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Feasibility Study of an Offshore Wind Farm in the Aegean Sea, Turkey

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Abstract

Offshore wind power technology holds the potential for tackling major problems associated with energy and climate change as well as triggering economic growth and providing employment opportunities. Offshore wind power has the potential to play a key role for Turkey in achieving stated 2023 energy targets due to the country's favourable geographic location and coastline. However, there are currently no offshore wind farm projects in Turkey. The aim of this study is to determine the feasibility of an offshore wind farm in the Turkish seas. Prior to that, offshore wind market in the EU is reviewed, and the current status regarding the wind power market and supporting mechanisms are reviewed regarding the situation in Turkey. A location is proposed in the Aegean Sea, based on consideration of wind speeds and other factors. Technical analysis is conducted with the use of windPro software, and potential annual energy production of the proposed project is calculated. Combined with the economic analysis, feasibility of such an offshore wind farm is discussed. Issues with the current supporting mechanism are identified, and solutions are proposed for the future development of offshore wind farms in Turkey.

Keywords: **Offshore wind power, Feasibility study, Aegean Sea**

1. Introduction

With accelerating industrialisation and increasing population trends worldwide, many concerns, such as increasing energy demand, fossil fuel depletion, and environmental issues have led countries to search for ways to develop renewable energy capacities. Wind energy is a promising source and has been exploited for electricity production since the 1980s. Research on wind energy gathered momentum, and wind energy penetration first began in the USA after the oil crises in the 1970s [1]. Then it shifted to Europe, with Europe becoming the leading market on the global scene for wind energy since the 1990s [2]. The European Union (EU) has set the 2020 targets to increase the use of renewable energy to 20% under the Directive 2009/28/EC. Today, one of the candidate countries for the EU, Turkey, has been a part of the G20 forum with a rapidly expanding economy with its GDP ranked 18th in the world [3]. All of this enables Turkey to be a major regional power. Marking the 100th anniversary of the foundation of the Republic of Turkey, Turkey set ambitious goals targeting the share of 30% renewable energy sources of total electricity generation and building 20 GW capacity of wind energy by 2023 [4].

Wind energy can be exploited in two ways: onshore and offshore. While onshore wind turbines have been utilised for over a century, offshore wind power has attracted enormous attention recently, and offshore wind power has been increasingly harnessed since 1991 [5]. Higher wind speeds and more stable wind flow beyond the coasts, due to the absence of the obstacles at sea capable of disrupting the wind flow, result in higher power potential of offshore wind energy when compared with the onshore [6]. Also, larger turbines capable of generating more power can be installed on the sea due to the ease of transportation of larger equipment by ships. Conversely, logistic challenges and physical barriers are encountered on onshore wind projects, such as relatively smaller roadways, bridges, etc. Larger turbine sizes reduce the costs of non-turbine project elements considerably. However, offshore wind power is still more capital intensive compared to the onshore counterpart [7].

Installed offshore capacity in the EU has grown considerably since it began in 1991, reaching 12.6 GW at the end of 2016 [7]. Even though Turkey is surrounded by sea on three sides, making it conducive to offshore wind energy, capacity has not

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yet begun to develop [9]. Moreover, there is a lack of research in offshore wind in Turkey. In this regard, a feasibility study of an offshore wind farm to be located in the Turkish seas is crucial for future planning and development of offshore wind policy.

Feasibility studies determine the attractiveness of investments based on the net annual energy production (AEP) estimation, price for purchased energy, and capital costs [10]. Various feasibility studies have been conducted for offshore wind farms. Pantaleo et al. [11] examined the feasibility of offshore wind farms in Puglia region. Cost estimation, cost of energy (COE) and profitability analyses, such as net present value (NPV) and internal rate of return (IRR), were determined for four different locations, with the most suitable location being selected. Similarly, Konstantinidis et al. [12] conducted a viability analysis of an offshore wind farm in the Greek sea area based on techno-economical study. Considering the effective wind farm siting and planning, annual energy generation was estimated using the software RETScreen. Followed by the cost estimation, viability of investment was investigated using NPV, IRR, benefit to cost ratio (BCR) and COE. Kim et al. [13] conducted an economic feasibility study and optimal site selection for offshore wind power development around Korean peninsula based on BCR. Effiom et al. [14] also completed an economic evaluation of the viability of offshore wind turbines in Nigeria. The evaluation was completed by deploying a mathematical model, and the COE was presented for various scenarios. Ozerdem et al. [15] conducted a feasibility study of onshore wind power for an area in Izmir, Turkey. This study utilized measured data for AEP estimation, and economic analysis was completed considering COE, NPV and payback period (PBP).

This study presents a techno-economic feasibility analysis of a proposed offshore wind farm in Turkey. Prior to the presentation of the feasibility study, the background to development of the offshore wind power technology is presented. Evaluation of the current support mechanisms in Turkey in line with wind energy development is also given.

2. Background

Total wind capacity of 153.7 GW has been reached in the EU, 12.6 GW of which is from offshore wind farms. In 2016, the EU investments in offshore wind power were the highest of the clean energy investments, including onshore wind, at 56%, which is equal to more than €18 billion [8]. The various advantages and cost reduction opportunities that offshore wind farms offer compared to the onshore counterpart, and the reduced associated risks have encouraged development of wind turbines on seas in the last decade [16]. The first offshore wind farm with a capacity of 4.95 MW, consisting of 11 450-kW turbines, was built in Denmark in 1991. Since then, the development of the offshore wind market has been on the agenda of the wind industry. Accumulation and transfer of experience gained in onshore wind led to the growth of the offshore wind industry gradually in 2000s [17]. Today, the largest operational offshore wind farm is the London Array (630 MW) which began operation in 2013. In 2016, 25 years on from the first offshore wind farm in Denmark, DONG Energy has started to construct the largest offshore wind farm, the Hornsea Project One, in the UK with a capacity of 1.2 GW consisting of 174 7 MW Siemens turbines [18].

As the experience of offshore wind developers and operators has increased, offshore wind power has become one of the fastest developing technologies today, and the offshore wind market is expected to be a future focus and a major contributor to renewable energy in the near future [7]. Figure 1 shows the increase in the EU offshore capacity since 1991. In the last ten years, the increase in the capacity is remarkably visible. As shown by Perveen et al. [19], the growth trend between 1992 to 1999 for onshore wind power capacity bears a resemblance to growth trend between 2008 to 2015 for offshore wind power capacity. Thus, the development of onshore wind power after 1999 suggests potential further growth for the offshore counterpart.

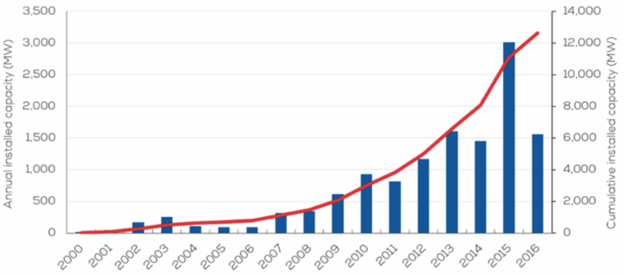

Figure 1. Cumulative and annual offshore wind capacity installations in the EU 2000-2016 [20]

From the very beginning, the EU has dominated the global offshore wind market, accounting for 88% of the total capacity today. The commercial success of offshore wind energy in the EU encouraged other world powers to start investing on offshore wind farms. China has built 1.6 GW of capacity since 2007, and Japan has recently built a capacity of 60 MW [21]. The first commercial project in the USA with a capacity of 30 MW started delivering power in late 2016 [22]. India has conducted intensive research on offshore wind power lately with the FOWIND project (Facilitating Offshore Wind in India), which is part-funded by the EU, and is planning to install its first offshore wind farm soon. As of end of 2016, there were 81 offshore wind farms in the EU spread across the North Sea (72%), Irish Sea (16.4%) and Baltic Sea (11.5%). Once the ongoing European projects reach completion, a total capacity of 17.4 GW will be achieved [23]. Over the last ten years, the share of offshore wind in the annual EU wind energy market increased gradually as seen in Figure 2 which shows the annual onshore and offshore wind power capacity installations in the EU.

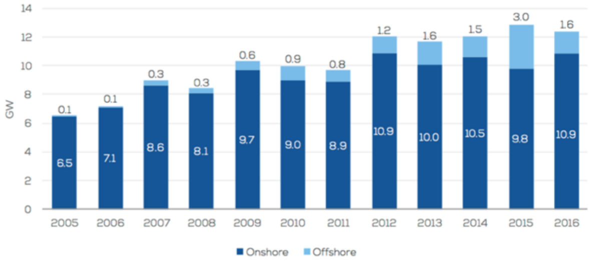

Figure 2. Annual wind capacity installation in the EU [8]

According to the European Wind Energy Association (EWEA), further 24.2 GW of offshore wind capacity has been approved, and is expected to be installed in the next decade [23]. Also, a total of 65.6 GW is under planning process. The EWEA has announced 2020 target as 23.5 GW, and 2030 target as 66.5 GW [24,25]. Rodrigues et al. [26] presented a comprehensive review of the recently planned and ongoing offshore wind farm projects in Europe.

Offshore wind farms operating in 11 European countries at the end of 2015, were capable of generating 40.6 TWh in a normal wind year. This corresponds to 1.5% of the total EU electricity consumption (2,770 TWh) [27]. By 2030, 3,187 TWh of electricity demand is expected according to the European Commission (EC) reference scenario [28]. According to the EWEA's wind energy projections for 2030 in the central scenario, offshore wind power will generate 245 TWh, covering 7.7% of the electricity demand whereas onshore wind is expected to generate 533 TWh, covering 16.7% of the total demand [25]. Wind Europe states that Europe has the potential to realise 3,500 TWh of offshore energy in 2030 [20]. If all this potential is harnessed, all of the energy demands can be met.

According to the European Environmental Agency (EEA), Europe's combined offshore and onshore wind energy technical potential is 20 times the energy demand in 2020 [29]. The technical potential is found to be 30,000 TWh for offshore and 45,000 TWh for onshore in 2030. This evaluation is for unrestricted case without constraints such as shipping routes, military use of offshore areas, oil and gas exploration, and tourist zones. The figures broken down by European Economic Area countries, including Turkey, are given in Figure 3 based on the available offshore areas given in the same study.

When considering the potential constraints, environmental constraints have little impact on onshore wind power, but social constraints are influential, thus reducing the onshore potential to 39,000 TWh. However, in the case of offshore wind, wind energy potential is highly affected by both type of constraints. "Using only 4% of the offshore area within 10 km from the coast and accounting for the restrictions imposed by shipping lane, gas and oil platforms, military areas, Natura 2000 areas etc., reduces the potential by more than 90% to 2,800 TWh in 2020 and 3,500 TWh in 2030" according to the EWEA [29]. Lastly, economically competitive potential for the offshore wind is found to be 3,400 TWh. Together with onshore wind, the economically competitive potential is three times the projected demand in 2020. However, EWEA's projected offshore wind generation for 2030 (247 TWh) is far from the economically competitive potential (3400 TWh). Realising all this potential by 2030 is dependent on many factors, including policy support and cost reductions.

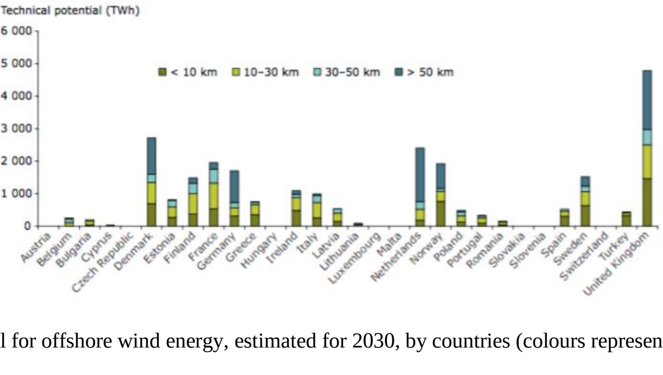

Figure 3. Unrestricted technical potential for offshore wind energy, estimated for 2030, by countries (colours representing the distances from the shore) [29]

2.1. Wind Energy Policy in Turkey

Even though Turkey has high renewable energy potential, a small number of promotional measures have been proposed, and no financial support was available until the early 2000s. The priority was given to large hydropower projects prior to this [30]. At first, renewable energy was encouraged by the Electricity Market Law (Law No 4628) in 2001 which paved the way to liberalised competitive power generation and distribution. The restructure of the electricity market began with the commission of Energy Market Regulatory Authority (EMRA) which is responsible for taking measures to promote the deployment of renewable energy by issuing licenses, setting up tariffs and assuring competition. The new law granted many opportunities to renewable energy companies. They were only required to pay for 1% of the total license fees; an exemption from annual license fees for eight years was also granted. The Turkish Electricity Transmission Company (TETC or TEIAS in Turkish) became obliged to assure grid connection priority for renewable energy plants. Thus, with this law, for the first time a "legal framework for promoting electricity generation from renewable sources was set and incentives such as, feed-in tariffs and purchase obligations, connection priority, reduced license fees, exemptions from license obligation for small-scale generators, reduced fees for project preparation and land acquisition were mentioned" [31].

With the enactment of the Law on Utilisation of Renewable Energy Resources for Generating Electrical Energy (the RER Law, Law No. 5346) in 2005, which aimed to expand renewable energy utilization economically and efficiently by various mechanisms, the license applications for renewable energy projects increased notably. One of the mechanisms the law introduced was fixed feed-in tariff (FiT) for all types of sources. Beyond 2005, unit capacity of wind turbine increased from kilowatts to megawatts, and since 2006 the installed wind power capacity has undergone a rapid increase [32]. With the RER Law, diversification of energy mix, reduction of greenhouse gas emissions, environmental protection, and development of domestic manufacturing sector for renewable energy technologies were planned [33]. With this law, some new incentives such as land appropriation and a purchase guarantee with a constant tariff was added to legislation [31].

In 2007, Energy Efficiency Law (No 5627) outlined the tangible measures, principles and procedures for energy efficiency in the industry, transport, building, services and electricity to ease the burden on the economy. This law revised the RER law, and slightly increased the FiT to €5-5.5 cent/kWh. With this revision, wind power producers were allowed to sell the electricity to the grid or engage with eligible customers at a higher guaranteed price [34].

In 2009, the Strategic Plan for 2010-2014 was published by Ministry of Energy and Natural Resources (MENR). With this plan, previously mentioned non-binding renewable energy targets were defined. 10 GW and 20 GW of wind energy was planned for 2015 and 2023, respectively.

The second important legislation is the amendment to the RER Law which was promulgated in 2010 (Law No. 6094). The Renewable Energy Support Mechanism was introduced, priority was ensured for grid connection to renewables, and FiT rates to be applied for the first 10 years of the operation were regulated according to the source type. According to the law, FiT is converted in to USD [35]. FiT for wind energy projects is regulated at $7.3 cent/kWh. Incentives for local content were also introduced. This allows a FiT bonus to be applied to locally manufactured electro-mechanical equipment used in power generating systems. Regarding the wind turbines, for locally manufactured turbine blades, turbine tower, generator and power electronics, and mechanical equipment in rotor and nacelle groups, a maximum FiT of $11 cent/kWh is applicable for 5 years. With the introduction of Renewable Energy Support Mechanism, renewable energy facilities under 500 kW became exempt from licensing. In 2013, Electricity Market Law was amended (Law No: 6446). According to this, the license exemption limit for individuals and corporate entities was increased to 1 MW. For over 1 MW, two-stage licensing was introduced. Power generating facilities are now required to obtain a pre-license, and then a full-generation license. The licenses comprise of a generation license, auto-generation license, auto generation group license, transmission license, distribution license, wholesale license and retail sale license, granted by EMRA [31].

Finally, in 2014 MENR published the National Renewable Energy Action Plan covering the period between 2014 and 2023. This action plan was prepared as a manifestation of its commitment to the EU accession and the targets set by the Directive 2009/29/EC. In the report, the term "binding" is used for Turkey's 2023 targets.

In 2015, Turkish grid operator, TETC, signed a long-term grid synchronisation agreement with ENTSO-E, the European Network of Transmission System Operators. According to this agreement, Turkey's electrical network will be integrated with the synchronous grid of Continental Europe. Thus, free flow of electricity between consumers on both sides will ensure a more secure, cleaner and affordable supply [36].

Kaplan [33] reviewed the current wind energy policies in the world, and asserted that the current feed-in tariff and regulatory policies in Turkey resemble the policies in US, China and some of the EU countries. However, according to Melikoglu [37], the major barriers for the wind energy development are the lack of "other support tools such as public finances, competitive public bidding, and public investment loans or grants, and fiscal incentives, capital subsidy, grant or rebate, energy production payments".

Local developers dominate the Turkish wind industry. According to Benli [38], the reason for this was the lack of long term fixed price PPAs. With the recent policy measures in the wind energy, most restrictions on foreign investment in the Turkish power sector have been lifted [9]. Melikoglu [37] states that Turkey should ensure $18.6-22.7 billion of capital investment to reach 20 GW of wind capacity. To reach this target by 2023, Turkey must install nearly 2 GW each year now henceforth. The grid connection capacity must be ready to support this. Currently, 1.8 GW of capacity is under construction in addition to the existing 4.7 GW of installed capacity. As stated by TETC's 5 Yearly Electrical Energy Generation Capacity Projection Report which was published in 2014, 15 GW of grid connectable wind energy capacity has been defined. Currently, an additional 3.1 GW of wind energy has already been licensed. In 2013, EMRA announced 3 GW of grid connection capacity for wind investors. In total, 1018 applications with a capacity of nearly 40 GW were made in 2015 [39]. In 2015, EMRA announced an additional 2 GW. The applications will be accepted in April 2018 [40].

2.2. Wind Energy in Turkey

As it is surrounded by seas on three sides, Turkey has significant wind power potential, especially due to higher power densities in the coastal regions [41]. According to the Turkish Wind Energy Association, as of the beginning of January 2017, the cumulative installed wind power capacity was 6.1 GW [42]. From 51 MW in 2006, more than tenfold increase in the wind capacity has been achieved in ten years. In 2016, Turkey installed the 7th largest capacity in the world [21]. Currently, installed wind capacity is 7.3% of the total potential, but none of this is from offshore projects [43]. Compared to European counties, Turkey has the highest technical wind potential for the wind class over 3 with 83 GW and 166 TWh annually [32,44]. The average wind speed in Turkey is 2.58 m/s with a power density of 25.82 W/m^2 [45]. Among seven regions of Turkey, the Marmara region has the highest annual average wind speeds, followed by the Aegean region [45]. As shown in the Europe wind map [26], the Aegean Sea has wind speed profiles similar to the North Sea where nearly 70% of the offshore projects are located today. Despite the considerable technical offshore capacity shown by EEA in Figure 3, Turkey is one of the countries shown in the figure which has not yet started to exploit this capacity. Moreover, there is a lack of planning or government policy related to offshore wind. In the National Renewable Energy Action Plan, the targeted 20 GW wind capacity has been outlined as onshore only.

According to Malkoc [46], Turkey has an economically viable wind power potential of 47,849 GW, of which 10,463 GW is from offshore wind for wind power class over four. When wind power class three (wind speeds of 6.5-7 m/s) is considered, this potential further increases to 17,393 GW [47]. As outlined in the National Renewable Energy Action Plan, 50 TWh of electricity must be generated from wind to reach the 30% renewable target in electricity generation by 2023. Even though it is not implicated in the action plan, offshore wind energy offers considerable energy generation when compared with its onshore counterpart, therefore every MW of offshore capacity is realistically more likely to contribute to Turkey’s 30% renewable target. As given in Turkish Wind Power Potential Atlas prepared by General Directorate of Renewable Energy (GDRE), the majority of the high wind speeds are observed throughout the Aegean Sea, and partially in Marmara Sea, central North Sea and Mediterranean Sea. Strong winds on the seas offer an excellent opportunity for Turkey to further ensure the security of energy and competitiveness in Europe.

Low carbon development can be accelerated with offshore wind power in Turkey within its grid which will be connected to Europe in the near future. Offshore wind holds a key role for Turkey in reaching 2023 targets and complying with the EU legislations. With implementation of right policy and the additional financial support provided by the Turkish government, offshore wind in Turkey can attract both local and foreign investors. However, a feasibility study is required to justify the viability of offshore wind farms in Turkey.

3. Materials and Methods

For the feasibility analysis, the Bozcaada region in the Aegean Sea has been proposed for the development of an offshore wind farm due to high wind speeds, and other important siting factors. Through the use of windPro software, two different locations have been proposed and the estimated annual energy generations calculated, combined with an optimisation for determining the most suitable project. The validation was achieved by modelling the existing onshore wind farm, BORES, in the Bozcaada region. Investment costs were estimated based on the empirical guidelines suggested by Dicorato et al. [48]. Finally, LCOE is estimated, and the investment viability is analysed through NPV and PBP. Scenarios which leads to economically viable investments are described.

3.1. Site selection

Wind resource, water depth and distance to shore were taken into account for site selection as suggested by ORECCA [49]. Previously, Argin and Yerci [50] presented a site selection analysis for offshore wind farm development in Turkey, and wind potential, territorial waters, military zones, civil aviation, maritime traffic, pipelines and underground cables were focused on as the selection criteria. Among alternatives given by Argin and Yerci [50], Bozcaada has been chosen as the suitable location to develop an offshore wind farm in the scope of this study. Bozcaada is an island with a population of 2,643, and it is located 8 km away from the province of Çanakkale as shown in Figure 4. It is located on the Aegean Sea, which has some of the highest wind speeds in Turkey. There is already an onshore wind farm on it with a capacity of 10.2 MW. Generated electricity on this wind farm is transferred to Çanakkale with submarine cables. Therefore, existing electricity transmission infrastructure between Çanakkale and Bozcaada may help to reduce the costs. Bozcaada is the 3rd largest island of Turkey, and it is one of the popular tourist locations in Turkey due to its beaches and wineries.

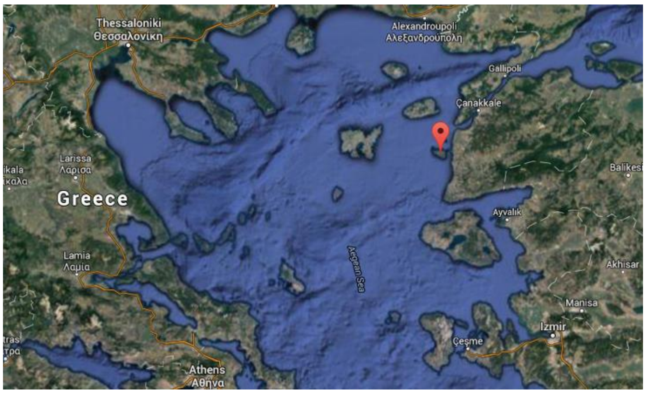

Figure 4. Project area in the Aegean Sea (red cursor showing Bozcaada)

GDRE published suitable areas for wind farm development in the province of Çanakkale. As seen in Figure 5, the offshore area around Bozcaada is shown to be suitable for wind farm development. Taking this into account, two different offshore areas around Bozcaada, where the wind speeds are highest, are proposed for offshore wind farm development in this study, and energy productions are calculated for both of the areas using windPro software. As the project size, 90 MW is selected, and considered sufficient as a demonstration project, since this hypothetical offshore wind farm is the first in Turkey.

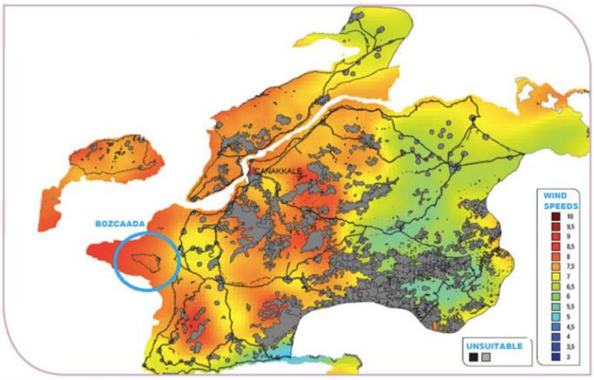

Figure 5. Suitable locations for wind power development in the province of Çanakkale (blue circle shows the area around Bozcaada) [51]

3.2. Technical Analysis

Technical analysis in this study was conducted by performing several simulations using windPro software.

3.2.1. Simulation Procedure

Google Earth overlay method was used in windPro to obtain the background map of the area being studied. For the elevation profiles, needed for describing the terrain, The Space Radar Topography Mission (SRTM) digital elevation model was chosen with 1 arc-second resolution. For conducting simulations correctly, elevation data must cover a distance of 7 km from the edge of the site [52]. The European Marine Observation and Data Network (EMODnet) was used for downloading the high-resolution bathymetry data, required to decide on the location of the offshore wind farm layout. Roughness data was extracted from CORINE land cover database with 100 m resolution. Roughness data must cover a distance of 20 km from the edges of the site in order to obtain correct results [52].

Wind data, consisting of wind speeds and wind directions, is of utmost importance in AEP calculations. In this study, due to lack of measured data for the locations of the proposed offshore wind farms, required wind data was obtained from EMD International’s mesoscale database. 1-year data were downloaded for both of the project locations. However, 1-year data is not representative of the winds during the whole lifetime of the project. In order to calculate correct annual energy production, 1-year data obtained, which is valid for the centre of the project site, must be correlated with a long-term reference data to make it representative of the long-term winds on the project site [53] The Measure-Correlate-Predict (MCP) method was used for this purpose. MERRA database is utilized for long-term data. Correlation coefficients are obtained as around 0.98. Given the fact that correlation coefficients above 0.90 are defined as very good according to Nielsen [52], correlation were achieved effectively.

3.2.2. *Site Location and Layout Optimization*

Site locations for the project were selected by considering wind resource map, sea depths, distances from the shore and the suitable areas as defined by GDRE. In order to obtain a capacity of 90 MW, 30 3MW turbines were chosen to be used in the farm layout. Wind farm layouts were defined based on the windPro's Optimization module results. The locations and layouts of projects are shown in Figure 6. Only northwest and southeast parts of the island were taken for the analysis, based on the resource map which will be shown in the results section, because these locations have higher wind speeds compared to east side of the island. The two projects were given the name of EGERES and EGERES2.

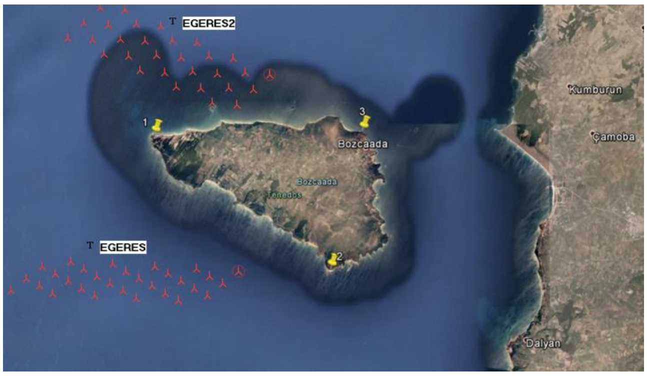

Figure 6. Locations and layouts of the offshore wind farms

Due to low ambience turbulence conditions on sea, wake effects can easily propagate over longer distances than on land [7]. As a result, downwind turbines located in the wake of upstream turbines are subjected to wake effects causing power losses and higher aerodynamic loads [7]. The increase in the aerodynamic loads on wind turbines can shorten lifespans. In order to prevent this, the design of the layout should be carried out in a way that wake effects can be minimised. This is achieved by placing the turbines at a certain distance from each other, so that turbulence and wake effects become negligible. However, placing them at large distances may lead to wasting of suitable area and higher costs due to longer inter-turbine transmission cables. Considering these issues, an optimisation should be carried out by compromising such factors in order to ensure a cost efficient offshore wind farm. Normally, for higher row and in-row distances, higher park layout efficiencies are achieved due to decreased wake loss effects. Layout efficiency, in this study, refers to final energy generation after wake loss calculations. However, once these distances increase in the layout, the distances of the turbines from the shore also increase, which result in greater water depths. Water depth has direct effect on capital costs [54]. In order to keep the project costs down, water depth was given priority in the optimisation process. Thus, even though higher energy generation could be achieved for various different layouts and locations, the optimum layouts for the projects were defined as presented in Figure 6. In defining optimum layout with the Optimization module, a range of values are entered for each parameter. Then, the module calculated the optimum parameters which lead to the highest park efficiency.

3.2.3. *Energy Calculation*

As for the wind turbines, the Siemens SWT-3.0-101 model was selected. Rotor diameter of the turbines are 100.6 m, and the rated power is 3 MW. Hub height was selected as 94 m. For wake effect analysis, the Jensen wake model was selected. The decay constant was chosen as 0.04 since the project is based offshore [52]. Simple reduction with 10% was defined in addition to wake losses. 10% is a rough estimation of the possible expected losses and uncertainties in the wind data, and it is a default value in windPro calculations. According to the classification organisation, DNV, standard loss categories include wake effects, availability of the wind farm and grid, turbine performance based on power curve, high wind hysteresis, wind flow, electrical issues such as substation and transmission losses, environmental issues, such as performance degradation, shutdown due to hail, lightning etc., and curtailment issues.

3.2.4. Validation

In order to validate the long-term correlated wind data, the existing onshore wind farm, BORES, was modelled and a comparison between actual power generation and the model results was made. The BORES wind farm has a 10.2 MW capacity, and it employs 17, 600 kW ENERCON E-40 turbines with a hub height of 40 m. It is located on the north western side of the island. Each wind turbine's location is published by GDRE [55]. Incorporating this information, the actual wind farm was modelled through windPro. However, hub height was selected as 44 m since 40 m is not selectable in the software. Hence, this imposes a slight error.

As presented by Senkal and Cetin [56], between 2001 and 2008, the BORES wind farm generated an average of 34.845 GWh with an average capacity factor (CF) of 39%. The modelled wind farm on windPro generates 37.407. GWh/year with a CF of 41.8%. Accordingly, the accuracies of generation and CFs were 0.931 and 0.933, respectively. These values were considered to be sufficient in validating the wind data used in this study. Thus, the wind statistics generated by the MCP module were assumed to be highly representative of the actual long-term wind.

3.3. Economic Analysis

For wind farm planning to be a viable process, the wind farm must generate sufficient quantities of energy in a long-term and cost-effective manner. Considering this, economic evaluation is necessary to facilitate the analysis of the viability of the proposed offshore wind farm in terms of costs of generating offshore wind energy and market value of the generated energy [57]. LCoE and NPV were chosen as the economic cost evaluation tool to be used in this feasibility study. For LCoE and NPV, formulas given by Heptonstall et al. [58] and Levitt et al. [59] are employed, respectively. In order to calculate these two important determinants of offshore wind economics, cost estimation must be carried out.

3.3.1. Cost Estimation

As a comprehensive concept, CAPEX includes the construction financing, development costs and operating capital besides the investment costs, and OPEX includes O&M costs as well as any other operating expenses. CAPEX estimations are performed considering the reported values of currently operating offshore wind farms. In the literature, numerous studies have presented CAPEX estimations for offshore wind farms [59,60]. On the other hand, OPEX is rarely reported by developers; so, high amount of uncertainty applies due to lack of empirical data [61,62]. However, in general, O&M costs account for 14-30% of the lifecycle costs [63] and around 50% of OPEX [61].

In this study, investment costs were estimated based on the empirical guidelines suggested by Dicorato et al. [48]. All stages up to onshore transformer were considered. For O&M costs, the correlation developed by Möller et al. [64] is used. All of the inputs and relevant assumptions made for the economic analysis are shown in Table 1. A discount rate of 10% was selected since this is a moderate value taking into consideration the actual discount rates found in the literature [58]. For the lifetime estimation, 20 years was chosen since this is the consensus of most of the wind turbine studies conducted to date [65,66].

MVAC transmission type was selected. Considering that a substation is required for projects with a capacity over 100 MW, or distances over 15 km from the shore, an offshore substation was omitted [17]. The diesel generators used in ensuring generation reserve were not included either. Power is transferred to the shore by 33kV cables. A transformer placed on the shore steps the voltage up to 154 kV. Stepped up power is transferred to transmission grid. According to The Electricity Market Grid Regulation of Turkey, power generating facilities over 50 MW must make the grid connection in the transmission grid level [67]. Therefore, the grid connection must be made to Çanakkale instead of Bozcaada due to the fact that the closest transmission transformer station to the project area is located in Ezine, Çanakkale [51]. In Turkey, transmission lines utilise mainly 154 kV and 380 kV [68]. The transmission transformer at Ezine is connected to a 154 kV grid. Half of the onshore cables were considered to be placed underground.

An existing offshore wind farm, Barrow, with 90 MW capacity (same capacity as planned in this study) employs 3-core XLPE insulated array cables with 120 and 300 mm^2 cross section [69]. Different sizing can be used in same array cabling system. Depending on the layout of the wind farm, cable sizes at the end of the feeder can be smaller than cable sizes closer to substations [17]. This implementation is done in order to reduce the costs. In this study, only one sizing, 300 mm^2, has been assumed for array cables. Considering Barrow offshore wind farm, a 120 MVA transformer station was selected. Reactive power regulation costs were excluded. Similar to [59], "policy incentives are excluded, depreciation is over the life of the plant, there is no capital structure apart from the discount rate, and the hypothetical sale price is constant over time." OPEX was assumed to be double the O&M cost based on the statement of [61], and a decommissioning cost has been omitted from calculations. FiT was converted into € by the exchange rate of 1.123 €/$.

Table 1. Inputs and assumptions for economic analysis

Input parameter	Value	Input parameter	Value
Turbines		**Onshore cables**	
Capacity	3 MW	Number of cables	1
Number of turbines	30	Total length per cable	17.5 km
Hub height	94 m	Array cable sizing	500 mm^2
Rotor diameter	100.6 m	Nominal voltage	154 kV
Layout		**Transformer**	
Average sea depth	19 m	Capacity	120 MVA
Average distance to the shore	14.4 km	**Energy**	
Transmission		Annual generation	373,039 MWh/year
Type	MVAC	Capacity factor	47.3%
Array cables	20	FiT	$73/MWh
Number of cables	3		€65/MWh
Total length per cable	8.25 km	**Project**	
Array cable sizing	300 mm^2	Lifetime	20 years
Nominal voltage	33 kV	Discount rate	10%
Export cables			
Number of cables	3		
Total length per cable	11.85 km		
Array cable sizing	400 mm^2		
Nominal voltage	33 kV		

4. Results

The results obtained for this study have shown that the rate of increase in the efficiency significantly drops after 900 m for row distance and 850 m for in-row distance within the entered range. So, 900 and 850 m were selected as the optimum distances. Also, lower row and in-row distances ensure lower costs associated with cabling.

It should be noted that southern side of the island has many residential areas and beaches, such as Ayazma Beach. Therefore, the turbines in the EGERES project were located further from the shore compared to the EGERES2 project due to possible visual impacts and social acceptance issues. On the other hand, there are relatively few residential facilities on the northern side of the island. Instead, there are mostly farms and vineyards in this part. Hence, turbines closer to the shore were considered to be suitable on the northern side

The resource map showing the mean wind speeds at a hub height of 94 m is shown in Figure 7. The sea on the northern side of the island has higher wind speeds, whereas the southern side is shielded by the higher elevations on the island; thus, wind speeds are lower compared to the northern part of the island. When compared with the elevation map, it can be explicitly said that the highest wind speeds are obtained at the highest points of the island. On the area between the island and the mainland, the wind speeds are comparatively lower than the western side of the island. Closer to the mainland, wind speeds decrease even further. Lastly, offshore wind speeds become nearly equal on the western side of the island beyond a certain distance from the island's shore.

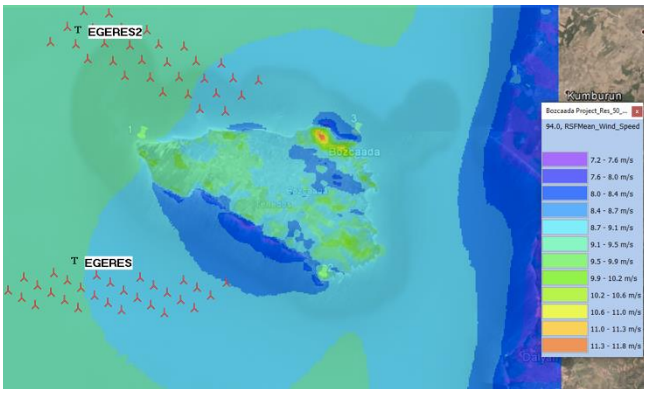

Figure 7. Generated resource map showing mean wind speeds at 94 m

The final results of the simulations are given in Table 2. According to the results, EGERES2 has higher AEP with 373.039 GWh. The gross value accounts for roughness effects, topographic effects, obstacle effects, air density correction. Result park refers to the energy production with wake losses. And lastly, results shown in red fonts represent the final generated energy considering the additional losses described earlier. The results obtained correspond with the wind resource map, because most of the turbines of the EGERES2 project are located in areas associated with higher wind speeds.

Table 2. Annual energy production calculation results

Wind farm	**Result park [MWh/yr]**	**Result-10% [MWh/yr]**	**Gross (no loss) [MWh/yr]**	**Park efficiency [%]**	**CF**	**Full load hours [hours/yr]**	**Mean wind speed at hub height [m/s]**
EGERES	402,207	**361,986**	417,115	96.40	45.9%	4,022	9 (at 94 m)
EGERES2	414,488	**373,039**	429,244	96.60	47.3%	4,145	9.2 (at 94 m)
BORES	41,564	**37,407**	42,542	97.70	41.8%	3,667	8.7 (at 44 m)

The results of the economic analysis are given in Table 3. The total investment cost was calculated to be in the region of €220 million. Figure 8. shows the cost breakdown of components for the EGEGES2 project.

Table 3. Results of the economic analysis

Investment cost	€220,659,882.86	total
	€2,451,776.48	/MW
O&M cost	€80,158,620.32	total
	1.82%	of CAPEX per annum
Annual revenue	€20,239,603.98	
PBP	10.90	year
NPV	-€48,348,724.68	
LCoE	€91.03	/MWh

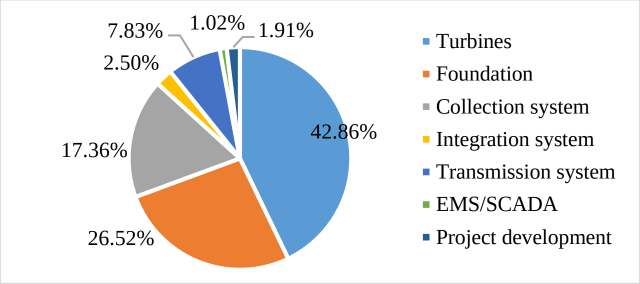

Figure 8. Cost breakdown of EGERES2 project

Additional simulations, through windPro software, employing Vestas V90-3.0 and Siemens SWT-3.6-120 wind turbines have shown that turbine selection has an effect on project viability. During these simulations, the number of turbines were kept constant. The relevant information about the wind turbines and results are given in Table 4. Lastly, the influence of the discount rate and FiT value on NPV is analysed as shown in Figure 9.

5. Discussion

The results of the simulations with windPro software have shown that the most optimal location for the offshore wind farm development is the northern side of Bozcaada. In this region, water depths are around 20-30 m, therefore it is conducive to shorter substructures which consequently leads to lower capital costs. Also, the land area which is exposed to the offshore wind farms consists mostly of farmland. Due to the lack of residential areas in this part of the island, social barriers will be reduced. Annual energy production is found to be 373.039 GWh/year.

Table 4. Comparison of results for different turbines

Turbine	Vestas V90-3.0	Siemens SWT-3.0-101	Siemens SWT-3.6-120
Project capacity [MW]	90	90	108
AEP [MWh/yr]	322,911	373,039	454,326
Rotor diameter [m]	90	100.6	120
Hub height [m]	90	94	89.5
Park efficiency [%]	97.2	96.6	95.8
Investment cost	€218,316,517	€220,659,882	€252,020,644
PBP [yr]	12.46	10.90	10.22
NPV	-€69,160,079.33	-€48,348,724.68	-€42,162,052.66

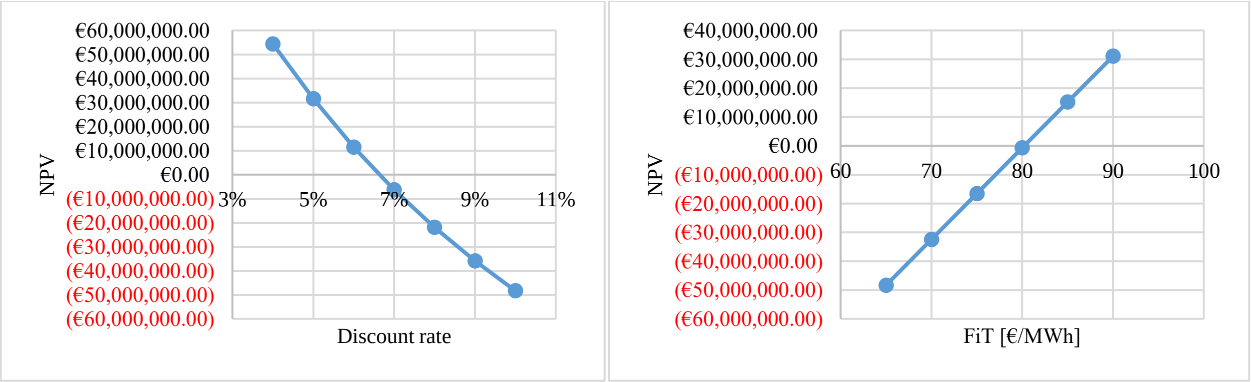

Figure 9. NPV of the project as a function of discount rate (for the FiT of €65/MWh) (left), and as a function of FiT (for the discount rate of 10%) (right)

The per MW cost is in line with estimations of Voormolen et al. [61] and the EWEA [70]. O&M costs account for 26.6% of the total costs. This is consistent with the statement of Martin et al. [63] and in close proximity to the values shown by Snyder and Kaiser [71]. Annual O&M costs accounts for 1.82% of the CAPEX. This result is quite close to the estimation in Heptonstall et al. [58] which assumes 1.6% of the CAPEX for annual O&M costs. OPEX was calculated as €21.488/MWh, which is also similar to results presented by Levitt et al. [59]. Lastly, NPV value was shown to be negative; therefore, under the current assumptions, the project is deemed unviable.

The calculated LCoE is in line with several projects in Europe as shown by Voormolen et al [61]. With a 10% discount rate, IRENA [72] presented a similar LCoE. Lastly, PBP and LCoE is similar to those obtained in the study of Konstantinidis et al. [12]. However, it should be noted that due to exclusion of several stages, such as contingencies and insurance, from CAPEX calculation, actual LCoE is expected to be higher than €91.03/MWh. Contingencies and insurance account for more than 10% of CAPEX [14,73].

When an offshore substation is considered, the share of integration system increases while the share of collection system decreases. This is due to decrease in the total length of MV cables. Addition of a substation results in an increase of close to €7.5 million. Therefore, this result justifies the utilisation of an MVAC system in this study. Additionally, when an offshore substation is used, the results are approximately similar to Dicorato et al. [48] and IRENA [72] which also consider a substation in their estimations.

Due to having a smaller rotor diameter, Vestas V90 turbines generate lower AEP compared to the original turbine, Siemens SWT-3.0-101, used in simulations. Even though there is a small change in investment cost, NPV was significantly reduced. On the other hand, employing the Siemens SWT-3.6-120 wind turbine, which is one of the most widely used wind turbines in European offshore wind farms [61], results in higher project capacity (108 MW), and correspondingly higher AEP. Due to a capacity of over 100 MW, an offshore substation was added to the project. Lower PBP, and higher NPV were achieved while investment cost was scaled up. However, park efficiency was reduced since the in-row and row distances were not changed. Thus, wake effect became more effective when compared with other turbines.

For a 10% discount rate, NPV results showed that the project is unviable since negative NPV represents a net loss. However, when the discount rate is reassessed at lower values, higher NPVs are obtained - for a 6.6% discount rate, NPV reaches €0. Today, institutional investors provide offshore wind farm producers with interest rates around 5% in low risks scenarios [74]. Considering this, when the discount rate is decreased further to 4%, positive NPV values of more than €50m are achieved as seen in Figure 9, for the current FiT value for wind energy, €65/MWh. When the discount rate is kept at 10%, the change in FiT would also ensure positive NPV. As seen in Figure 9, for FiT value of €80.2/MWh, NPV value of €0 can be achieved. Further increasing the FiT value increases the profitability of the project.

6. Conclusion and Recommendations

It can be seen that, in the right circumstances, offshore wind is an investment that pays off, and it has been an attractive asset for investors over the past two decades. Even though offshore wind power is more capital intensive compared to other renewable energy sources and it requires significant technological resources, the advantages offered by existing offshore wind farms, and the accumulation of technological experience achieved today have ensured successful utilisation of this reliable technology by many European countries. It may prove to be a very promising source of renewable energy for also Turkey in its aims to achieve 2023 energy targets due to its favourable location and coastline. In order to have a high level of wind penetration as planned in 2023 targets, development of offshore wind farms in Turkish Seas is inevitable.

The Aegean Sea has some of the highest wind speeds in Europe, and this untapped natural potential could attract interest from local and international investments in the near future. However, there has not been any ongoing research in Turkey in relation to this topic so far. The offshore wind potential of Turkey mainly depends on recent policy developments in the major climate and energy priorities. As a rapidly developing country, Turkey has declared its intentions to reduce GHG emission by 21% in COP 21. Also as an EU candidate, Turkey is committed to bringing its energy policies in line with EU norms. In this regard, relevant regulations will pave the way for the development of offshore wind power. Regarding the policy, current support mechanisms in Turkey are not sufficient, and an amendment would be required to the RER Law in order to make offshore wind power investments feasible and attractive. Fiscal incentives and public finance, which are widely employed in the EU countries, should also be introduced in Turkey by the government to support offshore wind power projects.

From the insights developed during this study, the current FiT for wind energy projects was found to be insufficient for offshore wind power development in Turkey. The assessment of NPV proved that there is a minimum FiT and discount rate for profitable offshore wind power. The evaluation of current supporting mechanisms within EU countries reveals that a separate, higher FiT is required for offshore wind power than the onshore counterpart. In comparison with some of the European countries which accelerated the development of offshore wind power, FiT in Turkey, 65 €/MWh, is significantly lower than 150 and 220 €/MWh in France, 138 €/MWh in Belgium, 154 €/MWh in Germany [75]. 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. Today, examples of offshore wind projects that were tendered below 50 €/MWh can be found in the EU [76]. Therefore, effective project management at government level which would result in lower LCoE is another factor in ensuring profitability. Also, considering the long timeframe for return of investment due to capital intensive nature of offshore wind power, the current policy of 10 years for FiT is making offshore investment unattractive in Turkey. After 10 years, profitability of the offshore wind projects may be based on the price set by the market which results in a risk.

Even though onshore wind growth has been achieved in Turkey in the last decade, offshore wind development cannot be easily extrapolated from onshore wind experience alone [77]. Therefore, an investment in technology research on offshore wind power is required in Turkey to initiate the development of the industry. In this regard, premiums in offshore wind FiT for domestic equipment will enhance the research activity. Premiums on, not only turbine parts as applied currently, but also transmission, cabling and foundation would ensure a benefit to Turkish industry from these premiums.

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Conflict of Interest

Although first author of this study is currently an employee at Siemens Wind Power, this study was carried out before his employment. The results of this study do not represent any links to his employment.

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