Support Structure Suitability for Offshore Wind Farms Development in Greece based on a Sustainable Site-Selection Framework

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Abstract. Site-selection and spatial planning form a crucial step toward the successful development of Offshore Wind Farms (OWFs). Deployment of wind turbines in different water depths has raised the issue of selection of the most suitable support structures. In this work, a well-structured site-selection framework is proposed for the appropriate OWF development in Greece. The methodology includes two successive phases: (Phs.1: Siting Phase) the identification of suitable sites for OWF installation using Geographic Information Systems (GIS) based on sixteen exclusion criteria (e.g., water depth and wind power density); and (Phs.2: Support Structure Suitability Phase) the determination of most appropriate and commercially available support structure(s) for each suitable site. The proposed exclusion limits are retrieved from the authors' systematic review in offshore wind energy research and based on the maximization of environmental sustainability, and the technical and economic viability of OWFs. Twenty sustainable site solutions of either fixed (e.g., jacket) or floating (e.g., Hywind) support structures are proposed. The suggested methodology could support policy makers towards the global and national proper development of such wind energy projects.

Keywords: site-selection; spatial energy planning; offshore wind; support structure; GIS

1. Introduction

Wind energy has a key role to the accomplishment of energy interdependency of European Union (EU), since it covers 16.4% (13.4% coming from onshore and 3% from offshore wind) of EU electricity demand (including United Kingdom) in 2020 (WindEurope Business Intelligence et al., 2021). The aforementioned portion corresponds to 458 TWh of electricity produced. Offshore wind installations are constantly growing, due to the multiple benefits they present in siting issues (e.g. space availability, power generation, landscape disturbances minimization). Offshore wind farm (OWF) installations form currently a great portion of wind energy market, since it corresponds to 11.40% (i.e., 25 GW) of Europe's cumulative wind power capacity (i.e., 219.5 GW) at the end of 2020 (WindEurope Business Intelligence et al., 2021). In Greece, wind energy market development focuses only on onshore installations, since OWFs have not been planned and deployed yet.

Site-selection and spatial planning have a crucial role toward the successful deployment of OWFs, since inappropriate siting may lead to uneconomic viability and social opposition of wind projects. Aiming to solve and avoid the above essential siting issues, Geographic Information Systems (GIS) have been utilized within a large number of studies in OWF siting applications (Castro-Santos et al., 2020; Christoforaki and Tsoutsos, 2017; Saleous et al., 2016; Spyridonidou et al., 2020). An additional and important issue in the OWF site-selection processes, is the selection of the most suitable support structure of wind turbines in different water depths, since this issue is directly linked with the economic viability of the project and the engineering limitations of each support structure in specific water depth ranges (Myhr et al., 2014).

In the present work, a site-selection framework is developed for the identification of sustainable OWF sites in Greece, considering essential siting constraints (e.g., territorial waters, wind power density), and for the suitability of each support structure within the sustainable sites, considering Levelized Cost Of Energy (LCOE) of each system in different water depths and other important parameters. The remainder of the paper is structured as follows. Section 2 presents the Siting and Support Structure Suitability Phases of the proposed framework in detail. The results of this work are presented and discussed in Section 3, while the concluding remarks of this investigation are cited in Section 4.

2. Materials and Methods

The site-selection framework is applied on national spatial planning scale. In particular, the study area includes the territorial waters of Greece and therefore any marine area further away of six (6) nautical miles from the coastline is excluded. The methodology is shown in Figure 1 and includes two successive phases.

In the Siting Phase (Phs 1.), exclusion criteria and incompatibility zones are defined (Table 1) based on: (a) authors' previous research (Spyridonidou and Vagiona, 2020); (b) the special characteristics of the study area; (c) the respective provisions and policies of the Greek Specific Framework for the Spatial Planning and Sustainable Development for the Renewable Energy Sources (SFSPSD-RES) (SFSPSD-RES, 2008); (d) the international guidelines for proper WF siting (i.e., National Renewable Energy Laboratory (NREL)) (National Renewable Energy Laboratory, 2015); and (e) the special siting requirements of offshore support structures. The exclusion procedure is implemented by using the geoprocessing tools of ArcGIS software. The output of the Siting Phase is the identification of the suitable offshore areas for sustainable OWF siting in Greece.

Table 1. Exclusion Criteria and Incompatibility Zones of Siting Phase based on Spyridonidou and Vagiona (2020).

Exclusion Criterion	Unsuitable Areas
Wind Velocity (EC.1) (Height: 50 m)	<6.0 m/s
Wind Power Density (EC.2) (Height: 50 m)	<200 W/m²
Territorial Waters (EC.3)	>6 nautical miles
Water Depth (EC.4)	>500 m
Distance from Residential Network (EC.5)	≤1.5 km
Military Zones (EC.6)	All
Underwater Cables (EC.7)	≤ 500 m
Landscape Protection/Visual and Acoustic Disturbance (EC.8)	≤5 km
Distance from Shipping Routes (EC.9)	≲5 km (≤3 miles)
Distance from Land and Marine Protected Areas (EC.10)	≤3 km
Distance from Migration Corridors and Bird Habitats (EC.11)	≤3 km
Distance from Civil Aviation Areas (EC.12)	≤3 km
Distance from Ports (EC.13)	>20km
Distance from High Voltage Electricity Grid (EC.14)	>20km
Seismic Hazard Zones	Zone III (0.36g)
Farm Minimum Required Area	<2.5km²

In the Support Structure Suitability Phase, the existing support structure applications in European OWFs (4C Offshore, 2021) are analyzed. Monopile (70.37% of fixed-bottom support structure applications), Gravity-Base (12.96%) and Jacket (10.19%) are currently the leading support structures for fixed-bottom installations, while Spar Buoy and Semi-Submersible are currently the leading support structures for floating installations, followed by Tension Leg Platforms (TLP) (Table 2). Hywind and WindFloat are in the commercial and precommercial phase respectively. The SWAY prototype is decommissioned; however the feasibility of these systems has been verified through extensive dynamic simulations over 8 years in Norwegian Sea (Inocean, 2018). The remaining floating concepts are under demonstration or their design is to be completed for large (5 to 7 MW) offshore wind turbines.

Table 2. Brief review of existing leading concepts and floating support structures on European scale.

Concept	Support Structure	Water Depth (m)
Hywind	Spar Buoy	100-700
SWAY		60-300
SeaTwirl		n/a – deep waters
WindFloat	Semi-Submersible	>40 (located up to 100 m depth)
Damping Pool		>30
Blue H	TLP	>50

The water depth classes within each specific OWF suitable site are then determined and reclassified in accordance with: (a) the design engineering limits; (b) the LCOE changes (Myhr et al., 2014); and (c) the existing support structure applications and recommendations in different water depths (4C Offshore, 2021).

The classification of OWF sites includes: (a) Sustainable Sites of Fixed-Bottom Support Structure Suitability; and (b) Sustainable Sites of Floating Support Structure Suitability. The most suitable fixed-bottom support structures (e.g., jacket) for the OWF sites in first category and the most suitable floating support structures (e.g., Hywind) for the OWF sites in the second category are further identified, in terms of design engineering limitations, economic viability, and commercial availability or verified feasibility of the system.

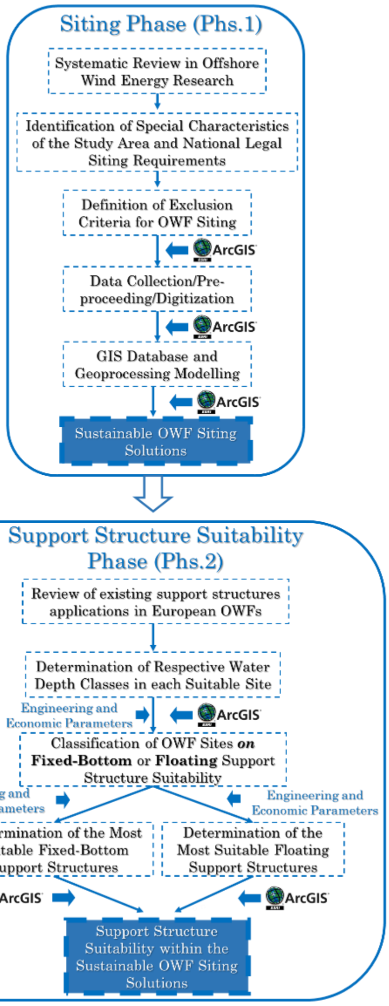

Figure 1. Schematic of the proposed methodological framework for site-selection and support structure suitability analysis.

The final outcome of both phases is a thematic map presenting the sustainable OWF sites (national scale analysis) and their most suitable support structures (site-specific scale analysis).

3. Results and Discussion

Twenty (20) suitable site solutions with a total surface area of 322.2825 km^2 form the final outcome from Phs.1. The offshore sites (Site.1, Site.9, Site.10, Site.11), present the highest wind energy potential, while there is no offshore site with wind power density lower than 300 W/m². 65% of the OWF suitable sites are pinpointed in the Aegean Sea, 30% in the Crete Sea, while only one site in the Ionian Sea.

The support structure suitability within the sustainable OWF sites is presented in Figure 2, considering all the above information and study results, the necessity of only one system deployment within each suitable site as well as the engineering design limitations and the LCOE of each system in different water depths.

Table 3. Support Structure Suitability within OWF Sites.

Site ID.	Water Depth (m)	Support Structure/Concept	Location
1	80-500	SWAY (80-300m), Hywind (300-500m)	South-East of Crete
2	300-500	Hywind	South-East of Crete
3	250-350	Hywind	North-East of Crete
4	150-400	Hywind	North-East of Crete
5	120-500	Hywind	North-East of Crete
6	60-450	SWAY (60-300m), Hywind (300-450m)	North of Crete
7	80-100	SWAY or WindFloat	North-West of Paros
8	80-100	SWAY or WindFloat	South of Syros
9	120-500	Hywind	North-East of Mykonos
10	100-400	Hywind	South-East of Tinos
11	200-300	SWAY or Hywind	West of Andros
12	100-200	SWAY or Hywind	North of Makronisos
13	60-120	SWAY	North of Makronisos
14	80-120	SWAY	North-East of Andros
15	25-50	Jacket	South-West of Euboea
16	300-500	Hywind	North-East of Diakopto
17	60-80	SWAY or WindFloat	South-West of Euboea
18	60-80	SWAY or WindFloat	South-West of Euboea
19	80-250	SWAY	North-West of Skiathos
20	150-300	SWAY or Hywind	West of Corfu

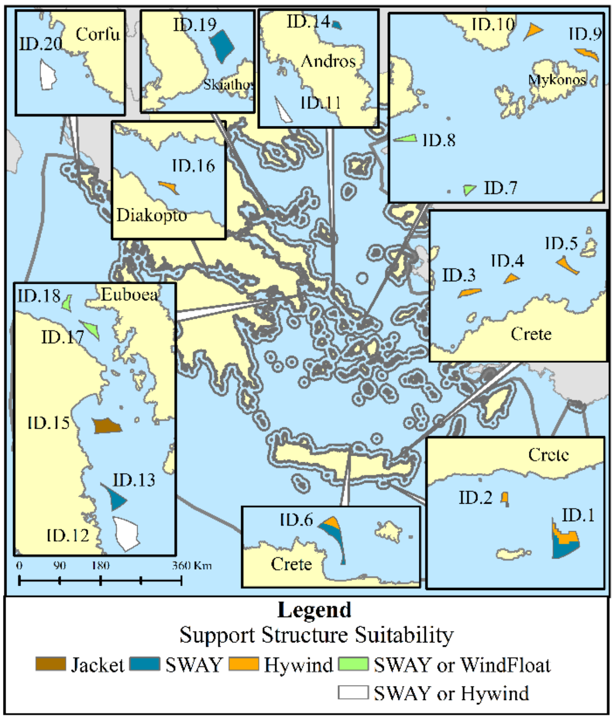

Figure 2. Support Structure Suitability in Sustainable Sites for OWF Development in Greece.

In Greece, 95% of the OWF sites require a floating support structure (Table 3). Hywind concept is the most suitable floating support structure for most sites, due to the commercial availability of the system, its suitability in quite deep waters (even greater than 300 m) and its LCOE stability in different water depths. In several cases, more than one support structure can be suitable for installation (e.g., Site.12 and Site.11). It should be noted that in two cases (Site 1. and Site 6.), two different systems are selected for the same site, due to the range of water depth.

4. Conclusions

At the present study, sustainable OWF sites are identified in Greece (on national scale) and the support structure suitability is analyzed for each site, considering economic and engineering parameters as well as exploiting the existing knowledge of support structure applications in European OWFs. Hywind is the most suitable floating concept for most OWF sites in Greece. In addition, almost all OWF sites require a floating support structure in Greece, due to the quite deep waters of the country. Thus, the proper and accelerated deployment of floating support structure designs is a crucial requirement for the sustainable deployment of OWFs in Greece.

The suggested framework and the OWF site solutions could support policy makers towards the global and national proper development of such wind energy projects. The methodology could be easily adopted and applied in other study areas and spatial planning scales. Lastly, the work could be easily updated, once all the floating support structures presented here are in the precommercial or commercial phase and/or their design is fully completed and verified.

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