

Wind resource assessment and site selection of offshore wind farms in the state of Kuwait

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ABSTRACT

Among several countries, Kuwait has made significant progress in transitioning to renewable energy. As a result, the onshore Shagaya renewable energy park was deployed in 2017 with a total capacity of 70 MW. To effectively progress in the development of offshore renewable energy, it is important to conduct a thorough assessment of wind resources. This paper thoroughly examines and identifies the optimal potential geographical locations for offshore wind farm deployment in Kuwait for the first time. In the initial phase, a number of offshore exclusion criteria were established and analyzed, including wind speed, water depth, exclusive economic zone, marine protected areas, subsea cable distribution, mine locations, annual dust deposition, and shipping traffic density. The second phase included the site selection process, during which the ArcGIS-ArcMap package was utilized to exclude pre-defined exclusion criteria. The results indicate that the highest wind speed ranges from 7.5 m/s to 8 m/s, covering a total offshore area of 1234.55 km². In addition, the offshore areas in Kuwait are generally shallow and have water depths ranging from 0 to 20 m, covering a total area of 7458.13 km² in the north. The three optimal offshore wind sites identified in Kuwait are Sabiya Power Station wind farm (Long. 48.3091, Lat. 29.5925), Port of Doha wind farm (Long. 47.9702, Lat. 29.5103) and Camp Arifjan wind farm (Long. 48.236, Lat. 28.9429).

KEYWORDS

Wind resource; wind site selection; offshore wind energy; exclusion criteria; wind speed analysis

Introduction

Fossil fuels have been identified as a significant contributor to climate change due to the high release of CO₂ into the atmosphere. Conversely, renewable energy sources such as solar and wind produce electricity without releasing harmful gases, effectively reducing the impact of climate change and its consequential damages. In addition, the dependence on fossil fuels for electricity generation exposes countries to price fluctuations, which can result in geopolitical instability. However, diversifying energy sources can improve energy independence and security. As a result, businesses and governments on a global scale widely recognize the significance and pressing need for transitioning to renewable energy. The collective recognition of the importance of renewable energy has led to increased investments and reduced costs of technologies. Moreover, supportive policies, in many countries, have been implemented to facilitate a smooth transition to renewable energy sources.

Kuwait is among several countries that have taken significant measures toward transitioning to renewable energy. This transition is a crucial aspect of Kuwait Vision 2035, which emphasizes the need to diversify energy sources for economic growth, including the incorporation of wind energy. As

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Table 1. Phases and technologies adopted for shagaya renewable energy park (Steensma et al. 2019.).

Attribute	Phase-1	Phase-2 (Al- Dibdibah project)	Phase-3
Technology	CSP, Wind & PV	PV	TBD
Power/Energy	50 MWe (CSP), 10 MWe (wind), 10 MWe (PV)	3,150 GWh/y	Up to 3.20 GWe

a result, Kuwait has successfully established the Shagaya renewable energy park, the nation's first renewable energy site developed by Kuwait Institute for Scientific Research (KISR). The Phase I of the onshore energy Shagaya park included the installation of a 10 MW Photovoltaic (PV) plant commissioned in May 2017, a 10 MW wind farm deployed in July 2017 and a 50 MW Concentrated Solar Power (CSP) plant commissioned in February 2019. By 2030, it is expected that the Shagaya renewable energy park will be expanded through Phase II and III, occupying 84 km² with a capacity of 3.2 GW, see [Table 1](#).

The status of wind energy in Kuwait reveals that the only operational wind farm is the onshore Shagaya wind farm, which has a capacity of 10 MW and employs 5 × 2 MW Gamesa G97 wind turbines with a hub height of 79 m and a blade length of 47 m. This particular wind farm is situated in the desert at coordinates 29°11'56.2"N 47°02'47.3"E.

The State of Kuwait is known for its desert-like environment, which is characterized by low and unpredictable rainfall and a dry hot climate. Kuwait experiences high temperatures during summer (May–September), reaching above 45°C, and relatively short winters (November–March) with average temperature of approximately 20°C (Steensma et al. 2019). Dust as well as sand storms are frequent extreme weather events in Kuwait, occurring frequently and with high severity at the Shagaya farm. Al-Dousari et al. (2019) reported that the average annual deposition rates of dust at the desert where the Shagaya farm is located is 339 tons/km². Al-Dousari et al. (2014) demonstrated that, when compared to coastal areas, the western areas experience a higher amount of deposited dust, see [Figure 1](#). Z₁ is the location of Shagaya Renewable Energy, which has a high potential for exposure to dust storms. In contrast, Z₂, Z₃, and Z₄ are identified as optimal locations for the offshore wind farm in this study, as will be discussed in the following sections. The impact of dust storms on zones Z₂ to Z₄ is minimal.

The capacity factor of the wind farm in the Shagaya renewable energy park would be significantly affected by dust and sandstorms. Al-Khayat et al. (2021) stated that dust accumulation contributed to 0.31% and 1.45% of energy losses per turbine in the first and second years of operation in the Shagaya Wind Farm in Kuwait. Despite cleaning exercises conducted to mitigate production losses, the cumulative effects of dust accumulation as seen in this case study can have long-term significant effects on the annual energy production of onshore wind farms in this terrain, which is consistent with findings from a similar study (Ramanan et al. 2022). Offshore wind energy is gaining significant attention in the renewable energy sector due to various valid reasons. One of these reasons is the consistent and abundant wind resources, which greatly enhance power generation. Furthermore, offshore wind turbines are less affected by harsh desert environments, resulting in a longer life cycle. In general, the marine environment tends to have lower levels of particulate matter compared to desert or land environments. Moreover, offshore wind energy provides greater flexibility for wind farm expansion (Klinge Jacobsen, Hevia-Koch, and Wolter 2019). Kuwait has planned to invest in renewable energy by 2035, aiming to meet 15% of their energy demands from renewable sources (Steensma et al. 2019). This in turn, requires a significant expansion and seamless transition to renewable energy, with a particular focus on wind energy, specifically offshore wind energy.

Aim and objective of the study

This study aims to analyze and examine the optimal locations for deploying offshore wind farms in Kuwait. This goal was achieved through two primary phases. During the first phase, multiple exclusion criteria were defined and thoroughly analyzed including (i) wind speed, (ii) water depth, (iii) exclusive economic zone, (iv) marine protected zones, (v) subsea cables distribution (vi) mine areas, (vii) Annual deposited dust and (viii) shipping density. Phase-2 involves the site selection process, where all exclusion criteria are combined

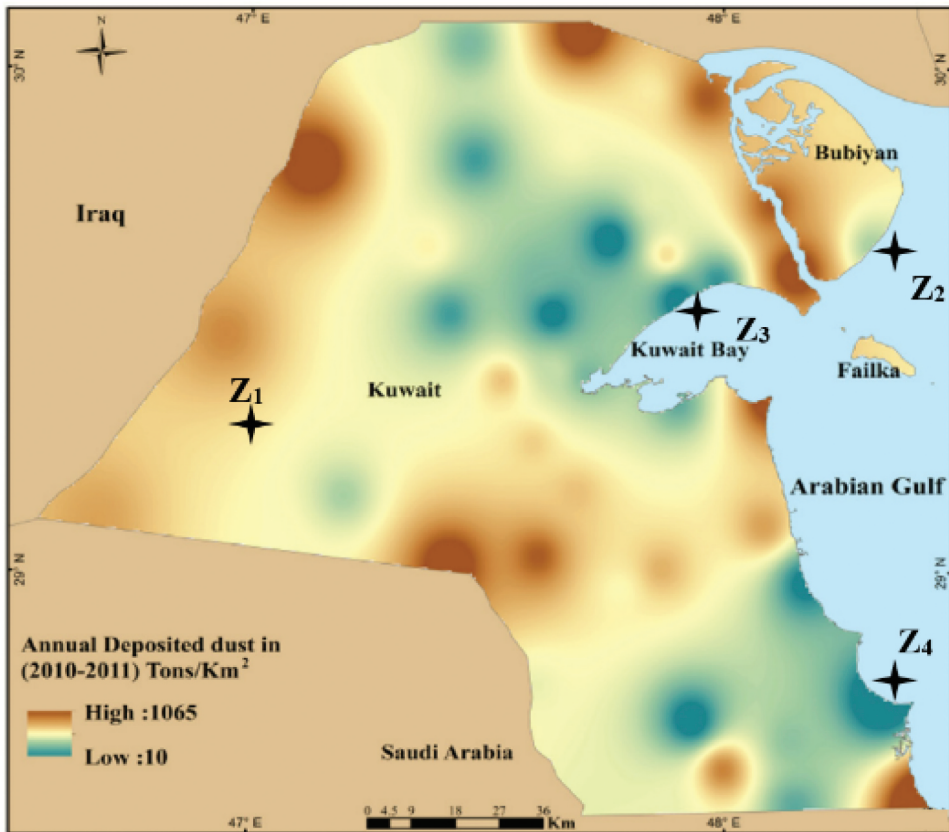


Figure 1. Annual deposited dust in Kuwait (Al-Dousari et al. 2019).

to identify potential optimal offshore wind sites in Kuwait. Detailed wind resource assessment will be carried out using ArcGis-ArcMap package. It is worth to mention that phase-3, which is not within the scope of this paper but will be covered in future publications, will focus on providing a detailed wind analysis of the selected offshore wind farms obtained from phase-1 and phase-2, as well as the design, modeling, and optimization of the potential offshore wind farms using WAsP and WindPro packages.

Importance and benefit of the study

To successfully transition toward offshore renewable energy, the first crucial step is to conduct a comprehensive wind resources assessment. The initial step within this assessment is to evaluate the geographical potential. This assessment will help in identifying the most suitable locations for wind farms, ensuring maximum potential power generation. However, wind speed is not the sole factor in this assessment, as there are several other criteria that need to be taken into consideration, as discussed earlier. Choosing inappropriate locations for wind farms can have significant consequences, impacting both the environment and the economic feasibility of the project due to the subsequent increase in the capital and operational costs. Therefore, this study analyses various exclusion criteria to select the most appropriate offshore wind farm locations in Kuwait. Although this study focuses on Kuwait, generally speaking, the methodology and advanced analysis approach implemented can potentially be applied by other countries that share similar climate and geographical conditions. Moreover, the summary of previous studies and the methodology used in this study can be highly beneficial to decision makers, developers and researchers.

This study makes a meaningful contribution by offering comprehensive data, a systematic methodology, and advanced analysis for selecting offshore wind farm locations in Kuwait. It identifies the most suitable sites to facilitate a smooth transition toward offshore wind farm deployment in the country. Unlike previous studies that relied solely on rigid threshold values for site selection, this research used ArcGIS and wind resource data to integrate exclusion and selection criteria, creating multiple classes for each parameter. Additionally, it calculated the total available area for each class. This approach provides more insightful recommendations for decision-makers, project developers, stakeholders, and researchers.

Relevant literature

Several studies have been published that outline the main criteria employed in the process of selecting wind farm locations. Typically, exclusion criteria are applied initially, followed by the implementation of selection criteria. Currently, there is no standardized wind site exclusion or selection criteria for both onshore and offshore wind energy. Therefore, it would be beneficial to review the main previous studies in order to identify the exclusion criteria and the buffer distances that were used. Upon closer examination of the literature, it is evident that there are two distinct approaches for assessing the geographical exclusion criteria for wind energy. These approaches include a binary exclusion (strict exclusion) without offset or buffer distances and a binary exclusion with buffer distances (C.-K. Kim, Jang, and Kim 2018; Mahdy and Bahaj 2018; Umoh et al. 2024). On the other hand, two main approaches are generally used to assess the suitability of wind sites. The first approach uses a suitability weighting index which incorporates specific quality factors that can help determine the geographical potential (Gavériaux et al. 2019; Umoh, Hasan, and Kenjegaliev 2025). The second approach involves using site eligibility characterization to identify and select the remaining sites (after exclusion) that are characterized by the highest quality resources, specifically focusing on the highest wind quality or the highest annual production potential (Argin et al. 2019; Maandal, Tamayao-Kieke, and Danao 2021). The suitability weighting approach relies on assigning a weight to each input factor and incorporating them into the geographical potential assessment. However, the majority of the studies that adopt this approach (although limited in number) subjectively or arbitrarily define these weights, which is one of the limitations of this approach. This approach could be enhanced by incorporating qualitative or quantitative studies to gather more robust data from experts in the field.

The binary exclusion followed by the qualitative site eligibility characterization approach is commonly used. This approach is typically employed when there are well-defined conditions, rules, and constraints that can be utilized to exclude certain areas from consideration. The offshore area in Kuwait is relatively small, and the constraints are straightforward, allowing us to fully apply the binary exclusion with buffer distances followed by selecting the suitable offshore sites that have highest wind resource quality and close proximity to ports and grid connection. This section will primarily focus on previous studies that have employed this approach. The objective is to provide a summary of the exclusion criteria and the specified buffering distances mentioned in literature.

Argin and Yerci (2017) discussed the main factors to consider when selecting an offshore wind farm in the Black Sea in Turkey. These factors include wind speed, territorial waters space, shipping routes, military zones, subsea cables/pipelines, civil aviation (e.g. landing and take-off points), as well as environmental and social concerns. They recommend maintaining a minimum buffering zone of 500 m from the subsea cables when installing wind turbines. They examined three offshore sites at hub height of 50, 80 and 150 m where the corresponding average wind speed are 5.52, 5.91 and 6.43 m/s. The minimum wind speed they used as a threshold was 3 m/s.

Maandal, Tamayao-Kieke, and Danao (2021) conducted a techno-economic study to evaluate the potential of offshore wind in the Philippines. Ten key exclusion criteria have been defined for the selection of offshore wind farm sites. These include, wind speed, shipping route, submerged cables, marine protected areas, oil/gas extraction areas, distance to grid, bathymetry, earthquakes zones, reefs zones and typhoons zones. A 3 km buffering zones from the shipping routes was specified, taking into account a 6.2 MW turbine with a hub height of 126 m. The same buffering zone was applied to both coral reefs and marine protected areas. In the case of oil/gas extraction, a buffer spacing of 5 km was specified

in the exclusion criteria. For bathymetry, they excluded the areas with water depth greater than 50 m. The sites located more than 120 km away from the grid were also excluded.

In their study, Hoogwijk, De Vries, and Turkenburg (2004) conducted an assessment of the geographical potential, as well as the technical and economic potential, for onshore wind energy on both regional and global scales. Four constraints were identified including wind regime, land cover, elevations, and urban areas (with dense populations). Only areas with wind speeds higher than 4 m/s at a height of 10 m were included. They justified the threshold of 4 m/s by stating that around 80% of the global area generates electricity with an annual average wind speed of approximately 4 m/s. Regarding the altitude, zones above 2000 m are excluded due to the challenging technical and economic feasibility of installing wind turbines in these areas (iMAGeteam 2001). According to Loveland and Belward (1997), they defined 1 km by 1 km urban area cells, which are subsequently excluded in the geospatial potential assessment.

A site selection study of a floating offshore wind (FOW) farm off the Galician area in Spain was conducted by Castro-Santos, Lamas-Galdo, and Filgueira-Vizoso (2020). They reported general restrictions such as environmental protected areas, navigation areas, rocky areas, Seismic fault-lines and fishing grounds. However, they did not clearly specify the threshold for wind speed. They included the areas within a bathymetry of 62–1000 m. While most published papers in literature primarily focus on onshore wind farm site selection and exclusion criteria, it would be beneficial for the scope of this paper to provide a summary of the exclusion criteria used for offshore wind sites, see Table 2. The aim is to highlight only the main exclusion criteria used for offshore wind energy, rather than providing a comprehensive review.

Exclusion criteria for the current study

Based on the above discussion, it is evident that geographical exclusion criteria for wind farms vary between countries. However, certain exclusion criteria can be applicable to specific locations. For example, Kuwait is situated in a region that is not prone to earthquakes and typhoons. The main criteria used in this study include wind speed, water depth, distance to ports, shipping density, exclusive economic zones (EEZ), marine protected zones, mine areas, and subsea cables.

Wind speed

Spyridonidou and Vagiona (2020) conducted a comprehensive systematic review of 53 studies on wind energy, focusing on the selection and exclusion criteria for both onshore and offshore wind farms. They identified a total of 19 offshore exclusion criteria. The review also pointed out that the average wind speed threshold used in the exclusion process of offshore wind sites ranges from 3 to 7 m/s, with 6 m/s being the most commonly observed value. On the other hand, for onshore sites, the predominant value is 5 m/s. In the case of floating wind turbines, it is noted in the literature that as the water depth increases, the wind speed threshold also increases, reaching 7 m/s or even higher (Cradden et al. 2016). The current study specifically focuses on fixed-bottom offshore wind turbine siting, and as a result, a wind speed threshold of 6 m/s has been chosen as an exclusion criterion.

Water depth

Bathymetry is one of the key parameters that influences the suitability of offshore sites. The water depth significantly affects the installation cost of the turbine foundation alongside the quality and intensity of the wind over the surface. The threshold of water depth used in the exclusion criteria depends on the type of offshore turbine foundation, whether it is fixed-bottom or floating. There are four common foundations for fixed-bottom wind turbines: monopiles, tripods, gravity-based, and jackets (Lavanya et al. 2020; Løken and Kaynia 2019), see Figure 2.

Table 2. Summary of geographical exclusion criteria for offshore wind site selection from the literature. Numbers provided are either buffer distances or excluding conditions.

Source	Argin and Yerci (2017)	Maandal, Tamayao-Kieke, and Danao (2021)	Castro-Santos, Lamas-Galdo, and Filgueira-Vizoso (2020)	Vasileiou, Loukogeorgaki, and Vagiona (2017)	Mahdy and Bahaj (2018)	Gavériaux et al. (2019)	T. Kim, Park, and Maeng (2016)	Cradden et al. (2016)
Region	Turkey	Philippines	Spain	Greece	Egypt	Hong Kong	South Korea	North-West of Europe
Type	Fixed Bottom (FB)	FB	Floating offshore wind (FOW)	Hybrid: FB & wave energy system (WE)	FB	FB		Hybrid: FOW+WE
wind speed or power density	✓<3 m/s	✓		✓<6 m/s	✓	✓<4 m/s	<200 W/m ²	✓<7 m/s
shipping routes	✓	✓3 km buffer	✓	✓	✓		✓	✓
oil/gas extraction				✓	✓		✓	
military zones	✓			✓	✓		✓	
subsea cables	✓500m buffer	✓5 km buffer			✓	✓200 m buffer	✓	
civil aviation	✓							
marine protected areas		✓3 km buffer	✓	✓	✓		✓2 km buffer	✓1 km buffer
distance to grid		✓>120 km			✓		✓>20 km	✓>150 km
distance to port		✓	✓<100 km				✓1 km buffer	✓<200 km
distance from shore				✓<25 km	✓<1.5 & >200 km	✓<1 km	✓>20 km	✓<15 km
Bathymetry (water depth)		✓>50 m	✓<62m & >1 km	✓FB: >60 m FOW: >500 m	✓<5 & >60 m	✓>40 m	✓>50 m	✓>100 m
earthquakes zones		✓	✓					
coral reefs zones		✓3 km buffer						
typhoons zones		✓						
Rocky areas (sea bed)			✓		✓			
Fishing			✓		✓		✓1 km buffer	

Díaz and Guedes Soares (2020), who reviewed the water depth required for various offshore fixed-bottom foundations, have reported that the monopile-type is typically suitable for sites with water depths ranging from 0 m to 30 m, although some industrial monopile wind turbines are now installed in deeper waters, up to 60 m (Jongen 2024). Additionally, the jacket structure is appropriate for offshore sites with depths ranging from 25 to 50 m. Gravity wind turbine foundations are typically installed in water with depths greater than 20 m, while the tripod structure (with three legs on the seabed) is suitable for water depths between 10 and 20 m. Table 3 presents the average water depth and associated average costs for various offshore fixed-bottom foundations worldwide. In their study, Sánchez et al. (2019) provided a summary of the average depth for several operational wind farms as of the end of 2018. The details can be found in Table 4.

The current study focuses on fixed-bottom wind turbine siting. However, for the sake of comparison, it is worth noting the water depth required for floating offshore wind farms. Floating wind turbines are designed to operate in deeper waters, typically at depths greater than 50 m. However,

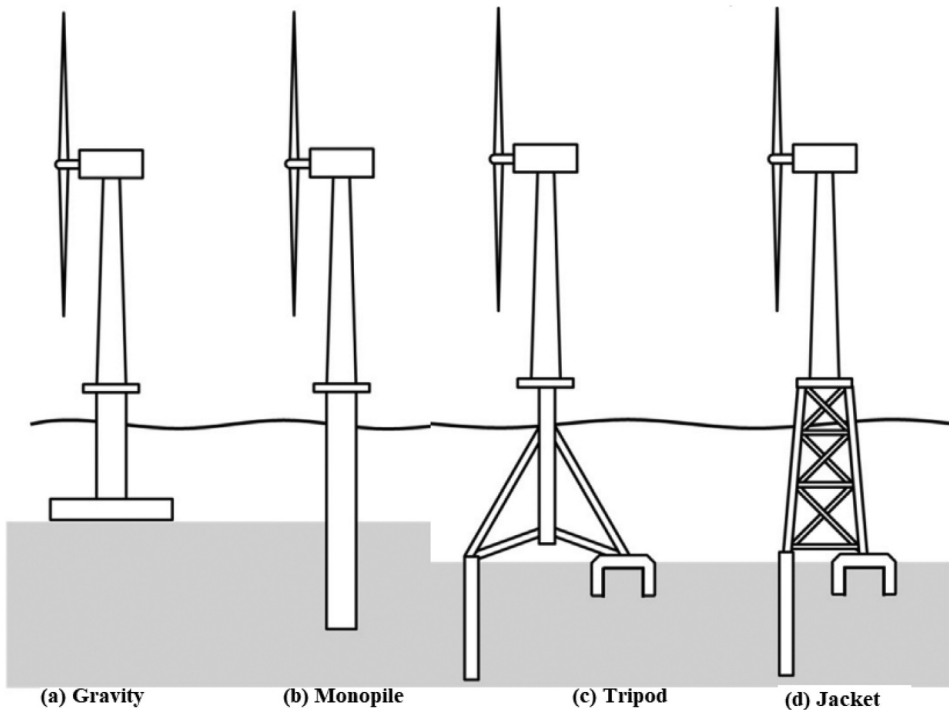


Figure 2. Four main types of fixed-bottom offshore wind turbine foundation (Oh et al. 2018).

Table 3. Water depth and costs of different types of offshore wind foundations (Díaz and Guedes Soares 2020).

Foundation type	Water depth (m)	Cost, (M€)	No of turbines	% of wind farms by foundation			
				Worldwide	Europe	Asia	America
Monopile	19	2.3	3854	63	70	43	0
Gravity-base	8.3	0.9	329	12	14	7	0
High-rise pile cap	5.7	1.2	307	12	1	40	0
Jacket	25.8	4.1	220	7	7	7	100
Tripod	37.4	5	212	4	5	0	0
Suction- bucket	7.5	1.4	55	1	0	0	0
Other types	7.1	0.5	18	3	2	3	0

according to a study by Cradden et al. (2016), wind turbines installed in water depths above 100 m may encounter challenges related to cabling layout. Currently, there are a limited number of floating wind farms operating at depths exceeding 100 m, with Hywind floating offshore wind farm in Scotland being one example, reaching a maximum depth of 120 m.

The maximum water depth in Kuwait is approximately less than 100 m, as will be shown in the results section. The majority of offshore sites in Kuwait fall within the range of 0–20 m, which is a typical range for fixed-bottom offshore wind farms. This suggests that Kuwait's offshore areas can be considered shallow water, which implies that floating foundations will not be considered for future offshore wind developments in the country. Therefore, we have set the threshold for water depth at 1000 m in ArcMap, effectively including all offshore areas within 100 m.

Proximity to ports

Multiple studies have been conducted to assess the suitability of offshore sites by considering the distance to the shore. Some of these studies have specifically looked at the minimum distance to shore,

Table 4. Summary of average water depth & distance-to-shore for some operational offshore wind farms (Sánchez et al. 2019).

Location	Wind farms	Power installed (MW)	Power installed (%)	Water depth (m)	Distance-to-coast (km)	Depth/Distance to shore ratio
North Sea	61	12,933.0	55.4	23.4	30	0.78
Irish Sea	15	2,938.0	12.6	13.1	10.1	1.29
Eastern China Sea	16	2,574.0	11.0	5.3	16.7	0.32
Baltic Sea	20	2,186.0	9.4	12.4	10.9	1.14
Yellow Sea	13	1,365.0	5.8	7.5	11.3	0.66
South China Sea	10	777.0	3.3	6.5	8.3	0.78
English Channel	1	400.0	1.7	29	13	2.23
Japan Sea	6	66.0	0.3	13.4	1.5	8.94
Philippines Sea	7	53.0	0.2	39.9	6.3	6.34
Atlantic Ocean	4	42.0	0.2	21.4	7.3	2.95
Lake Vanern	1	30.0	0.1	9.5	4	2.38

taking into account the social impact of visibility and noise of wind turbines (Gavériaux et al. 2019; Vasileiou, Loukogeorgaki, and Vagiona 2017). Other studies (T. Kim, Park, and Maeng 2016) have focused on the maximum distance required, considering the economic and environmental implications of long distances on cable layout and operations and maintenance (O&M) transit costs. A few studies, including the one conducted by Mahdy and Bahaj (2018), have taken into account both the minimum and maximum distance as part of their exclusion criteria. According to their findings, for fixed-bottom offshore wind turbine installation, the minimum and maximum distances from the shore are reported to be 1.5 and 200 km, respectively.

Various studies have included distance to the port as one of the exclusion criteria when assessing the suitability of the offshore wind farms. For example, Castro-Santos, Lamas-Galdo, and Filgueira-Vizoso (2020) reported a minimum distance of 100 km. However, many operational wind farms are actually located within 30 km of the port (Sánchez et al. 2019). This proximity helps reduce installation and maintenance costs, see Table 4. A closer examination of the literature on operational offshore wind farms reveals that the distance to shore or ports ranges from ~ 0 to 110 km. For example, Oh et al. (2018) reviewed 65 offshore wind farms with distances to the shore varying between 0 (such as the Lely offshore wind farm in the Netherlands with a monopile turbine foundation) and 110 m (such as the Global Tech I offshore wind farm in Germany with a Jacket type foundation). Therefore, in this study, offshore wind sites located more than 110 km away from the ports will be excluded.

Other exclusion criteria

It may not be feasible to develop offshore wind farms in areas with high shipping density. The routes and channels for shipping are typically designed to reduce travel distances, making it impractical to modify these routes for offshore renewable energy projects. Thus, it is crucial to carefully choose the best locations for offshore wind sites. Several studies, including the ones mentioned in Table 2, have excluded shipping routes both with and without buffer distances (Argin et al. 2019; Emeksiz and Demirci 2019). The high shipping density in Kuwait, as will be shown in the results section, was concentrated into the region near the port of Shuaiba in the south. As a result, this area has been considered for the site selection process.

Currently, there are no offshore oil/gas wells in Kuwait as all oil and gas wells are located onshore. This simplifies the design of cable corridors, potentially results in a reduction in the length of subsea cables needed providing additional space and flexibility for the development of offshore wind projects. Previous study as shown in Table 2 specified different buffering distances for existing subsea cables. In this study, the subsea cables have been identified and excluded with a buffer of 5 km (Maandal, Tamayao-Kieke, and Danao 2021). In addition, the current study excluded marine protected areas.

Materials and methods

This section provides full details about the methodology employed including the sources of data collected for site exclusion criteria and the details about the integrated approach to analyze the data using ArchGIS package.

Data collected

As discussed in the literature section, the exclusion criteria that will be implemented in this study are wind speed, water depth, exclusive economic zones, marine protected zones, subsea cables network, and potential mine areas. Table 5 provides a summary of these criteria, including the data source, the buffer and the file format extracted.

Methodology framework and data analysis approach

The methodology framework includes three stages: data collection, exclusion analysis, and site selection, see Figure 3. The data collection stage involves gathering all the data presented in Table 5, as well as the details on all ports and annual deposited dust in Kuwait. This stage also includes data cleaning. During the second stage, the exclusion criteria were implemented to remove areas that were not suitable. Finally, the areas that have displayed the highest wind speeds, and are situated outside of the high shipping density zone but in close proximity to ports, have been chosen.

Esri's ArcGIS ArcMap 10.8 software was used in this study. It is a useful tool used for the creation, editing, and analysis of geospatial data. It allows for the creation of digital maps by combining different layers. Therefore, to exclude unsuitable areas, the offshore wind speed distribution of Kuwait is first defined using raster data. Raster data is a digital representation of geospatial information, where the surface is divided into small pixels or a matrix of cells or grids, with each cell containing its own value information, such as water depth or wind speed. The restricted layers mentioned in Table 5 are then superimposed onto the map, excluding them with the specified buffer distances. The BUFFER tool was used to add the predetermined buffer zones to some exclusion criteria. All layers were converted to raster using the Polygon to Raster conversion tool to enable computation on the RASTER CALCULATOR. The RECLASSIFY spatial analysis tool was utilized to assign values "0" and "1" to non-feasible and feasible zones, respectively; while the SETNULL function within the RASTER CALCULATOR was used to excluded sites which are not feasible for offshore wind development. The site suitability was then analyzed based on technical considerations, considering the highest wind speed zones with lower shipping density and proximity to the ports.

Results and discussion

Offshore wind speed

Wind speed data were obtained from Global Wind Atlas at the hub height of 100 m. The wind speed distribution of the offshore in Kuwait is shown in Figure 4. The CLIP tool in ArcMap was used to exclude

Table 5. Exclusion criteria used for the current study.

Component	Criteria	Source	Format
Mean Wind speed @ 100m	<6m/s	Global Wind Atlas (2024)	Raster
Water depth	>1000m	General Bathymetry Chart of the Oceans (2022)	Raster
Exclusive economic zones	Study area	Marine Regions (2019)	Shapefile
Marine protected zones	All	UNEP-WCMC and IUCN (2022)	Shapefile
Underwater cables	5km buffer	Koordinates (2019)	Shapefile
Mine areas	2km buffer	Ministry of Communications, Kuwait	Coordinates

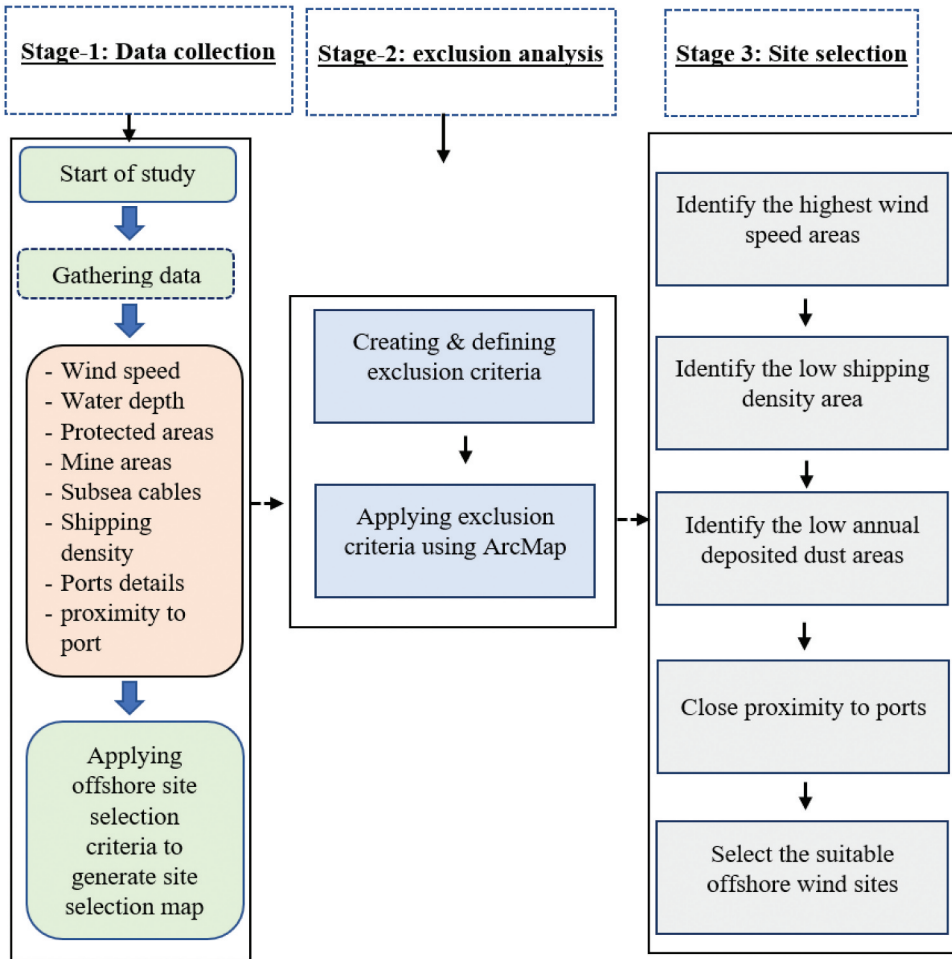


Figure 3. Methodology framework.

the onshore wind data and focus only on the analysis of offshore wind distribution. The wind data represents the long-term average wind speed for the years 2008 to 2017, as obtained from the ERA5 reanalysis data (Global Wind Atlas 2024). The wind speed data has been categorized into five groups using ArcMap, ranging from 5.7 to 8 m/s. The cluster with the highest wind speed is located in the range of 7.5 m/s to 8 m/s, as shown by the dark green regions, covering a total area of 1234.55 km². The largest area, covering 8974.66 km², belongs to Class-3, where the wind speed ranges from 6.5 to 7 m/s, see Table 6.

It is seen in Figure 4, the highest offshore wind speed zones in Kuwait are located at the north (around Bubiyan island) and the west along the coastal area between Al-Ahmadi and Khafji. The offshore regions in Kuwait are characterized by a non-uniform shallow water, as will be discussed in the next section. The complex terrain of Kuwait, which includes mountains on the east near Iran, poses challenges in correlating wind speed with water depth. Unlike in other countries with deep water, where stronger wind speeds are directly related to water depth, this correlation is not as straightforward in Kuwait.

Water depth

Bathymetry data of Kuwait was extracted from General Bathymetry Chart of the Oceans, GEBCO (2022) as a raster format. This layer was then projected onto ArcMap using the WGS 1984 Geographic

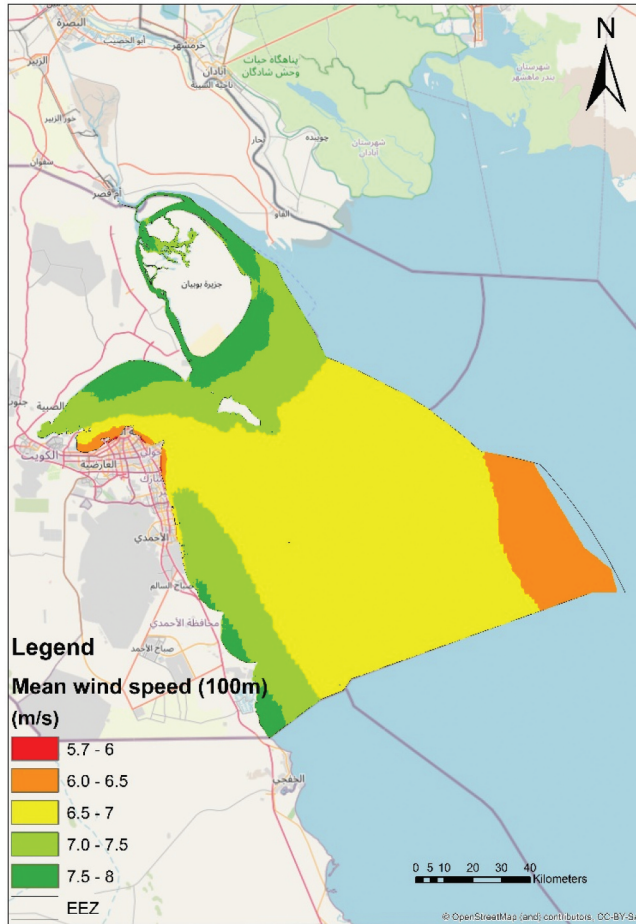


Figure 4. Offshore wind speed profile in Kuwait at 100 m.

Table 6. Offshore wind speed classes with corresponding total areas.

Class	1	2	3	4	5
Wind speed (m/s)	5.7–6	6–6.5	6.5–7	7–7.5	7.5–8
Area (Km ²)	4.80	1367.53	8974.66	2956.75	1234.55

Coordinate System, consistent with all other layers in this study. The Reclassify tool was implemented to classify the water depth into five groups as shown in Figure 5. Bathymetry of Kuwait is characterised as shallow. Almutairi (2015) and Khalaf et al. (1982) reported that the maximum water depth is approximately 30 m. According to Figure 5, the dominant water depth ranges from 0 to 20 m. The offshore areas in Kuwait consist mostly of water depths ranging from 0 to 20 m, covering a total area of 7458.13 km² in the north, see Table 7. In addition, there are areas with water depths ranging from 20 to 50 m, covering an area of 7153.74 km², located in the southern region. Due to the shallow water depth (<50 m), the entire offshore region was taken into consideration without any exclusion zones. Mean tidal ranges in Kuwait have been found to be between 2.2 m during neap tide to 4.25 m in the spring phase (Lafta, Altaei, and Al-Hashimi 2020). This could hold implications for the design of bottom-fixed offshore foundations and cables, as well as the planning of maintenance and service operations of offshore wind farms (BVG Associates 2019).

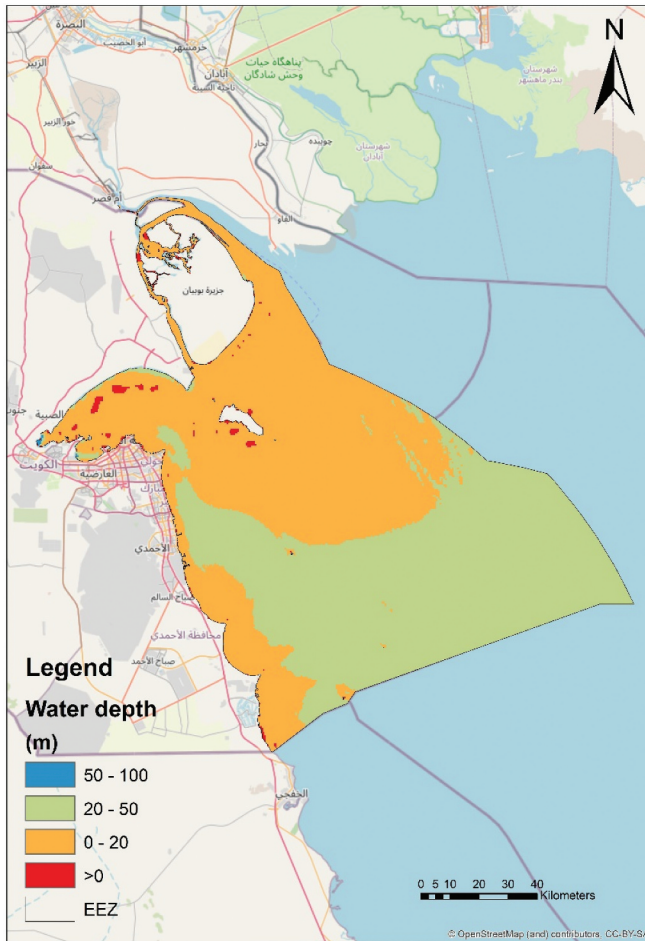


Figure 5. Bathymetry of Kuwait.

Table 7. Water depth in Kuwait.

Water depth (m)	<0	0–20	20–50	50–100
Area (Km ²)	113.69	7458.13	7153.74	4.45

Ports and shipping density

There are three main ports in Kuwait: port of Doha, port of Shuwaikh and port of Shuaiba as shown in [Figure 6](#). The GPS coordinates of these ports with total areas are summarized in [Table 8](#). Shuwaikh port is the primary commercial port. It comprises a total of 21 berths, with 14 berths having a depth of 10 m, 4 berths with a depth of 8.5 m and 3 berths with a depth of 6.7 m (KGO 2023). The Shuaiba port in Kuwait is the second main port, equipped with various platforms to handle commercial traffic and oil product containers. The current facility offers a total of 20 berths, each with depths from 10 to 14 m. The Port of Doha is ranked third, with a depth of 4.3 m (KPA 2016).

The data for the shipping density in Kuwait was extracted, as a Raster file, from (Halpern et al. 2015) and imported in ArcMap as a raster layer. The shipping density is a vessel density map that represents the number of vessels per unit area (cells) per unit time (month). The Reclassify tool in ArcMap was used to categorize the shipping density into five groups. According to [Figure 7](#), it is evident that the port of Shuaiba has a significantly higher volume of vessel traffic in comparison to the other two ports.

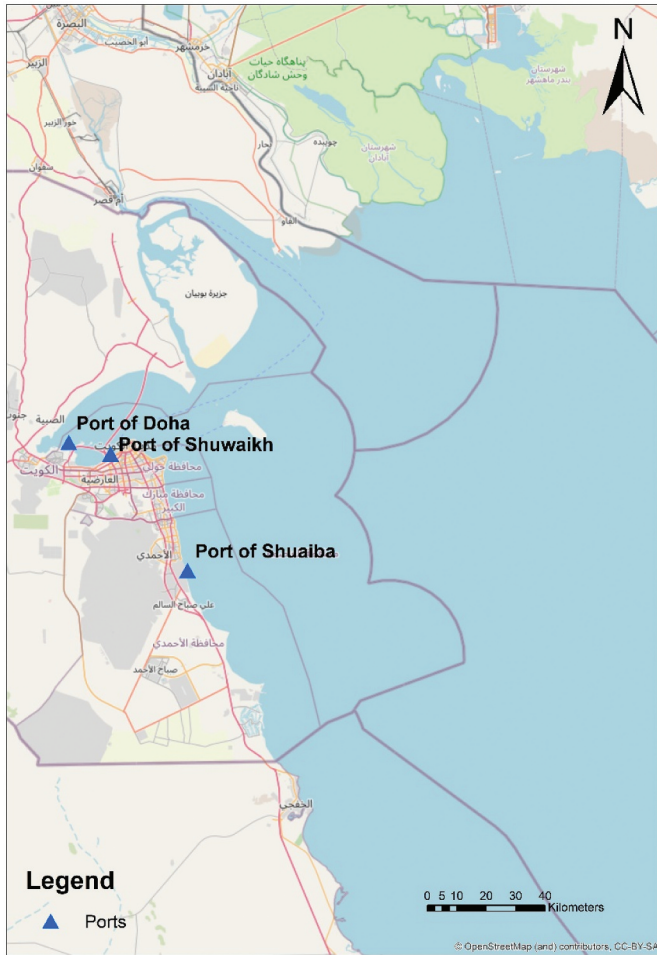


Figure 6. Three main ports in Kuwait.

Table 8. GPS coordinates of the ports in Kuwait.

Ports	Area (km ²)	Longitude	Latitude
Port of Doha	2.6	47.7999	29.3858
Port of Shuwaikh	4.4 (3.2 onshore + 1.2 offshore)	47.9277	29.355
Port of Shuaiba	4.068	48.162	29.0451

Marine protected areas and subsea cables

The data on marine protected areas was sourced from UNEP-WCMC and IUCN, an online worldwide database for marine protected areas including natural reserve zones, coral reef areas, natural biotic zones and wildlife sanctuary areas. Underwater cables are very critical and need to be included in the exclusion criteria. The data for the subsea cables was obtained from Koordinates, an online geospatial database that includes information on underwater cables around the world. The shapefile of the subsea cables was used in ArcMap to exclude certain areas with a buffer distance of 5 km. Figure 8 shows the excluded marine protected areas and the underwater cables.

Kuwait is a wealthy oil-producing country within the GCC nations. The potential areas for offshore oil and gas deposits are shown on the map in Figure 9, based on data from Päivi, Ketil Rød, and Thieme (2007). According to Hagagy (2023), the drilling of Kuwait's first offshore oil field is expected

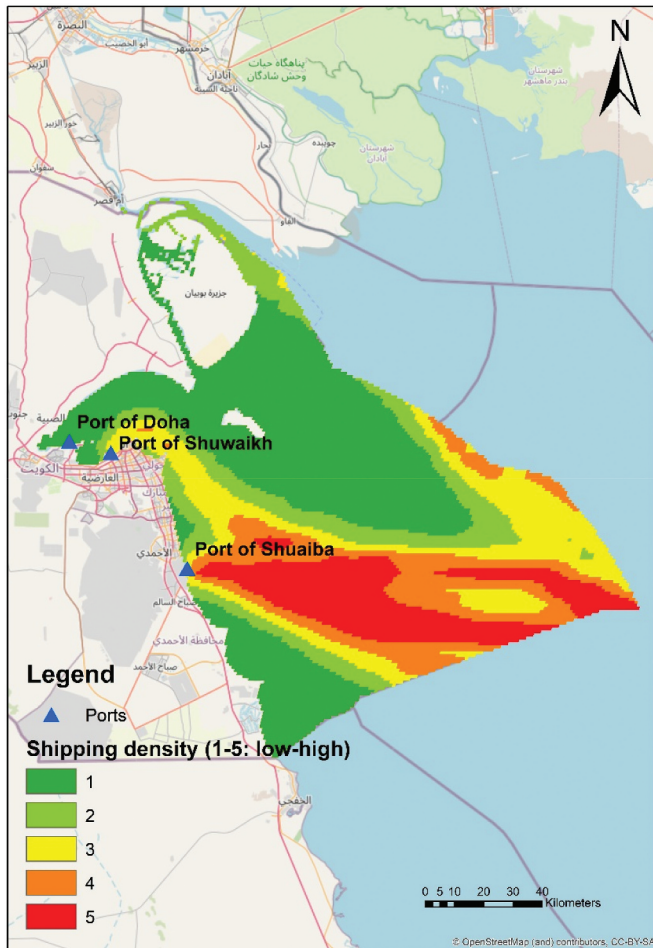


Figure 7. Shipping density.

to be completed by 2026. Additionally, Kuwait announced the discovery of a large offshore oil and gas field east of Failka Island, though the exact location has not been disclosed (Cavcic 2024). Since the offshore oil fields are located far from the selected three wind farms, as discussed in the results section, they were not included in the exclusion analysis.

Site selection map

As previously mentioned, the initial stage of wind site assessment was the exclusion phase. By applying all geographical exclusion and selection criteria discussed in the previous sections, the optimal three offshore wind farms were identified. Figure 10 shows the locations of these three wind farms displayed on the previous geographical maps.

The results indicate that the three high-potential wind farm sites are located in areas with the highest wind speeds, proximity to ports, lower shipping density, and minimal annual deposited dust. Figure 11 shows the three selected sites including Sabiya Power Station farm, Port of Doha farm, and Camp Arifjan farm. It should be noted that these sites were named based on their proximity to certain landmarks located in their respective areas. Table 9 displays the main characteristics of the three selected offshore wind farms. It is found that Sabiya Power Station farm has the highest mean wind

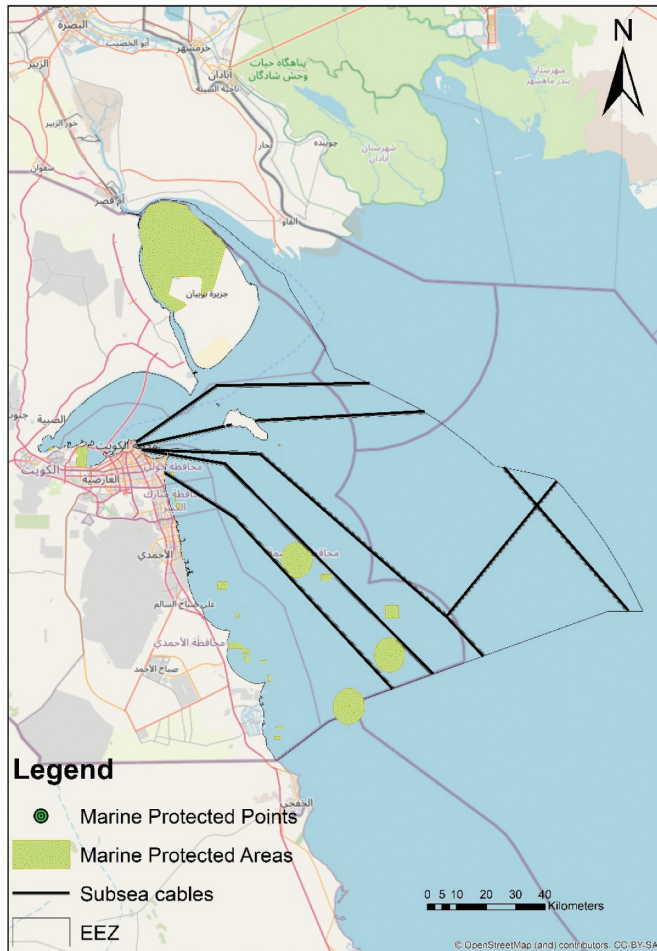


Figure 8. Marine protected areas and subsea cables.

speed of 7.13 m/s at 100 m elevation, compared to the Port of Doha and Camp Arifjan farms which have 6.86 m/s and 6.43 m/s, respectively. In addition, the Sabiya Power Station site is located 1.7 km from the shore and 45 km from the Shuwaikh port. While the Port of Doha and Camp Arifjan sites are closer to the shore, their average wind speeds are still lower than that of the Sabiya Power Station site. Water depth of all three selected wind sites are less than 10 m which is within the suitable water depth for fixed-bottom offshore wind turbine sitting.

Statistical analysis of the wind resources for the three selected offshore wind sites

Statistical analysis was conducted to explore and analyze the wind resource at the three selected locations that exhibited the highest potential wind speed. The locations have been assigned the names: port of Doha, Sabiya power station and Camp Arifjan as shown in Figure 12.

Rose diagrams

Wind speed data has been extracted from Global Wind Atlas. The wind speed rose diagrams for the three locations are shown in Figure 13.

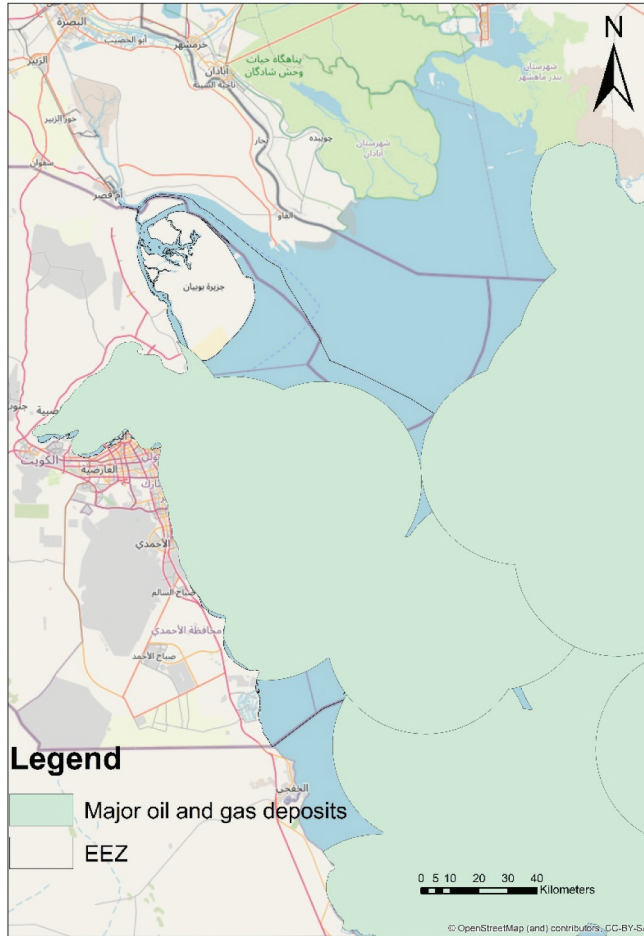


Figure 9. Major oil and gas deposits in Kuwait.

Figure 13 indicates that the majority of the wind comes from the northwest. The wind speed is slightly higher in the Sabiya and port of Doha sites compared to Camp Arifjan. Specifically, the port of Doha and Sabiya experience more frequent high wind speeds at around 36%, while Camp Arifjan has around 32%.

The wind power density is given by (Mattar and Guzmán-Ibarra 2017);

$$\frac{P}{A} = \frac{\rho_{air}}{2} \int_0^{\infty} u^3 f(u) du \quad (1)$$

where P/A is the power density (wind power P per harnessed area of the site), ρ_{air} is the air density (1.225 kg/m^3 at 15°C), u is the wind velocity and $f(u)$ is the probability density of the wind which is given by;

$$f(u) = \frac{k}{s} \left(\frac{u}{s}\right)^{k-1} e^{-\left(\frac{u}{s}\right)^k} \quad (2)$$

where k and s are the shape and scale factors respectively.

The power rose diagrams in Figure 14 indicate that the wind power potential is greater in the Sabiya and port of Doha compared to Camp Arifjan.

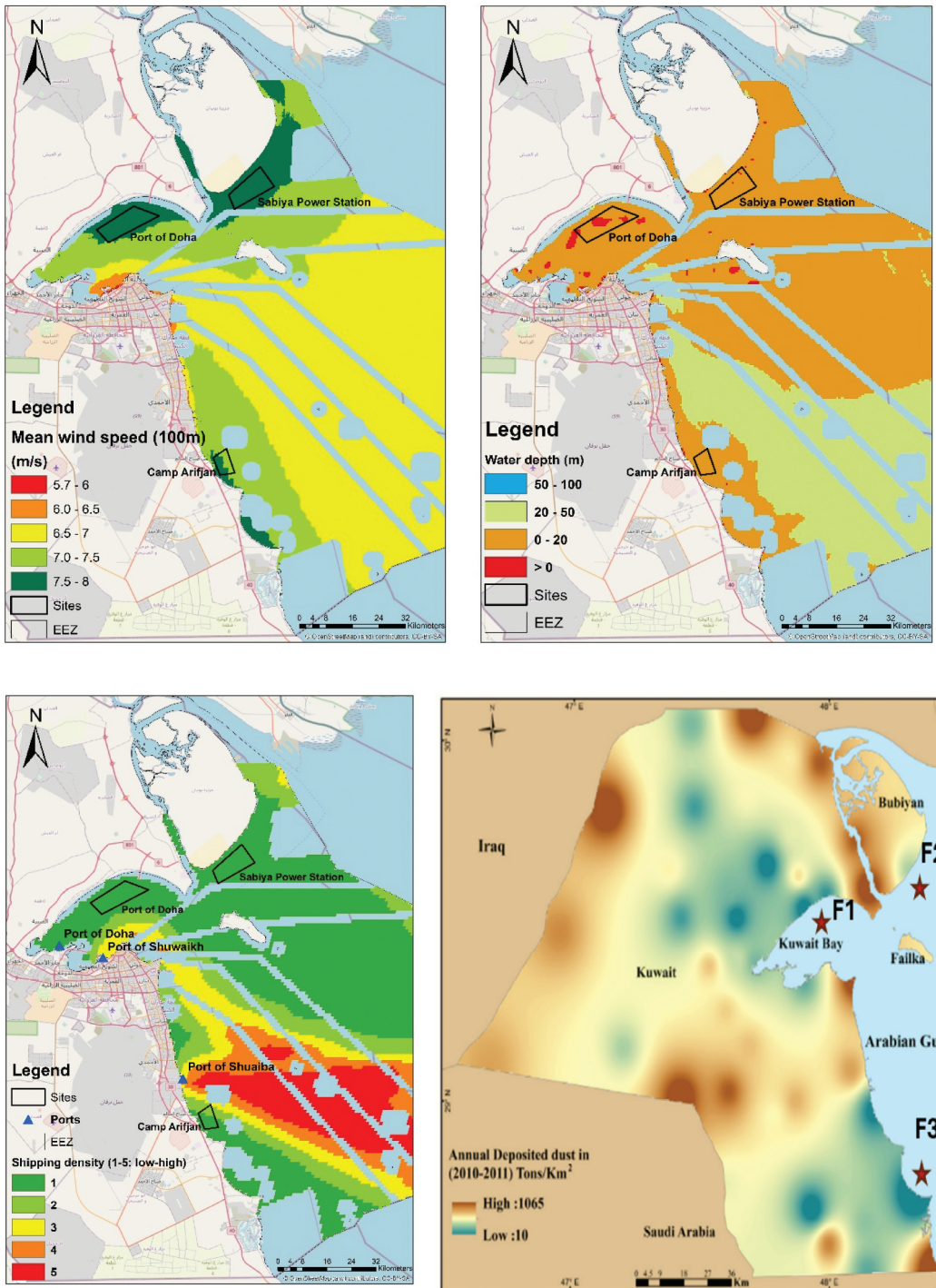


Figure 10. Locations of the three selected offshore wind sites in Kuwait, displayed on maps showing wind speed, water depth, shipping density, proximity to the port, and the annual deposited dust (F1-F3: locations of the three sites).



Figure 11. Three selected offshore wind farms.

Table 9. Overall characteristics of the three selected wind sites.

Site	Location			Distance from shore (km)	Port		Shipping density	Water depth (m)	Avg. Wind speed (m/s) @ 100m
	Long (°)	Lat (°)	Area km ²		Distance from port (km)	Nearest port			
Sabiya Power Station	48.3091	29.5925	78.1	1.7	45	Shuwaikh	Low	1	7.13
Port of Doha	47.9702	29.5103	86.9	3.2	17	Doha	Low	4	6.86
Camp Arifjan	48.236	28.9429	30.5	1.5	12	Shuaiba	Low	8	6.43

The mean power density is shown in Figure 15. As expected, the highest power density is observed in the north, including port of Doha and Sabiya power station wind sites, with a maximum power density of approximately 522 W/m².

Wind index

The wind index (WI) is a parameter used to measure the variability of the wind. In other words, the wind speed data has been normalized around the mean. This allows to determine



Figure 12. The centred pin points of the three locations (each 9 km²) at highest wind speed zones.

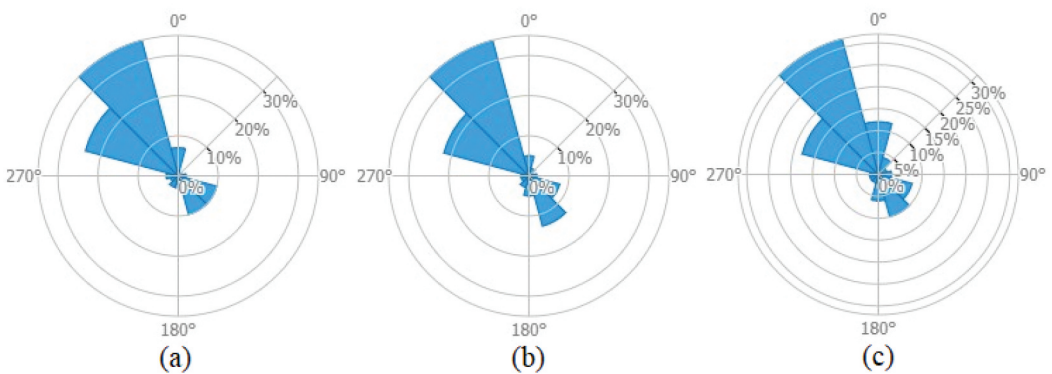


Figure 13. Wind speed rose diagram for (a) Port of Doha, (b) Sabiya power station, (c) Camp Arifjan.

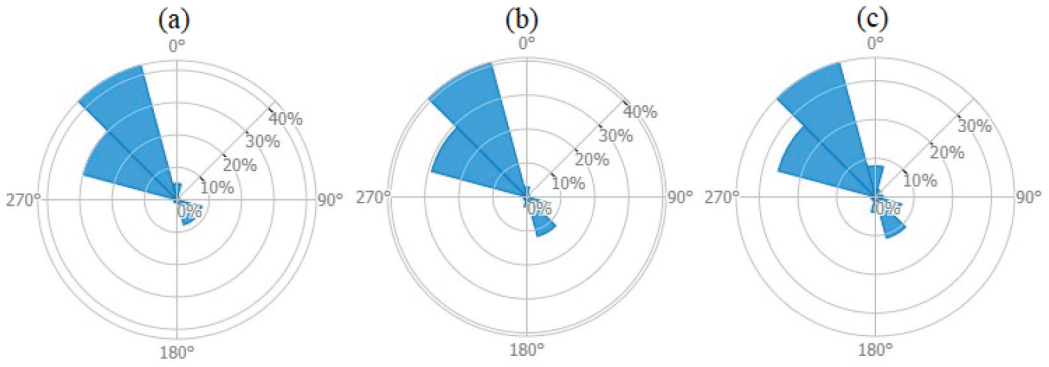


Figure 14. Power rose diagram for (a) Port of Doha, (b) Sabiya power station, (c) Camp Arifjan.



Figure 15. Mean power density.

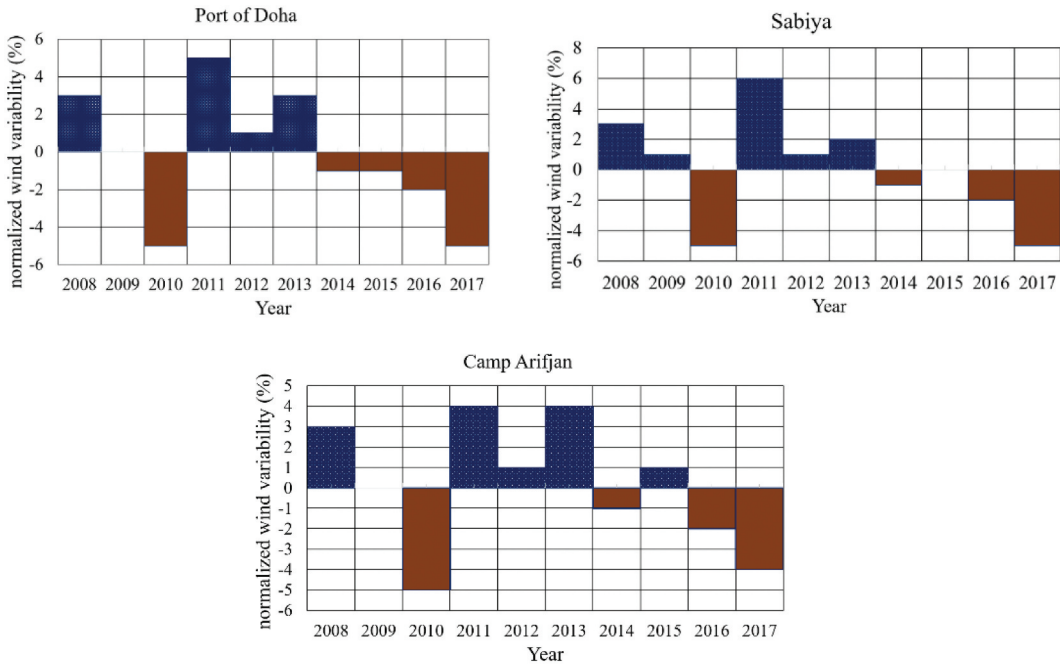


Figure 16. Wind variability for (a) Port of Doha, (b) Sabiya power station, (c) Camp Arifjan.

how much the wind speed varies above or below the mean. Wind variability, during the ten years (from 2008 to 2017) for the specified three offshore locations, are shown in Figure 16 where the percentage wind variation above and below the normalized mean wind speed can be identified. The highest deviation from the mean wind speed was observed at Sabiya in 2011, with an average wind speed that was 6% higher than the mean.

The wind speed variations around the normalized wind speed index of 1 are depicted in Figure 17, showing the monthly changes. It can be observed that all three locations exhibit similar trends, with the peak wind speed occurring in June and July, approximately 25% to 30% higher than the mean. The lowest wind speed occurred in November, 13 to 19% below the mean.

The highest wind speeds are found to occur at a peak between 22:00 and 02:00 UTC. This peak has an approximate increase of 20% above the mean wind speed, as shown in Figure 18. High wind speeds during early morning and late night, especially in June and July, can also be observed from the temporal wind intensity plots shown in Figures 19 and 20. This information is valuable for determining the optimal time to perform regular maintenance on installed wind turbines. The data in Figure 20 also confirms the early analysis, indicating that the wind resource potential in the Sabiya and port of Doha are higher compared to that in Camp Arifjan.

Conclusions

A set of exclusion criteria was defined and examined to select the optimal locations for the deployment of offshore wind farms in Kuwait including, wind speed, water depth, marine protected areas, subsea cable distribution, annual dust deposition, and shipping traffic density. A wind speed map of the offshore area in Kuwait has been created with five classes ranging from 5.7 m/s to 8 m/s. It was observed that the cluster with the highest wind speed falls within the range of 7.5 m/s to 8 m/s, covering a total area of 1234.55 km². The water depth in Kuwait is relatively shallow in which the offshore areas in Kuwait primarily have water depths ranging from 0 to 20 m, covering a total area of 7458.13 km² in the north.

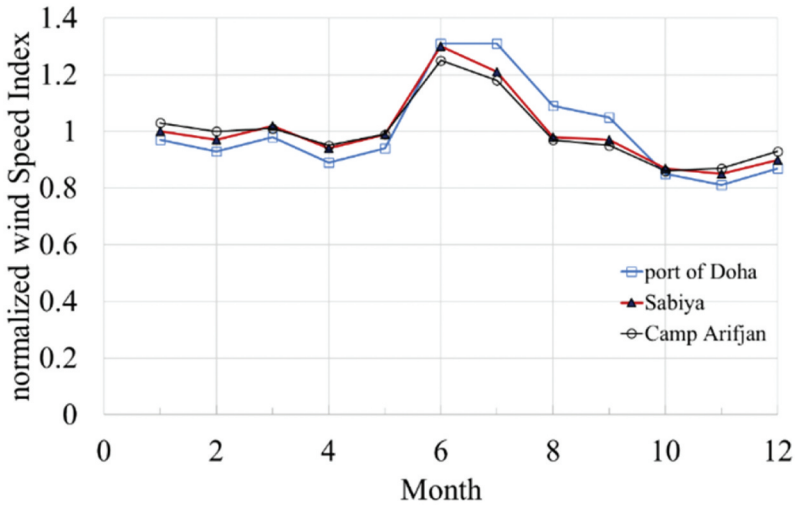


Figure 17. Average wind variation from January (1) to December (12).

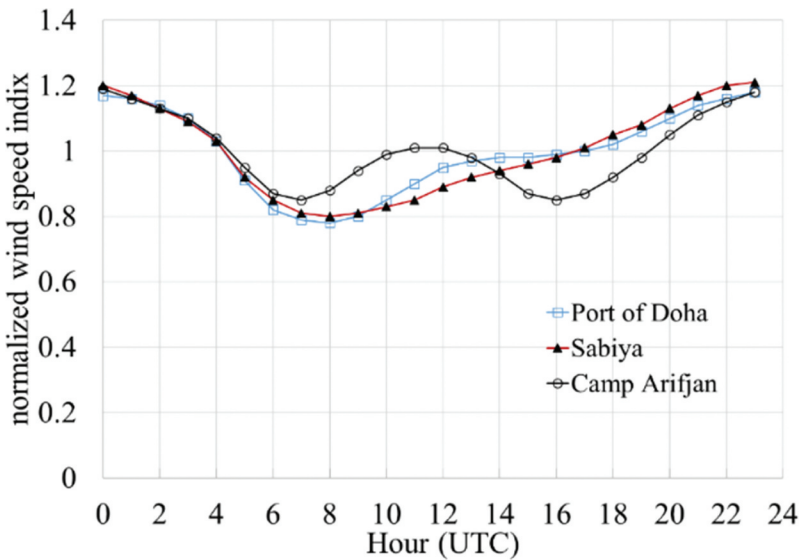


Figure 18. Wind variation during the day.

It was found that the port of Shuaiba experiences a higher volume of vessel traffic compared to the other two ports, the port of Doha and the port of Shuwaikh. The three offshore wind farms that meet the selection criteria and have the highest wind speeds and are located outside of high shipping density zones but in close proximity to ports are selected. These suitable sites are (i) Sabiya Power Station wind farm with a total area of 78.1 km² (Long. 48.3091, Lat. 29.5925), (ii) Port of Doha wind farm with a total area of 86.9 km² (Long. 47.9702, Lat. 29.5103) and (iii) Camp Arifjan wind farm with a total area of 30.5 km² (Long. 48.236, Lat. 28.9429).

The analysis of the three selected sites indicates that the wind speed is slightly higher at the Sabiya and Port of Doha sites compared to Camp Arifjan. Particularly, the Sabiya and port of Doha sites experience more frequent high wind speeds at around 36%, while Camp Arifjan site has around 35%.

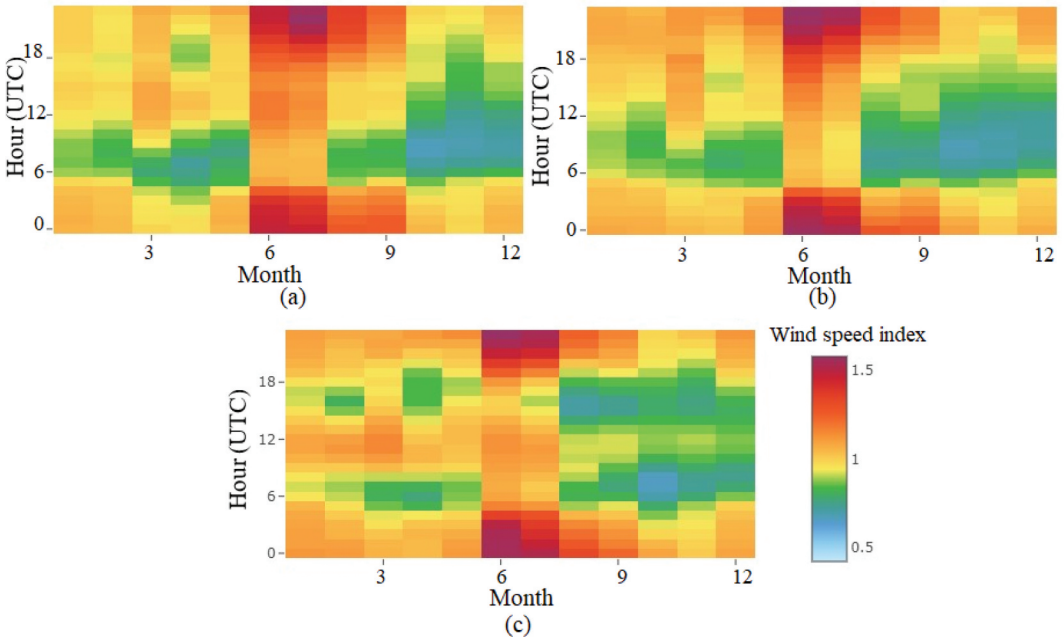


Figure 19. Wind speed index (a) port of doha, (b) sabiya, (c) camp Arifjan.

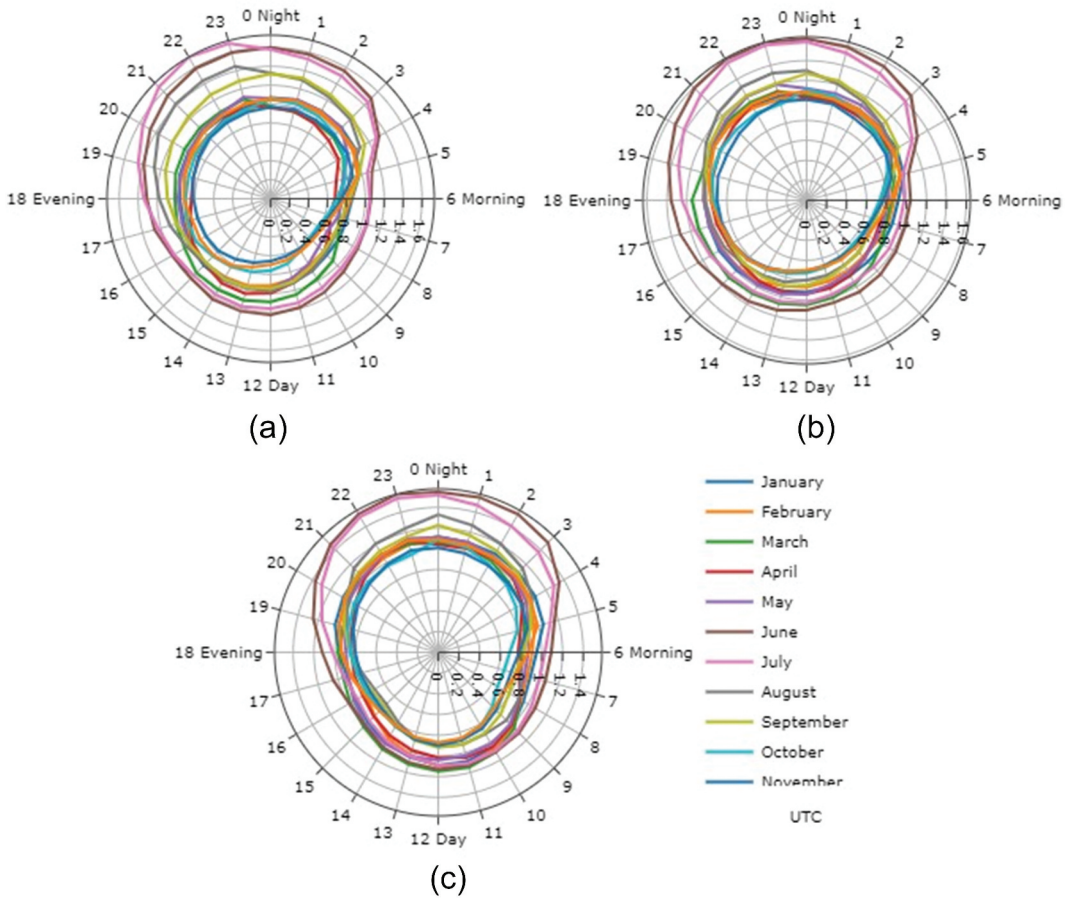


Figure 20. Wind variation with daily hours (2008–2017): (a) port of Doha, (b) sabiya, (c) Camp Arifjan.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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