ORIGINAL PAPER

The technical and economical feasibility study of offshore wind farms in Turkey

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Abstract

A large part of the electricity generation is from imported fossil fuels, which makes Turkey heavily dependent on fossil fuels. For this reason, Turkey aims to increase the ratio of renewable energy resources in the total installed power. Among renewable resources, Turkey's wind energy potential is very high. Although the onshore wind power installed capacity has increased significantly in the last ten years in Turkey, offshore wind energy deployment has not gained satisfactory attention even though the country is surrounded by seas on three of its sides. Therefore, the installation of Turkey's first offshore wind farm, which will be established by the Turkish government was accelerated by opening a tender in 2018. Three potential candidate regions were identified, two located in the Aegean Sea and one in the Black Sea. This paper performs a comprehensive techno-economic analysis of offshore wind farm projects in identified three regions. It was calculated that the total offshore wind power capacity at the specified sites is 3,329.4 MW. In addition, offshore regions were compared in the scope of the methods used in the economic analysis. In this context, the best results an obtained in the Saros OWF region. This study aims to contribute scientifically to the region's offshore wind energy development.

Graphical abstract
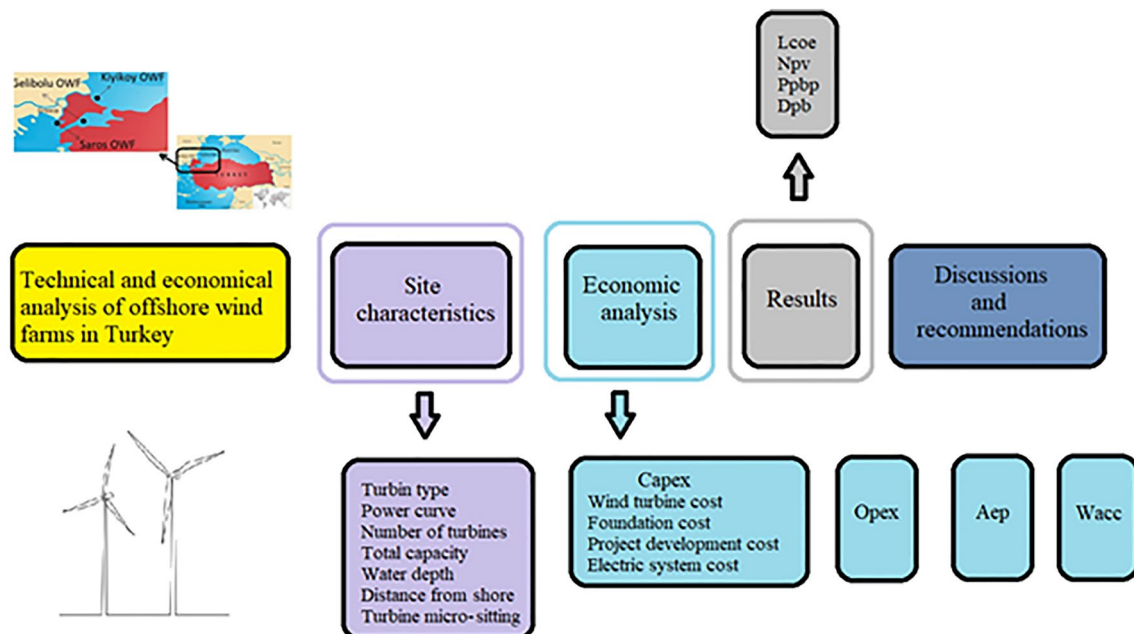
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Introduction

Due to rising natural gas and oil prices, depleted fuel reserves, and obligations to reduce CO_2 emissions to avoid climate change, renewable energy sources (RES) such as solar, hydro, wind, and bioenergy are becoming more popular (Bilgili et al. 2021). In comparison to conventional energy sources, these sources provide numerous economic and environmental benefits. Renewable energy is derived from resources that cannot be depleted and produce less pollution (Kumar et al. 2022). This separates renewable energy from fossil fuels and encourages many countries, including Turkey, to use RES through incentive and subsidy programs.

Among various RES, wind energy, in particular, has become a cost-competitive technology that has been rapidly growing around the world in recent years (Deveci et al. 2020). Wind energy has two production options: onshore and offshore. Offshore wind energy potential is currently in a considerable implementation state and is expected to grow more rapidly in the future. In the offshore wind power segment, the USA, Asia, and five countries in Europe will connect nearly 6.1 GW by 2020, increasing the global offshore wind energy capacity to over 35 GW (Pacheco et al. 2017). Offshore wind turbines represented 6.7 percent of total capacity at the end of the year, accounting for 6.5 percent of all new wind power capacity installed globally in 2020. In 2020, the United Kingdom (UK) maintained its lead in overall capacity (10.4 GW), followed by China (10 GW), Germany (7.7 GW), and, the Netherlands (2.6 GW). Several countries changed their 2030 offshore wind power capacity targets in 2020, including the UK (which raised its target from 30 to 40 GW) and Germany (which raised it from 15 to 20 GW). Government commitments for offshore wind power capacity by 2030 totaled 111 GW in early 2021 (REN21 2017).

For offshore projects, high cost, difficulty to build, grid access, planning uncertainties, access to finance, economies of scale, and subsidies for traditional energy are among the key barriers (Rechsteiner 2021). It is vital to immediately reduce existing barriers through a set of supportive policies and implementation measures. Advances in technology and efficiencies, financial instruments, and innovative business models will enable the development of offshore wind energy (Bilgili and Alphan 2022).

The attractiveness of investments is determined by estimating net annual energy production (AEP), capital costs, and the cost of purchased energy (Satir et al. 2018). Before deciding whether to invest, for OWFs in particular, an appropriate plant profitability assessment is required due to cost structures that are highly dependent on site conditions, resulting in higher capital (CAPEX) and operational (OPEX) expenditures. Feasibility analysis for OWFs yields predictions regarding CAPEX and OPEX costs, including the net present value (NPV), payback period (PBP), internal rate of return (IRR), and levelized cost of electricity (LCOE), which are accurate predictors of power plant profitability. OWFs have a higher levelized LCOE and, a lower IRR than their onshore counterparts (Cali et al. 2018). While the cost of offshore wind is still not competitive today, the average LCOE for offshore wind overall has dropped from \$ 0.162/kWh in 2010 to \$ 0.084/kWh in 2020 (IRENA 2021). The weighted average cost of capital (WACC) for energy investments in fossil-fuel or renewable-energy technologies is a key factor in investment decisions. WACC varies significantly across countries and technologies (Polzin et al. 2021) and it also varies with time as technologies mature (Egli et al. 2018). For example, Steffen (2020) found the highest WACC in offshore projects and the lowest WACC in solar PV projects. In another project, only Belgian OWF projects have been studied in two studies for the same year. The interview-based estimate by Voormolen et al. (2016) is more than 7% higher than the financial market-based estimate by Estache and Steichen (2015). Many models are used to estimate the cost of capital; however, difficulties arise in their application. Very few models take a consistent perspective and use differentiated costs of capital at the level of technologies, countries, and/or regions (Hirth and Steckel 2016). For example, uniform WACC overestimates and underestimates renewable energy adoption in safer and risky countries (Schmidt Tobias 2014). Therefore, WACCs differentiated by country and technology should be integrated into energy-economy system models. As a result, these models will improve investment decision representation and provide consistency with observations and real-world data (Polzin et al. 2021).

Turkey's energy demand, like that of other developing countries around the world, is rapidly rising. Turkey's energy consumption is increasing at a faster rate as the economy develops and the population grows (Telli et al. 2021). By the end of 2020, the installed capacity and overall electricity production are, respectively, 96.7 GW and 305.458 GWh (Emeksiz and Demirci 2019). Figure 1 presents the share of installed capacity of energy resources as of the end of 2020 (TMMOB 2021). In addition, The Paris Climate Agreement was ratified by Turkey in 2021. For the first step, Turkey has committed to cutting carbon emissions by 21% by 2030 and reaching "net-zero" emissions by 2053.
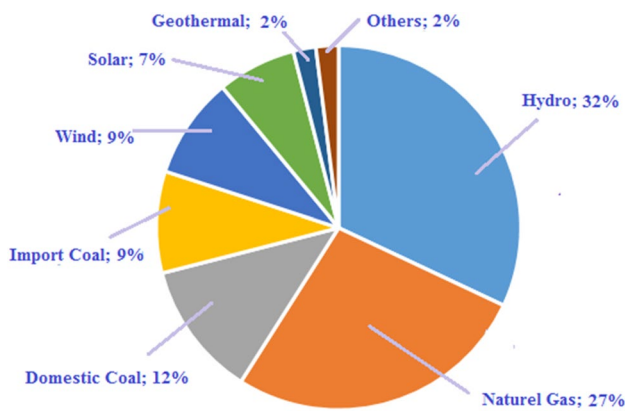
Fig. 1 The share of energy resources at installed capacity as of the end of 2020 (TMMOB 2021)

Literature survey

Köroğlu (2011) investigated OWF design criteria, grid connectivity problems, and analyzed the comparison and technical of grid connectivity methods. Güzel (2012) studied design criteria for OWF and examined a case study for Bozcaada and Gökçeada locations on the Aegean Sea. Akpinar (2013) assessed the wind energy potentials of coastal regions in northeastern Turkey near the Black Sea and discovered that wind energy resources are low. Ilkiliç and Aydin (2015) investigated the wind power capacity of all Turkish coastal areas and found out that the coasts of Aegean, Marmara, southern Anatolia, and northern Anatolia locations have maximum wind power potential. Argin and Yerci (2016) studied the suitability of 54 coastal locations for OWF development using location selection criteria. They found that the location selection criteria are critical in determining OWF development at a coastal location. According to İlhan and Bilgili, Turkey's offshore wind energy potential exceeds 10 GW, accounting for 22% of total wind power capacity (Ilhan and Bilgili 2016). Besides, they suggested Gökçeada, Bozcaada, Samandağ, Amasra, and İnebolu locations for the installation of OWF. Argin and Yerci (2017) examine the offshore wind power capacity of Turkey's Black Sea coastal location using location selection criteria, including the restrictions resulting from geographical, social and environmental features of the location. Despite its long coastline, their research shows that the Black Sea location has a limited number of offshore wind power generation sites.

Cali et al. (2018) conducted a thorough technical and economical feasibility study of OWF projects in three of Turkey's most hopeful wind regions. The proposed OWF projects are only economically viable if certain techno-economic conditions are met. Among proposed projects, The Bozcaada OWF truly is the best investment opportunity.,

with an LCOE of $ 81.85–109.55 per MWh. Satir et al. (2018) determined the feasibility of an OWF in the Turkish seas. In their studies, technical analysis was carried out by making various simulations with windPro software. This software has determined that the northern side of Bozcaada (in the Aegean Sea) is the best location for OWF development. Argin et al. (2019) used the multi-criteria site selections (MCSS) technique to identify the best OWF locations in Turkey among the 55 coastal locations, taking into account technical power capacities. Based on MCSS analysis, Bandirma, Bozcaada, Samandag, Inebolu, and Gokceada coastlines are the most appropriate OWF development regions. The total estimated offshore wind power capacity in the specified areas is found to be 1,629 MW.

Tercan et al. (2020) created an integrated methodology for determining the siting of bottom-fixed OWF in the sea area of the Izmir location (Turkey) and, in the Cyclades (Greece). The result indicated that in the Turkish region, 519 km^2 (10.23 percent) of the study area is suitable for OWF, whereas only 289 km^2 (3.22 percent) of the study location is appropriate in the Greek region. Aslan (2020) examined wind speed data from 18 different onshore, offshore, and coastal locations in the Turkish Province of Çanakkale. The performance of four onshore wind turbines and three coastal and offshore wind turbines was compared. Estimation of energy costs (C), NPV, PBP, benefit–cost ratio (BCR), and IRR were used to make comparisons. Best results were achieved in onshore Bozcaada, Canakkale Airport, and offshore and coastal locations of Lapseki/Zincirbozan L. and Bozcaada/ Damlacık L. Güner et al. (2021) stated that Sinop Province in Turkey is a region worth researching with its wind potential. In their study, suitable site selection was made first, followed by wind potential and power calculations. In the final step of their study, the cost of the required investments and the PBP of the investment was calculated using the levelized cost method. They revealed that the cost of electrical energy per kWh will be 7 cents. The investment's PBP, which includes operational expenditure (OPEX), has been calculated to be nearly 11 years. In addition to these studies, a detailed literature study on offshore research in Turkey is given in Table 1.

Aim of study

Over the last two decades, Turkey's population growth and rapidly growing economy have not only driven strong growth in energy demand but also increased import dependency. For this reason, Turkey intends to raise the proportion of renewable energy in total installed power. Among all the RES, wind energy is successful in Turkey due to its geographical location (Cali et al. 2018). Turkey has an estimated wind power capacity of 83 GW, making it the country

Table 1 Literature study on offshore research in Turkey

References	Location	Power density (W/m²) 10 m	Power density (W/m²) 50 m	Power density (W/m²) 100 m	Power density (W/m²) 150 m	Mean wind speed at 50 m (m/s)	Mean wind speed at 100 m (m/s)	Mean wind speed at 150 m (m/s)	Number of turbines	Total capacity (MW)	Tower spacing in a row	Tower spacing between rows	Distance of the closest turbine to the shore (m)	Distance of the farthest turbine to the shore (m)
(Argin et al. 2019)	Bozcaada					7.13		8.28	223	669	5D	10D	335	7360
	Bandirma					5.09		5.93	97	291	5D	10D	300	6640
	Inebolu					4.94		5.76	92	276	5D	10D	300	1930
	Gokceada					5.17		6.04	74	222	5D	10D	150	3620
	Samandag					5.27		6.16	57	171	5D	9D	175	1225
(Akdag and Yeroglu 2020)	Bartin			348			8.77		62	205	3D	8D		3000
(Argin and Yerci 2017)	Amasra		294		469	5.52		6.43						
	Cide		84		134	3.32		3.87						
	Inebolu		172		273	4.94		5.76						
	Sinop		70		111	3.57		4.08						
(Deveci et al. 2020)	Karasu					3.66		4.17						
	Amasra					4.88		5.57						
	Inebolu					5.54		6.32						
(Argin and Yerci 2016)	Gökçeada	4.12												
	Bozcaada	5.6												
	Samandag	4.24												
	Amasra	4.57												
	Inebolu	4.03												
(Cali et al. 2018)	Bozcaada					7.13		8.28	223	802.8	4.7D	9.3D		
	Bandırma					5.09		5.93	97	349.2	4.7D	9.3D		
	Gökçeada					5.17		6.04	74	266.4	4.7D	9.3D		
(Aslan 2020)	Çanakkale Strait Exit		904			9.04								
	Lapseki Zincirbozan L		938			9.16								
(Güzel 2012)	Bozcaada			1497			10.22		99	356	5D	10D		
	Gökçeada			610			7.38		56	140	5D	10D		
(Genç et al. 2021)	Samandağ		1027											
	Saros		913											
	Istanbul		580											

with the highest wind power capacity in the Organisation for European Economic Co-operation (Argin et al. 2019). The installed wind power capacity in Turkey is expected to reach 10,000 megawatts (MW) by the end of 2021, an increase of approximately 1,200 MW. Wind energy, which meets for about 8.5 percent of the total electricity production in Turkey, is expected to replace natural gas imports of 1 billion dollars. Although Turkey has recently focused on onshore wind energy, offshore applications have yet to be established. Turkey is surrounded on three sides by the sea and has a generally suitable seafloor as well as a long coastline with huge wind capacity. Turkey has a total of 12 GW of technical offshore potential in areas with a water depth of less than 50 m. When the water depth reaches 1000 m, 57 GW more capacity can be increased. Thus, Turkey is a pretty suitable region for OWF installation (World Bank 2019).

The investigations and studies with regard to Turkey's offshore wind power are relatively new. When the previous studies are analyzed, mostly they focus on offshore potential estimation, site selection, and feasibility analysis. However, this study also includes the economic aspects and analysis of Turkey's offshore wind energy, which is very neglected in the literature. Furthermore, the study deals with some potential technical and economic barriers that this energy might face in the future. Last but not least, discussions and suggestions on the way in which these barriers could be removed can be seen as a contribution to the literature. It is expected that this study will make a significant contribution to possible future offshore projects in Turkey.

Site selection

Turkey has a land area of 780,000 km^2 and is located between Asia and Europe. The country has rich offshore locations because it is surrounded by three seas, namely the Aegean, Mediterranean, and Black Seas. Furthermore, the Marmara Sea is located within the country's borders. But, thanks to its strategic position, which provides special shore security, and proximity to the sea territorials of neighboring countries, a detailed analysis is required to forecast Turkey's offshore wind energy potential (Argin et al. 2019).

For this purpose, it is necessary to conduct a preliminary investigation of restricted regions. Depending on the site characteristics, the perspectives could include, but are not limited to, military exercise areas, navigation routes and harbor entrance, environmental restrictions, gas and oil extraction, gravel and sand extraction, marine archaeology regions, underwater cables, seascape, and landscape as public heritage, aquaculture, offshore energy projects that have already been installed in the region of interest, as well as relevant site characteristics (e.g., distance to shore and the maintenance and operation base, water depth, geology, safety, regulatory and social problems). Considering the conditions

of the Turkish seas, several factors were considered by the Turkish government to determine the suitability of the site for an OWF installation (Cali et al. 2018). As a result of this evaluation, three regions were determined as offshore regions. In this study, a techno-economic feasibility study of these regions was conducted.

To increase the economic feasibility of appropriate OWF locations, turbine micro-sitting is carried out using four key factors; distance to shore, sea depth, turbine spacing, and wind direction. Wind turbines in each region are installed perpendicular to the primary wind direction to maximize wind energy use. Also, as shown in Fig. 2, wind turbines are arranged in rows with a spacing of 5 rotor diameters (D) within each row and 10 D between rows to reduce wake effects, as recommended in (Cali et al. 2018).

After the micro-sitting of offshore wind turbines, turbine selection was made in these regions. Table 2 and Fig. 3 show the models and technical specifications of the selected turbines.

Features of offshore wind farms

The average wind speed, power density, water depth, and capacity factor values for the 3 OWFs examined in this study are determined from the Global Wind Atlas internet address (GWA). This web address uses the WASP program. Table 3 shows the analysis results, which include wind power density, wind speeds, and capacity factors. Table 3 also shows the features of the OWF.
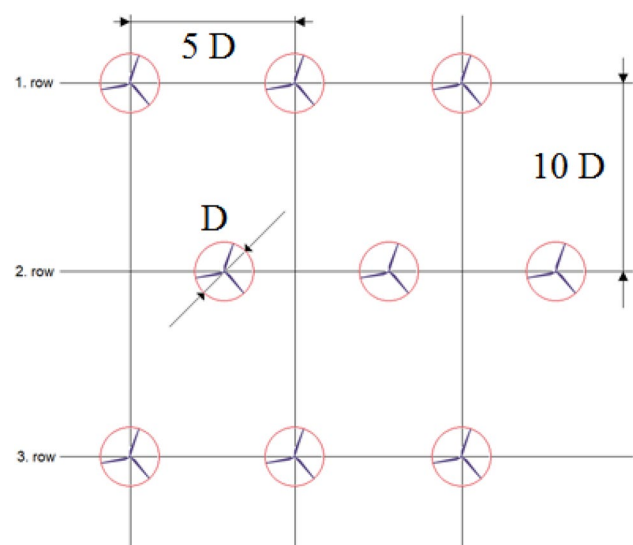

Fig. 2 Micro-sitting of the offshore wind turbines

Table 2 Technical properties of selected turbines

Technical properties	Kiyikoy	Gelibolu	Saros
Turbine type	Vestas V126-3.0	Vestas V126-3.3	Vestas V126-3.45
Rated power (kW)	3,000	3,300	3,450
Cut-in wind speed (m/s)	3	3	3
Rated wind speed (m/s)	12	12	12
Cutout wind speed (m/s)	22.5	22.5	22.5
Rotor diameter (m)	126	126	126
Rotor Swept area (m^2)	12,469	12,469	12,469
Number of blades	3	3	3
Turbine specific power capacity (W/m^2)	240.6	264.7	276.7
Tower hub height (m)	100	100	100
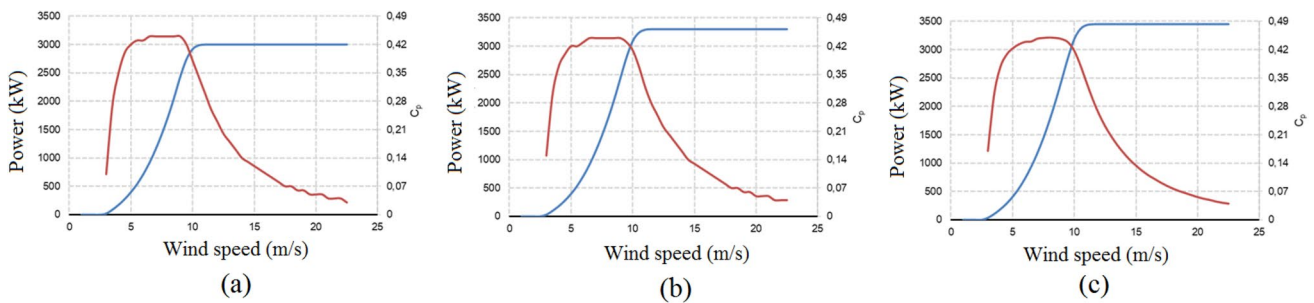
Fig. 3 Power curves of references offshore wind turbines **a** Vestas V126-3.0 **b** Vestas V126-3.3 **c** Vestas V126-3.45

Table 3 The designed offshore wind systems for the three coastal locations of Turkey

Characteristic	Kiyikoy	Gelibolu	Saros
Mean wind speed at 100 m (m/s)	6.3–6.96	7.0–7.76	7.38–8.69
Mean power density at 100 m (W/m^2)	300–433	450–637	500–735
Mean capacity factor at 100 m (%)	31–35	38–44	37–51
Water depth (m)	5–70	5–75	5–100
The distance between the closest turbine and the shore (m)	45	97	45
The distance between the farthest turbine and the shore (m)	11,000	6,350	12,180
Number of turbines	228	327	454
Sea surface area (km^2)	263	182	367.62
Number of turbines per GW	333	303	290
Area needed per GW (km^2)	384.5	168.66	234.7
Total capacity (MW)	684	1,079.1	1,566.3
			3,329.4

Siting analysis for selected regions

The three regions listed in Table 3 are considered for the technical features and siting analysis. Kıyıköy is a village in the district of Vize in the Krklareli Province of northwestern Turkey. It is located on the Black Sea coast. Kiyikoy currently has two onshore wind farms with an overall capacity of 73 MW. Analysis conducted for Kiyikoy at 100 m height is shown in Fig. 4. The average wind speeds at 100 m range

from 6.30 to 6.96 (m/s), while the wind power density varies between 300 and 433 (W/m^2). The wind directions are mainly from the northeast to the southwest and from the north to the south. Figure 5 illustrates the suggested OWF at Kiyikoy shores, as well as the sitting of turbines. Offshore wind turbines are placed on the north and northwest sides of the region to capture the most energy from the wind, as shown in Fig. 5 because the primary wind direction is from northeast to southwest in Kiyikoy. The mean capacity factor
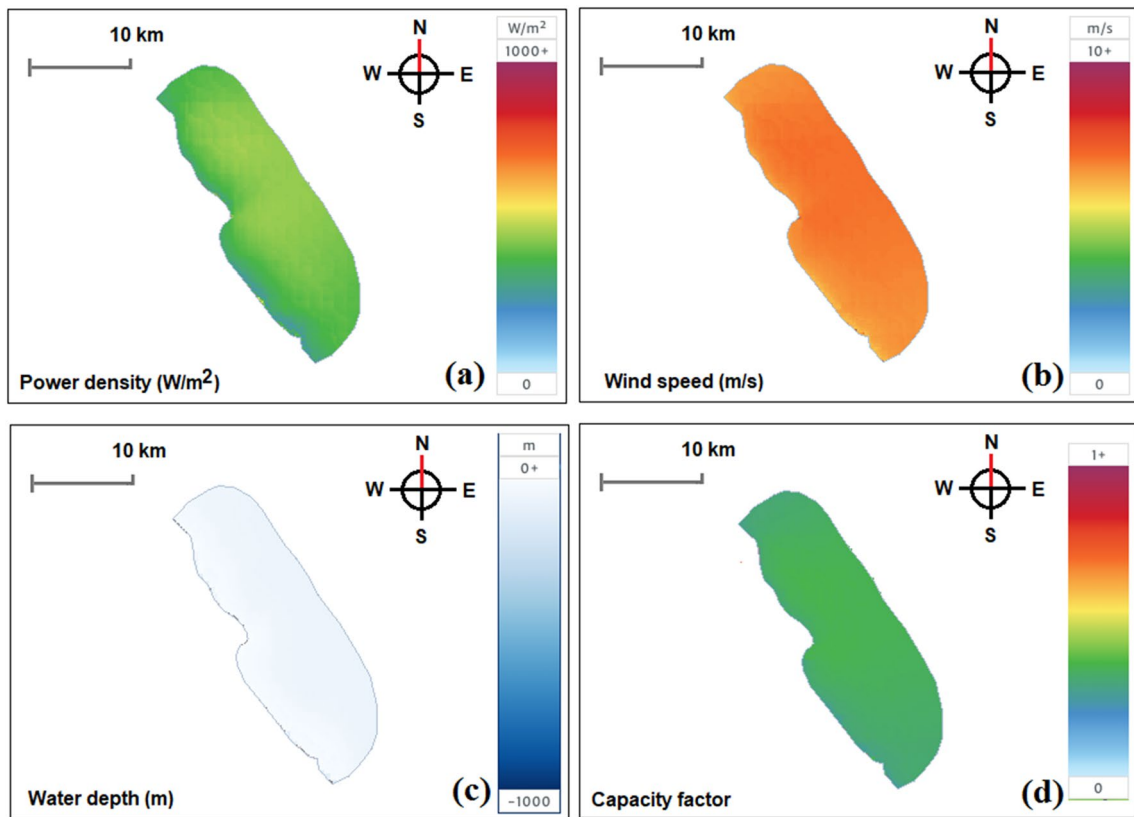
Fig. 4 Characteristic features for Kiyiköy OWF **a** power density (W/m^2) **b** wind speed (m/s) at 100 m. **c** water depth (m) **d** capacity factor
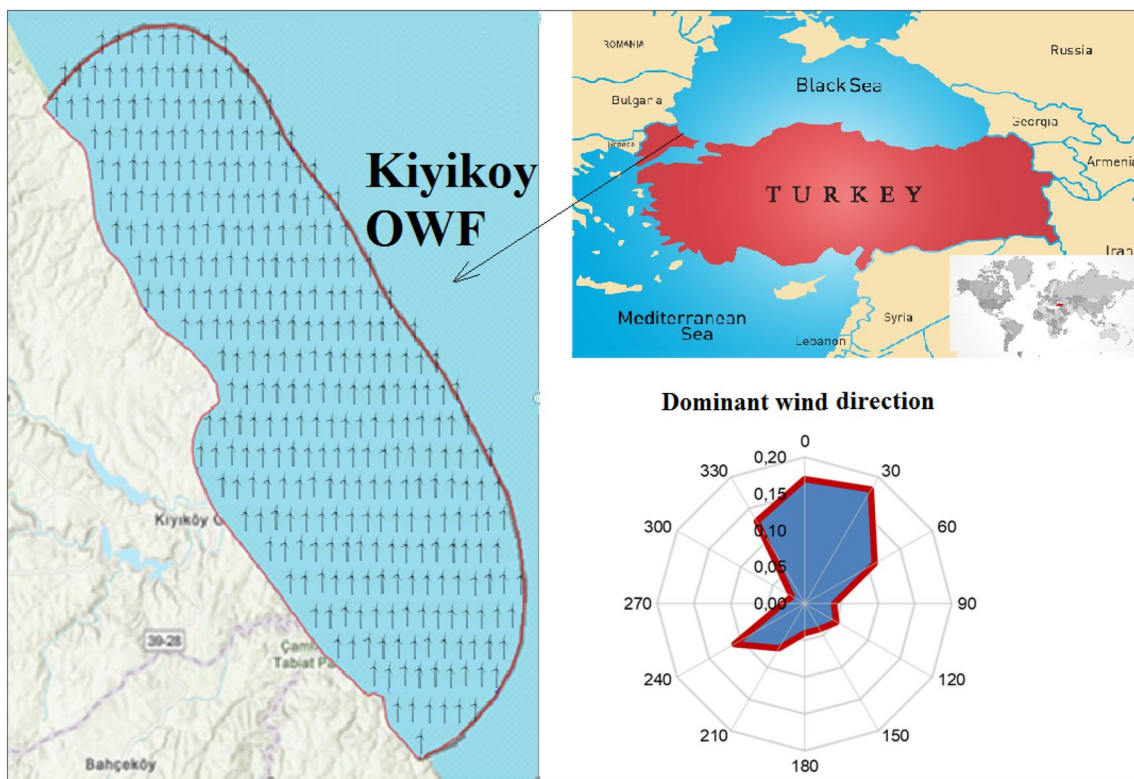

Fig. 5 The proposed site and siting of offshore wind turbines at Kiyiköy

at 100 m varies between 31 and 35 (%). Wind turbines are installed up to a depth of 70 m by the location's primary wind directions. The total number of offshore wind turbines is determined by distances between the turbines, the blade size, and the available surface area at the chosen location. It is determined that the chosen location of 263 km² at Kiyikoy can house up to 228 wind turbines. It is calculated that a total of 684 MW of power is produced according to the number of wind turbines. The closest and farthest wind turbines are 45 m and 1100 m away from the coastline, respectively.

Gelibolu is located on the Gallipoli Peninsula, between the Aegean Sea and the Dardanelles Strait. Because of the high wind power density, the area has a significant number of onshore wind power plants with an overall capacity of 236 MW. Wind speeds height change in the range of $7 \leq V \leq 7.76$ m/s at 100 m height. According to the results obtained at 100 m height, the mean power density varied from 450 to 637 (W/m²) in this region. The analysis results are shown in Fig. 6. As illustrated in Fig. 7, the wind direction is from northeast to southwest. As a result, turbines can be installed in this area in these directions to maximize energy output. The selected area is a relatively small sea surface area as compared to the Kiyiköy and Saros OWF. The mean capacity factor at 100 m varies between 38 and 44 (%). The wind turbines are installed up to a sea depth of

75 m according to the primary wind direction in the location. Overall installed power of 1079,1 MW can be obtained in Gelibolu with an overall of 327 turbines on an area of 182 km². The closest and farthest turbines are about 97 and 6350 m from the coastline, respectively.

The Gulf of Saros (Saros Bay) is a northern Aegean Sea inlet. The bay is 35 km wide and 75 km long. Saros currently has one onshore wind farm with a capacity of 132,89 MW. The analysis results are shown in Fig. 8. As shown in Fig. 9, the wind directions are mainly from the northeast to the southwest. According to the analysis results for Saros Bay, maximum power of 1566.3 MW is obtained with 454 turbines when a surface area of 376.62 km² is used. In comparison to its Kiyiköy and Saros counterparts, in the selected location, the sea part is relatively deeper. Wind turbines are installed up to 100 m sea depth according to the primary wind direction of the location. In addition, the selected site has a more wind speed as compared to its other two counterparts. The mean wind speed ranges from 7.38 to 8.69 (m/s), while the wind power density varies between 500 and 735 (W/m²) at a height of 100 m. The mean capacity factor at 100 m varies between 37 and 51 (%).

The designed OWFs coastal regions are summarized in Table 3. The average wind speed at 100 m height values of Kiyikoy, Gelibolu, and Saros regions is, 6.8, 7.5, and 8.4 m/s,
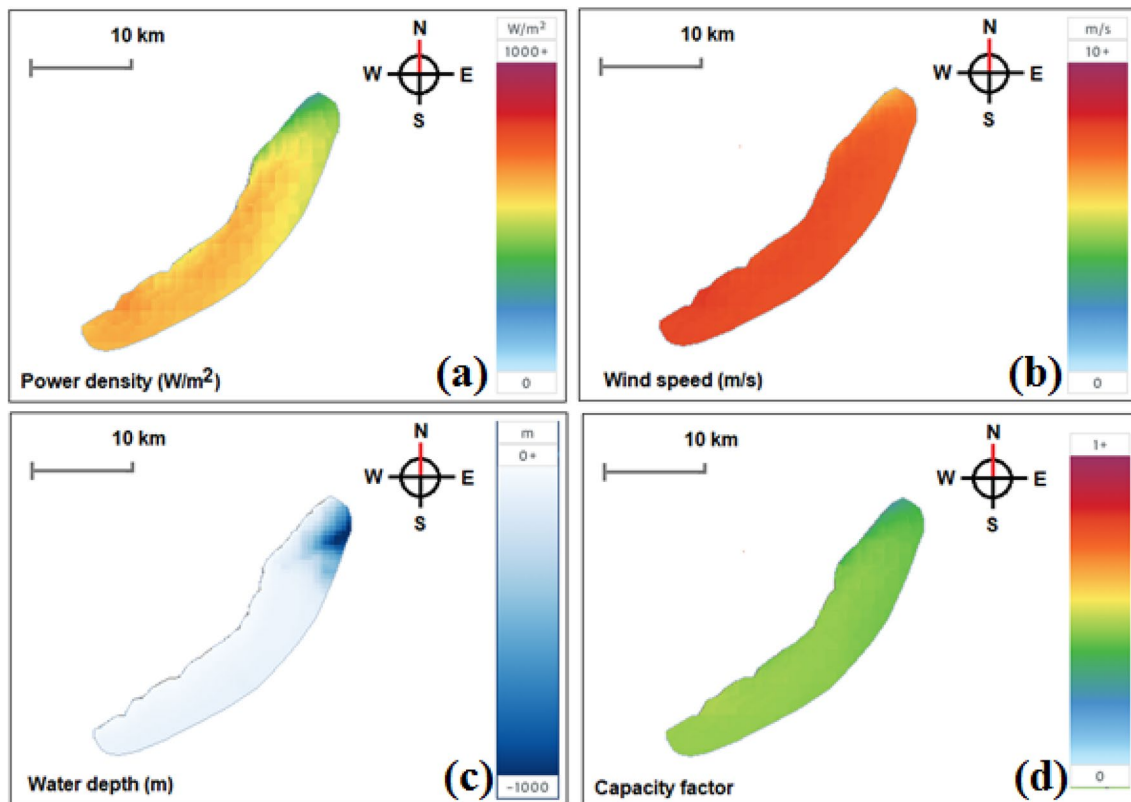

Fig. 6 Characteristic features for Gelibolu OWF **a** power density (W/m²) **b** wind speed (m/s) at 100 m. **c** water depth (m) **d** capacity factor
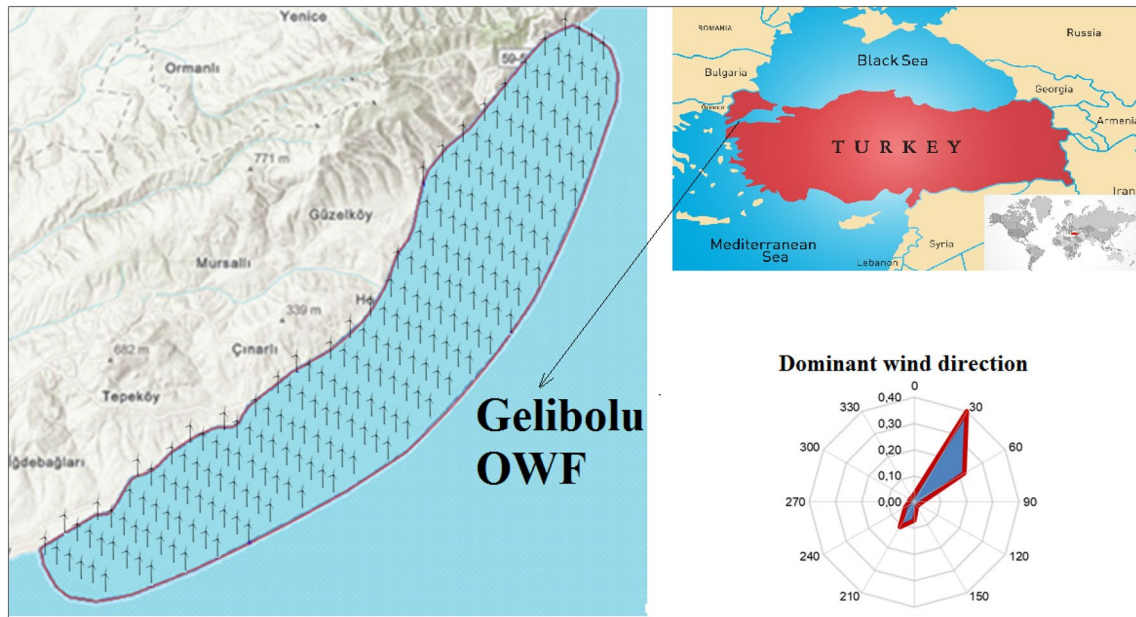
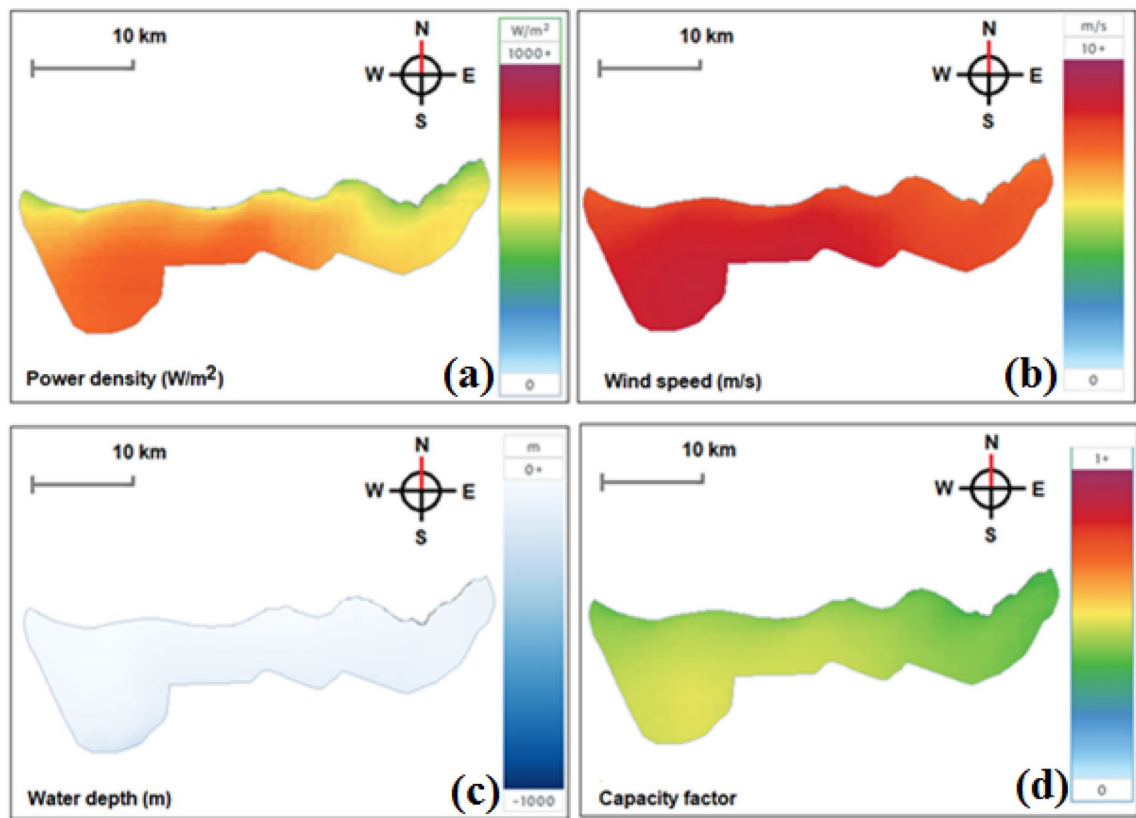**Fig. 7** The proposed site and siting of offshore wind turbines at Gelibolu

Fig. 8 Characteristic features for Saros OWF **a** power density (W/m^2) **b** wind speed (m/s) at 100 m. **c** water depth (m) **d** capacity factor

respectively. It is seen in Table 3, the highest value of the mean power density is 735 W/m^2 at Saros, while the lowest value is 300 W/m^2 Kiyikoy at 100 m. In addition, the water depths are changing from 5 to 100 m for selected sites. The average water depth values of Kiyikoy, Gelibolu, and Saros are 45, 50, and 60 m, respectively. Besides, the selected region
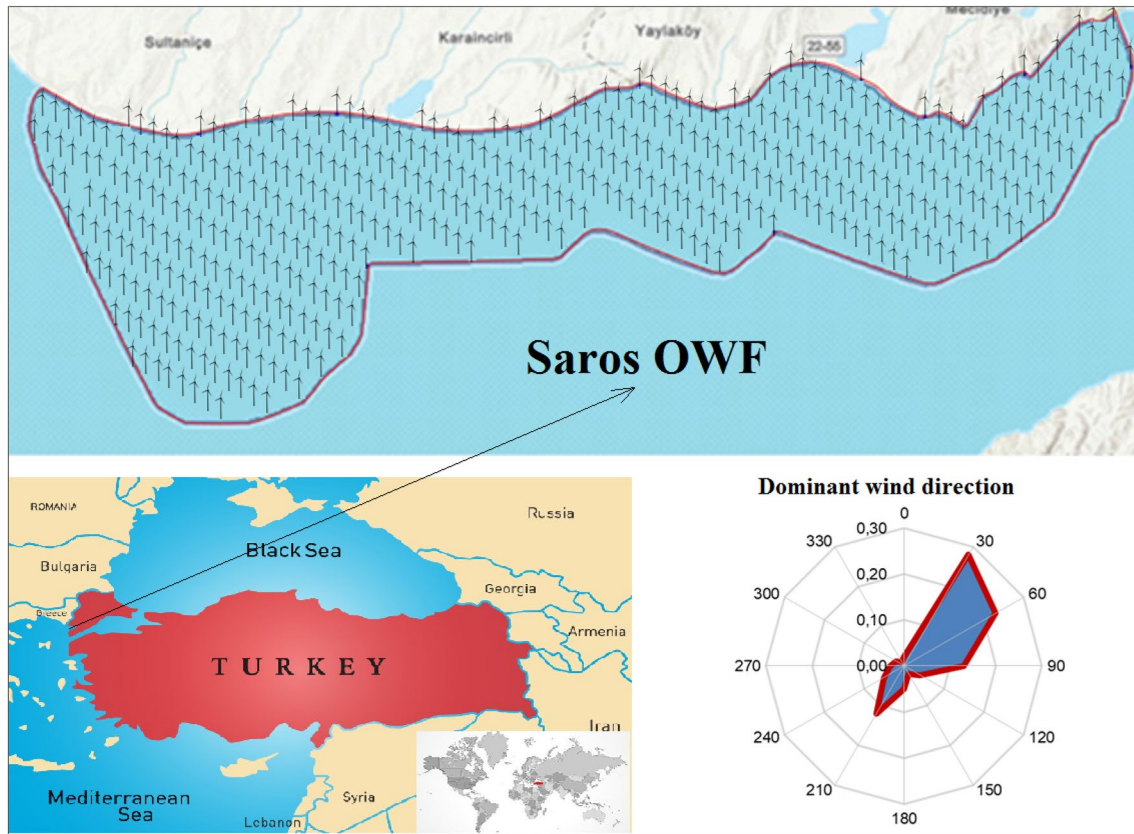
Fig. 9 The proposed site and siting of offshore wind turbines at Saros

Techno-economic analysis

needed per GW (km^2) of values of Kiyikoy, Gelibolu, and Saros regions is 384.5, 168.66, and 234.7, respectively. Within the selected OWFs, an OWF with a maximum offshore capacity of 1566,3 MW could be installed in Saros. As reported in Table 3, for the offshore wind farm, the Saros region seems to be the most promising and convenient site for the production of electricity from wind speed.

Economic analysis is useful in identifying the most influential parameters that influence the change in outcomes (Pyakurel et al. 2021). The LCOE, NPV, present payback period (PPBP), and discounted payback period (DPP) are important investment indicators that help OWF developers make decisions. Each indicator provides critical information regarding the cash flow. All indicators are considered by investors before making a final investment decision because one indicator cannot accurately represent all investment Dynamics (Xiang et al. 2021).

LCOE takes into account the CAPEX, the Annual Energy Production (AEP), and, the OPEX of the OWF, according to Eq. (1) (Tsvetkova and Ouarda 2021).

$$\text{LCOE} = \frac{\sum_{i=1}^{N} \frac{\text{CAPEX}_i + \text{OPEX}_i}{(1+\text{WACC})^i}}{\frac{\sum_{i=1}^{N} \text{AEP}_i}{(1+\text{WACC})^i}} \tag{1}$$

where $CAPEX_i$ is denotes investment in year i, $OPEX_i$ is maintenance in year i, i are the total cost of capital expenditure, WACC is the annual discount rate and, AEP_i is the annual energy production, N is the project lifetime.

The NPV is the net value of all cash inflows and cash outflows from the project, discounted back to the beginning of the investment. If the NPV exceeds zero, the project is economically feasible because it is profitable. As a result, the NPV is calculated using (Rinaldi et al. 2021).

$$\text{NPV} = \sum_{i=1}^{N} \frac{\text{AEP}_i \text{FIT} - \text{CAPEX}_i - \text{OPEX}_i}{(1 + \text{WACC})^i} \tag{2}$$

where FiT is wind electricity sell price.

The present payback period (PPBP) is also another common method of analysis used to determine the annual profitability of investments. It is the year when the total NPV of all benefits equals the total NPV of all costs. The following equation can be used to calculate it (Aslan 2020).

$$\text{PPBP} = \frac{\text{CAPEX}}{\text{AEP.FIT - OPEX}} \qquad (3)$$

As shown in Eq. (4), the discounted payback (DPP) period is used to determine how long it will take to recoup an investment's cost.

$$\text{DPB} = X + \frac{Y}{Z} \qquad (4)$$

where X is the last period with a negative discounted total cash flow ($); Y is the absolute value of the discounted total cash flow at the end of period X ($), and Z is the discounted cash flow in the period following X ($).

The overall cost of the OWF, which includes CAPEX and OPEX, is first calculated in order to decide the economic indicators. The cost of installing, purchasing, and decommissioning the plant is referred to as CAPEX, whereas OPEX refers to the ongoing cost of maintaining and operating the OWF. Second, the net AEP is calculated using the plant's technical specifications, like electrical losses and capacity factors. The final step entails calculating the revenue generated by the energy sale. This calculation takes into account financial parameters such as the plant's available operational lifespan, FiT, and WACC.

CAPEX

CAPEX includes the costs of the turbine, foundation, electric system, and project development.

The wind turbine cost is calculated for turbines between 2 and 5 MW. The total turbine cost, which includes installation and transportation, is estimated to be 10% of the wind turbine cost, which is given by (Dicorato et al. 2011).

$$C_{\text{turbines}} = 3.245.10^{-3} \ln(p) - 412.72 \ [k\text{€}] \qquad (5)$$

where P is the installed capacity of offshore wind power.

The cost of the support system (tower and foundation) includes installation, manufacturing, and transportation. The support system's transportation and installation costs are estimated to be 50% of the overall system's manufacturing costs. In Ref (Dicorato et al. 2011), Eq. (6) can be used to formulate it.

$$C_{\text{support}} = 480.P(1 + 0.02(d - 8))\left(1 + 0.8.10^{-6}\left(h.\left(\frac{D}{2}\right)\right) - 10^{-5}\right) \ [k\text{€}/\ turbin] \qquad (6)$$

where h [m] is hub height, d [m] is sea depth, and D [m] is rotor diameter.

We assume $ 1130/kW for electrical infrastructure based on NREL offshore wind cost breakdown estimations (Rubio-Domingo and Linares 2021).

The development of the project, as well as other costs like design and engineering costs, and construction phase insurance are predicted to be $ 280.38 per MW based on (Cali et al. 2018).

OPEX

The operational and maintenance cost (O&M cost) of an OWF, as well as other cost components like royalties, administrative cost, and insurance premiums, are all included in the OWF's OPEX. For wind offshore projects built-in 2020, the OPEX is estimated to be 59,9 K€/MW/year (based on the Danish Ministry. (Danish Energy Agency 2018)).

AEP

AEP is the annual energy production. The AEP output of turbines can be calculated by using the installed power of wind farm (N_e), the capacity factor (C_f), and efficiency (η) (Ozdilim 2017):

$$\text{AEP} = 8760.N_e.C_f.\eta \qquad (7)$$

In this study, the net AEP is determined by subtracting electrical cable losses (3%) and wake effects (2%) from the gross AEP.

WACC

WACC is considered a suitable instrument to measure the relevant cost of capital and investment risks. The WACC is a useful indicator for assessing the entire cost of capital and is used as a sufficient measure for determining the proper discount rate in the financial evaluation of RE projects (Stocks 1984). According to the model-based research, the assumed cost of capital or discount rate has been recognized to have a significant impact on cost-effective technology choices (Hirth and Steckel 2016). The following mathematical formula presents the WACC indicator (Angelopoulos et al. 2016).

$$\text{WACC} = \frac{E}{E + D} * C_e + \frac{D}{E + D} * C_d * (1 - \text{CTR}) \qquad (8)$$

C_e: cost of equity, E: market value of equity, C_d: cost of debt, CTR: corporate tax rate, D: market value of debt.

Because of heterogeneity in the finance supply side, differentiated WACCs can emerge by country, technology, and over time (Egli et al. 2018). These differences; first of all, the investment risk differs depending on the RE technology

(Polzin et al. 2019). Second, the total investment risk is influenced by the country in which RE projects are being implemented. Third, investment risks associated with both technology and country may change over time (Mazzucato and Semieniuk 2018). For those reasons, coming up with a correct presumption about the cost of capital in energy models and investment opportunities remains difficult. As a result of these challenges, the scholars used a wide range of estimation methods, from qualitative interviews to financial market econometrics. The estimation methods can be divided into four categories, which are summarized below (Steffen 2020).

(1) Survey of expert estimates: Since deal data is scarce, many studies rely on expert estimates from RE market participants, which are frequently supplemented by archival data. There are studies on this subject (Szabó et al. 2010). Kumar et al. (2017) interviewed "country experts"; Ardani et al. (2013a, b) communicated with market participants; Angelopoulos et al. (2017) discussed 80 experts, and carried out some of the studies (Wood and Ross 2012).

(2) Replication of the auction results: Apostoleris et al. (2018) and Dobrotkova et al. (2018) used a different method for estimating the cost of capital, relying on non-financing information for projects awarded a PPA through competitor auctions. They targeted to decompose the cost structure of award-winning projects. They take advantage of the fact that a lot of non-financial information about the winning bids is in public.

(3) Project finance data elicitation: The most basic method of calculating the RE cost of capital is to gather and evaluate the costs of various capital components from particular RE projects finance deals, as listed in documents held by the financial institutions. Because project finance data is often secret, obtaining such information can be difficult. (Krupa and Harvey 2017). Nonetheless, a few scholars have been successful in collecting data, beginning with Lorenzoni and Bano (2009), who conducted an investor survey, and Shrimali et al. (2013) conducted interviews with project developers to elicit financial parameters.

(4) Analysis of financial market data: This estimation method can be divided into two general approaches. The market cost of debt: The price at which investors would be willing to buy a company's debt is referred to as the market value of debt (Sweerts et al. 2019). Although no project is typically funded with bank loans or bonds, these methods are used to estimate the debt cost of special RE assets. Kitzing and Weber (2015) used archival data on typical swap premiums and bank margins to calculate the risk-free rate. Estache and Steichen (2015) used data from the financial statements of Belgian renewable energy producers. Market return on equity: The Capital Asset Pricing Model (CAPM) calculates an investment's expected return (cost of equity) using its systematic risk. For RE projects, the following formula is used to calculate CAPM (Angelopoulos et al. 2016):

$$C_e = r_f + \beta(r_m + r_f) \tag{9}$$

where $(r_m + r_f)$ is equity market premium, r_f is the risk-free rate, and β is the only relevant measure of a stock's risk. In capital asset pricing, the beta coefficient is a critical feature. Whereas beta is commonly used as a risk measure in developed markets, the classic CAPM appears to be less appropriate for emerging and developing markets (Donovan and Nuñez 2012).

Empirical WACC estimates for many countries now are available that can be used by energy economists and energy system modelers. Even so, the overall coverage is fragmented, with so many countries investigated in only 1 or 2 two articles. When we discuss the suitability of methods, eliciting deal data appears to be better suited for the assessments of single markets, rather than cross-country assessments. Expert estimation surveys appear to be less suitable to obtain precise values, but more appropriate for initial estimation of the cost of capital in a broader range of countries. The replication of auction outcomes has proven to be a valuable addition to expert interviews. But, this method is dependent on the quality and extent of available non-financing data. The financial market data method appears to be appropriate for analyses comparing the cost of capital in various countries for which market data is available from financial information providers. However, this method appears to be less appropriate for comparing technologies within a country. CAPM estimations provide the method's limited empirical support, as proved by Fama and French (1993) and others. As a result, each method has different advantages and disadvantages according to country and technology, researchers select the estimation method based on the best available data, keeping in mind the suitability of the various approaches, and incorporating all incremental improvements made by previous studies (Steffen 2020).

It is quite difficult to calculate the WACC empirically in this study because there are no offshore projects in Turkey. Turkey is an OECD member and developing country. Therefore, the WACC rates of OECD and developing countries are taken as a reference. In the literature, different estimation method results have been found for WACC. When we summarize these results; Sharma (2016) made a financial and economic evaluation to find the WACC. The author found the Project's WACC is roughly 5.9% in the UK. Roth et al. (2021) conducted interviews in eleven European countries on the estimation of the WACC rate. The maximum WACC

was determined as 9.0% in Germany. Polzin et al. (2021) calculated the average WACC of 10.03% for European countries using the GEM-E3-Power model. Steffen (2020) used several empirical methods to calculate the WACC rate. As a result of the study, the WACC for OECD countries was found to be approximately 8.3%. Lozer dos Reis et al. (2021) stated that the WACC was calculated as 10% for non-OECD countries in their study. In general, in the literature, it has been observed that WACC vary between 5 and 10% in countries whose economy is similar to that of Turkey. For this reason, the WACC is taken range from 5 to 10% in this study.

Results and discussion

OWF economic feasibility studies are carried out in three regions of Turkey. The proposed OWFs' project lifespan is assumed to be 25 years. Turkey has determined two different FiTs. Firstly, the base FiT of 7.3 $/kWh is used, which corresponds to the export of all mechanical and electrical OWF equipment. Secondly, considers a maximum FiT of 11 $/kWh, which corresponds to a case in which all mechanical and electrical OWF equipment is manufactured in Turkey. In this study, the base FiT of 11 cent/kWh is used. In addition, the NPV value is calculated for the FiT of 8 $/kWh determined by the Turkish government. It is accepted that WACC between 5 and 10% perform financial analysis. The real interest rate is determined as 0.03 by averaging the inflation rate and the nominal discount rate over the previous ten years. (Gönül et al. 2021). It is assumed that the initial investment cost is paid using this interest rate at equal intervals over 25 years using bank loans. In additıon, taxation rates are ignored in this study.

CAPEX, OPEX, and AEP values

Table 4 shows the comparisons of Total CAPEX, CAPEX, OPEX, and AEP analysis results in all locations as expected, according to the overall installed offshore wind power potential, the highest overall CAPEX value for Saros OWF where sea depth is maximum is estimated to be around $ 6258 million. Comparisons between those found in the literature

and the results presented here show that the results are reasonable. The average CAPEX per installed capacity (MW) for OWF is 3799 ($/kW) according to the NREL report (Walter Musial et al. 2020). The CAPEX ($/kW) calculated as a result of this study ranged from 3798 to 3995 ($/kW), depending on the location, demonstrating the reasonableness of the values. Annual OPEX values for Kiyikoy and Saros OWFs range from $ 46.9 million to $ 107.4 million, respectively, based on the cumulative installed offshore wind power potential.

Table 4 summarizes the three OWFs' net AEP values. According to the installed offshore power capacity and capacity factor, the Saros OWF has the highest net AEP at 5,735,289,384 kWh per year, while the Gelibolu and Kiyikoy OWFs have significantly different net AEPs. Kiyikoy station has the lowest net AEP value of 1,878,441,840 kWh.

LCOE, NPV, PPBP, and DPB values

Table 5 summarizes the projected LCOE, NPV, PPBP, and DPB values for the three OWF projects. It was observed for each location that the points with the lowest CAPEX/MW do not coincide with the points with the lowest LCOE because the levelized cost of energy includes the AEP. Furthermore, because of the small difference in CAPEX values between regions, LCOE is a better indicator for determining the best location of OWFs. The Kiyikoy OWF has a higher per MWh LCOE than the other two counterparts, despite having a lower CAPEX. According to IRENA (2020), the global weighted average LCOE calculated using project data for 2020 was $ 84/MWh. The Netherlands had the minimum weighted-average LCOE for projects commissioned in 2020, at $ 67/ MWh China had the second-lowest weighted-average LCOE. Prices for projects scheduled to be completed in 2023 are expected to range between $ 50/ MWh and $ 100/MWh. CAPEX is a significant factor in calculating the LCOE. Reducing CAPEX by 40% (from 10 to 6%), for example, reduces LCOE by up to 20% (Lozer dos Reis et al. 2021). As shown in Table 5, the Kiyikoy OWF has a positive NPV of $ 95,271,878 indicating that it is economically viable. At the end of its lifespan, the Gelibolu OWF's NPV can reach $ 830,512,136. It is possible to say

Table 4 CAPEX, OPEX, and AEP values of the proposed OWFs

	Kiyikoy	Gelibolu	Saros
Total CAPEX (million $)	2597	4169	6258
CAPEX ($/kW)	3798	3864	3995
OPEX (million $/ year)	46.9	74	107.4
AEP (kWh)	1,878,441,840	3,681,910,782	5,735,289,384

Table 5 LCOE, NPV, DPB, and PPBP values of the proposed OWFs

	Kiyikoy	Gelibolu	Saros
*NPV ($)	11,860,249,188	23,890,899,679	37,409,374,511
NPV ($)	95,271.878	830,512,136	1,488,353,145
LCOE ($/MWh)	104.4	85.1	81.4
PPBP (year)	15.23	11.84	11.24
DPB (year)	19.78	11.23	10.25

*NPV were calculated based on, the FiT value is 8 cent/kWh

that the Gelibolu OWF project appears to be economically feasible. The NPV of Saros OWF has a positive value of $ 1,488,353,145. Similar to Kiyikoy and Gelibolu OWF, the project of Saros OWF is economically feasible. The Saros OWF has a higher net NPV thanks to a big capacity factor and the sitting of more turbines, which in turn makes the region more favorable. If NPV, FiT is calculated as 8 cent/kWh, OWFs are almost not economically feasible. Higher WACC and interest rates, higher CAPEX values, and lower FiT and capacity factors make the investigated OWFs economically unfeasible.

It is clear from Table 5, the PPBP values of Kiyikoy, Gelibolu, and Saros stations are 15.23, 11.84, and 11.24 are calculated. Figure 10 shows Kiyikoy OWF's discounted cash flow over the project's lifespan for both WACC rates. The DPBP value is found when the NPV value starts to be positive after 19 years. The Kiyikoy OWF is estimated to have a DPBP value of 19.78 years in the best case. Figure 11 depicts the Gelibolu OWF's net discounted cash flow distribution over its lifespan for both WACC rates. The DPBP value is calculated at 11.23 years in this region (Fig. 12). Figure 13 shows the NPV values for WACC which range from 5 to10%. As illustrated in Fig. 13, the NPV value never reaches the negative for the studied
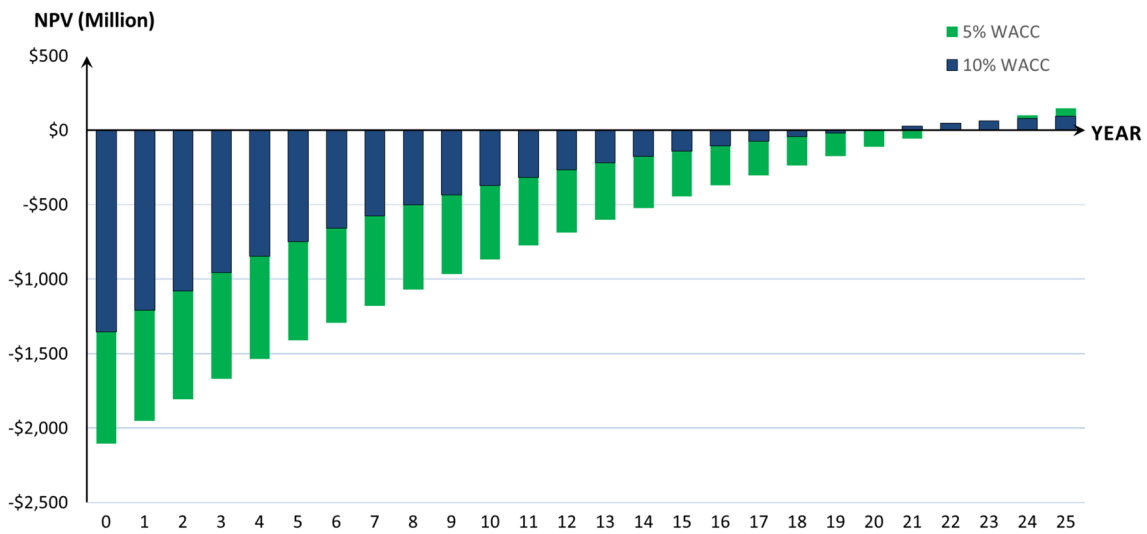

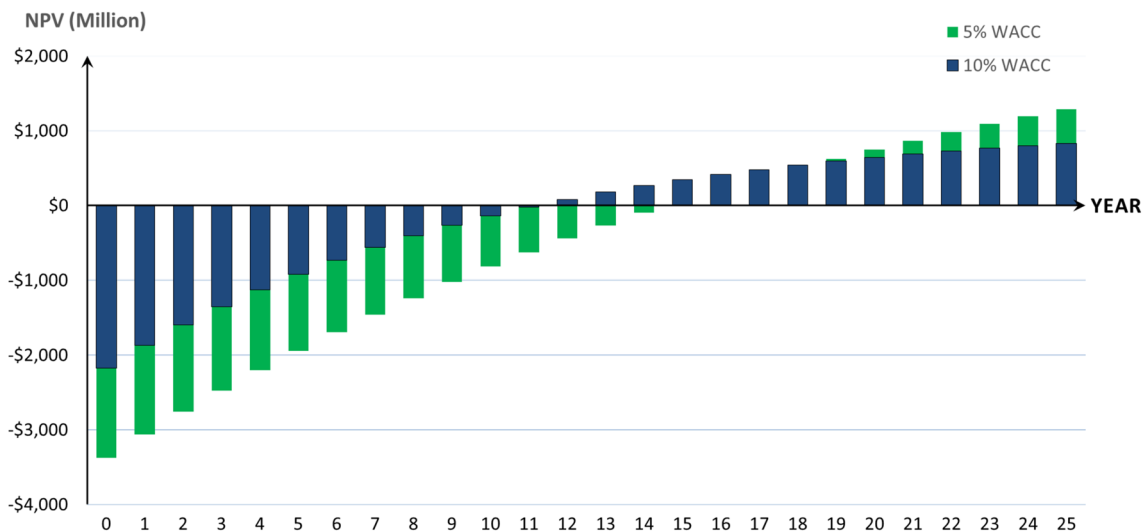**Fig. 10** Kiyikoy OWF's discounted cash flow for both WACC rates

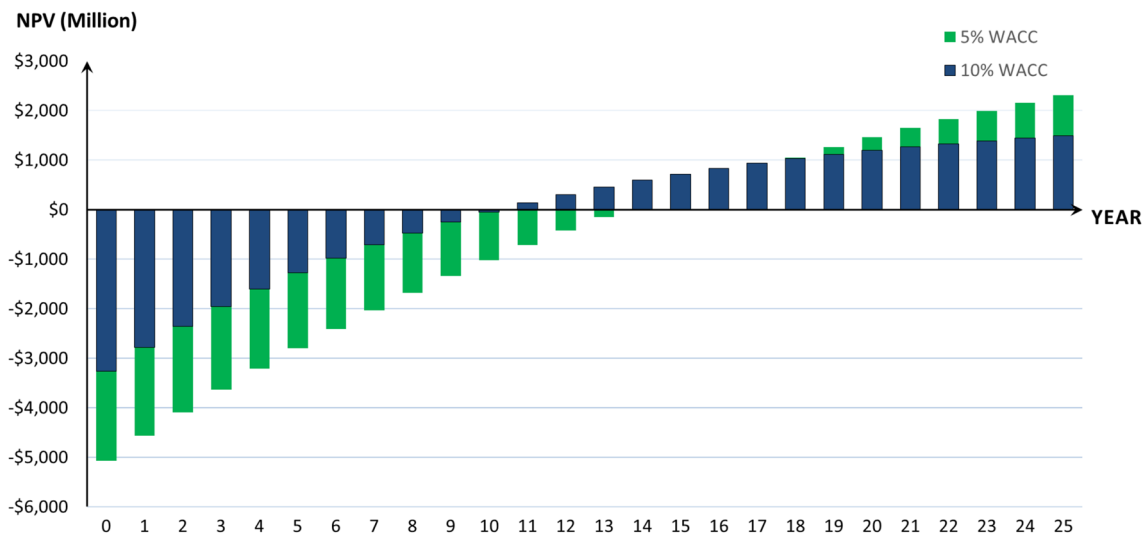**Fig. 11** Gelibolu OWF's discounted cash flow for both WACC rates

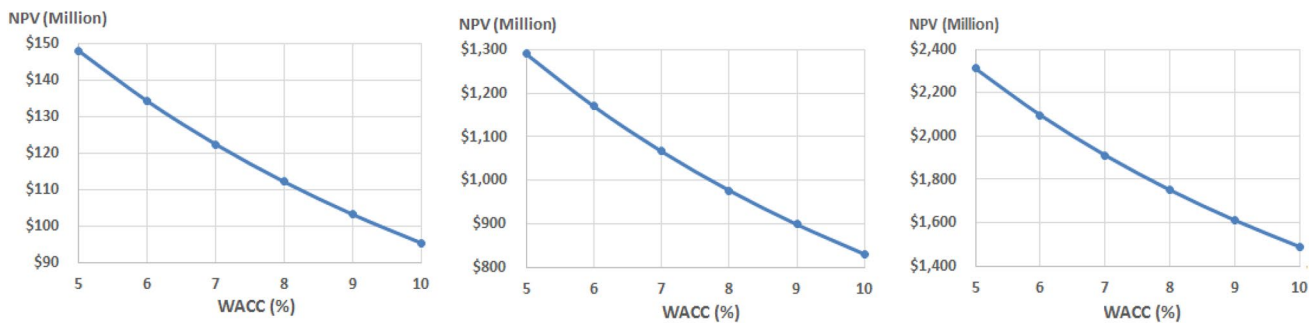**Fig. 12** Saros OWF's discounted cash flow for both WACC rates

Fig. 13 The variability of NPV in terms of WACC **a** Kiyikoy OWF **b** Gelibolu OWF **c** Saros OWF

WACC rates. It means that 3 OWF projects are economically feasible. Values shown in Fig. 13 were statistically analyzed by Analysis of Variance (ANOVA) for robustness check. Statistical significance was based on the confidence level of 95% ($p < 0.05$). The Model P-value of 4.17E-05 was calculated. P-value less than 0.0500 indicates model terms are significant. The estimated coefficient of determination for the model in this study ($R^2 = 0.989$) demonstrates good prediction agreement between the WACC and discount rates.

If turbines are built far away from the shore and in deeper waters, the LCOE value increases. For more OWF capacity, it is found that the MCSS analysis is needed before installing OWFs. Turbine power and the capacity factor is also important for the LCOE. Project finance has been of great importance for offshore projects (Egli et al. 2022). FiT level and duration, WACC, and interest rate are the most effective financial parameters (Steffen and Waidelich 2022). A fixed tariff lowers price risk, which in turn affects return on investment, whereas a variable tariff structure raises uncertainty. FiT duration helps determine project risk; a long-term deal reduces risk, while variability in duration rises it. Interest rates and WACC change dynamically over time, increasing financial risk and uncertainty. Investment risk is significantly impacted by credibility and predictability. Reducing risks is particularly important for offshore investments due to the resulting high financing requirements and their high upfront capital.

Support policies can be increased for RE investors' perceptions of risk and return. In future studies, more policy design options and their risks and return should be explored, broaden the range of policy assessment, scholars should explore the risk/return preferences of RE shareholders over the period, identify the consequences of potentially undesirable policy sets, and one should consider the socioeconomic consequences of assisting various kinds of investors (Polzin et al. 2019).

Conclusion

This article presents a techno-economic feasibility study for OWF projects at three locations in Turkey. The offshore wind power capacity values of Kıyıköy, Gelibolu, and Saros stations in this study are 684 MW, 1079.1 MW, and 1566.3 MW, respectively. Even only three offshore projects correspond to approximately 30% of the total wind installed power for Turkey.

CAPEX estimates for the Kiyikoy, Gelibolu, and, Saros OWF projects are $ 3798, $ 3865/kW, and $ 3995/kW, respectively. The reason for the difference in CAPEX is the variation in depth. The water depth is an important parameter for the CAPEX value. The Saros OWF has the highest NPV compared to the other two OWFs, so it is the most promising region for electricity generation from wind power. WACC is an important parameter in the discount of a project's expected cash flows and thus plays an important role in the financial evaluation of offshore wind projects.

The LCOE is important investment indicator that help OWF developers make decisions. In this study, the estimated LCOE values are $ 81.4/MWh, $ 85.1/MWh, and $104.4/MWh for the Saros, Gelibolu, and Kiyikoy, respectively. In the report published by IRENA for 2020, the average LCOE value was $ 83/MWh for Europe and $ 85/MWh for Asia. Compared to the IRENA (2020) report, LCOE values per MWh are similar for Saroz and Gelibolu OWFs, but considerably higher for Kiyikoy OWF. Because AEP, WACC, and CAPEX all have a massive effect on LCOE, improving data in those areas should be a priority in future projects.

Since offshore wind energy is a new issue in Turkey and this energy potential has not been fully discovered, the country does not have a specific policy regarding offshore wind energy. To enable the development of offshore wind energy, Turkey may consider the following recommendations:

- The Turkish government determined the offshore wind auction ceiling prices of 8 cents/kWh. This FiT is still far from enabling offshore wind power to be economically utilized as a RES in Turkey. Supported by the relevant policies, an increase in the FiT would ensure the profitability of offshore wind projects in Turkey; and would attract more domestic and international investors. As well as an improvement at FiT, reducing LCOE will significantly increase profitability.
- The current FiT level for offshore wind energy projects is paid for in the first 10 years. After 10 years, the profitability of the projects may be decreased based on the price set by the market. The uncertainty can be reduced by extending the current support duration by ten years.

- The Turkish government applies lower tax brackets to power plants. The development of new tax structures that includes tax credit mechanisms or lower tax percentages might increase the economic competitiveness of OWF investment in Turkey.
- Subventions for direct capital investment; and low-interest loans for cheaper financing would be beneficial in addressing the capital-intensive nature of OWFs. These will contribute to the development and construction of offshore wind power projects.

Preliminary assessments show that there is a significant amount of offshore wind potential off the Turkish coast. Turkey can benefit from its own clean energy resources while reducing its reliance on foreign energy suppliers by utilizing offshore wind. However, there is still no offshore wind farm in this country. Several researches have been published in the literature that study mostly the technical analysis of offshore wind energy on Turkish seas. Combined with the technical analysis, this study aims to conduct the economic feasibility analysis of offshore wind farms for selected regions in the Turkey. The results may assist public and private sectors in decision-making processes regarding the offshore wind energy source.

Declarations

Conflict of interest The author has no conflicts of interest to disclose.

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