates high winds at night, have paved the way to introduce economically viable large-scale wind power projects to the UAE's electricity grid.

Declaration of competing interest

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

Acknowledgements

This study was conducted at Khalifa University of Science and Technology. The authors thank Abu-Dhabi Spatial Data Infrastructure (AD-SDI), the National Oceanographic and Atmospheric Administration (NOAA), OpenStreetMap, and Flanders Maritime Institute for providing the data. We want to thank Dr. Stephanie Clarke for proofreading the manuscript and Sibghat Ullah for his support.

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