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Investigating the potential and feasibility of an offshore wind farm in the Northern Adriatic Sea

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Abstract

The use of offshore wind power is becoming increasingly important towards a sustainable growth worldwide. In Italy, as well as in other countries where wind energy is provided only by onshore plants, the interest in the deployment of offshore wind resources is rapidly growing, despite relatively modest average wind speeds, compared to typical wind conditions in the North Sea. Research efforts have, so far, addressed the exploration of the most promising locations, based on wind characteristics; however, more extended evidence of technical and economic feasibility is now needed to raise awareness in the decision makers and secure to this source of renewable energy a proper role in the future energy policies. Within such a context, the paper presents the first feasibility study for the development of an offshore wind farm off the coast of Rimini, in the Northern Adriatic Sea. The study is based on an anemometric campaign started at the site in 2008 to provide a statistical assessment of the wind characteristics and the related wind energy potential, and on a 10-year wave measurement record next to the area, together with a thorough analysis of the site geological and environmental characteristics. Environmental data are interpreted with a proper consideration of the extreme events distribution and relevant results are used to select the most appropriate commercially available wind turbine and to design the site-specific support structure. A comprehensive evaluation of the investment costs and revenues is then carried out with reference to two wind farm layouts (a first smaller, constituted of 15 elements, and another one, featuring up to 60 elements) and in relation to two different scenarios, conservative and comparatively more realistic. Results of the study clearly show that the Northern Adriatic Sea is potentially suitable for the development of a large wind farm and should encourage investments on more advanced experimental campaigns and related studies in order to prove the feasibility of innovative technological solutions that would substantially increase the profitability of such installation.

INTRODUCTION

The ocean energy sector has undoubtedly got a great potential of making an important contribution to the supply of renewable energy and the percentage of electricity that could be produced from offshore wind farms (OWFs), worldwide, has been estimated to be around 7% by 2050 [1]. According to [2], Korea, Spain, Norway, Portugal as well as the US are emerging countries in the deployment of offshore wind resources, as also documented by several research works carried out in the last years. Established practice in those countries is consistent with the trend, where several pending projects are still awaiting for their approval and only few demonstration prototypes have been actually installed, as it happens for instance in the US [3], where the production of wind energy is primarily onshore while the harvesting of offshore energy is mainly related to oil and gas extraction.

The situation in Italy is alike: the wind energy is entirely provided by onshore plants, for a total rated capacity of 8.66 GW at the end of 2014 [4], and the experience in the offshore field is well consolidated only in the oil and gas sector (Italy currently has 100 productive platforms in activity [5]). In the country interest is now growing towards the deployment of OWFs, as it is also documented by Tradable Green Certificates made available since 2009, and towards the support of the high investment costs required by wind power in the marine environment [6].

In the last few years, a significant research activity has been devoted to map wind speeds and wind energies over the Mediterranean basin, in order to identify suitable areas for offshore wind deployment [7], [8] and [9]. Relevant results would locate the most promising spots in Southern Italy. The already published feasibility studies are consistent with these findings, addressing the deployment of offshore wind farms along the southern coasts, off Puglia [10] and Sicily [11] regions. In such studies, the offshore wind turbines (OWTs) are located a few kilometers from the shoreline, where a reasonably shallow water (less than 35 m deep) is still found and no special technology for the foundation systems is required.

The widespread presence of deep water near shore would provide a natural constraint for the diffusion of wind plants, as related environmental impact becomes critical to obtain construction permits in high-density touristic areas [12, 13]. The use of floating wind turbines is recognised as a possible solution, as they can be installed in deep waters [14]. However, the development of such structures is still subjected to serious technical challenges, notably for the design of mooring and anchoring systems under complex non-linear and dynamic loading conditions [15] and [16]. Furthermore, economic feasibility has been assessed for water depths greater than 60 m [17], where other issues related to the distant wind farm location can arise, as discussed in [18].

According to [19], more than twenty projects for OWFs have been presented along the southern Italian coasts in the last years, whose realization was denied or temporarily stopped due to siting issues, which were found critical either by the relevant Municipalities or by the Ministry of the Environment and the Ministry for Cultural Heritage.

As a consequence, interest is now moving to different locations, so far not adequately considered as a possible location for the deployment of an OWF. According to [20], the potential of such areas need to be first comprehensively investigated, taking into account the technical and the economic aspects with a suitable methodology. Direct measurements of environmental conditions are also crucial for such a study; previously published feasibility studies of OWFs on the Italian territory, in fact, made use of extrapolated environmental data [10] and [11]. However, the importance to collect actual data at the installation site has been highlighted under different circumstances: in order to incorporate local variables [21], to select the most appropriate distribution for the local wind climate description and to minimize possible estimate errors in offshore wind energy [22]. Furthermore, most investors require such information as they would not rely solely on wind data coming from a numerical model extrapolation [23].

Within such context, the study presented herein - with reference to a case assessment in Italy - aims at encouraging the deployment of offshore wind farms, by responding to the current need of detailed, applied and consistent evidence of the actual feasibility of wind farms in countries where the exploitation of offshore wind is still being considered only as a possible but not profitable option.

The study represents the first, field data based, feasibility study of an OWF in the Northern Adriatic Sea, off the coast of Rimini. The area has been selected according to the crucial indications of local public administrations, as it presents very favourable siting conditions and no particular natural constraints. To reliably assess the wind potential, an experimental campaign was launched in the area in 2008 to measure wind speeds and frequencies. Wave conditions were ascertained by a directional wave buoy installed in 2007, few kilometers north of the area. The study aims at taking into account technical and economic aspects using an interdisciplinary approach, as suggested in [24] and [25].

The paper is organized in three parts. First, a thorough description of the site is given and the experimental data are presented and interpreted with a proper consideration of the extreme events distribution. The second part addresses the technical feasibility, relevant to the selection of the most suitable offshore wind turbine (OWT) and to the preliminary design of the tower and the support structure, based on the interpretation of the field data previously presented. The third part is concerned with the economic aspects, examined on two distinct OWF layouts: a first smaller, constituted of 15 elements, and another one featuring up to 60 elements. Two different scenarios, conservative and comparatively more realistic, are considered for both layouts to complete the evaluation of the investment profitability.

The procedure adopted for a preliminary feasibility study is described in full detail, so that it could be easily repeated and applied on essential data in areas with similar features.

1. DETAILS OF THE STUDY AREA

1.1 Site description

The area of study is located in the Northern Adriatic Sea, off the coast of Rimini (Italy) as depicted in Fig. 1, on a schematic map of the current sea uses [26]. Within the boundaries of territorial waters, 12 km far from the coast, the area is approximately 8 km wide and 20 km long and overlaps a wide district for gas extraction, already provided with several productive platforms. Military zones are also present in the proximity, though located distant enough, as well as sand deposits for beaches nourishment. Aquaculture is practiced sufficiently far away, along the boundary of the nursery area, next to the coast. The directional wave buoy named “Nausicaa” and the methane platform “Azalea B”, hosting the anemometer for wind speed measurements, are highlighted on the map. The industrial port of Ravenna is located north of the area, approximately 60 km from Rimini. As observed, five productive gas platform are found in the area. After their construction, an environmental impact assessment study was carried out for platform “Regina”, following a 3-years period data collection [27]. The analyses were focused on the effects of the structure on the hydro-biological conditions, on the chemical and physical properties of the silty sediments and on the metal concentration in local organisms, benthos and fishes. The study showed no significant effects on relevant water and soil properties, but a biodiversity enrichment was detected, as typically expected next to offshore steel structures.

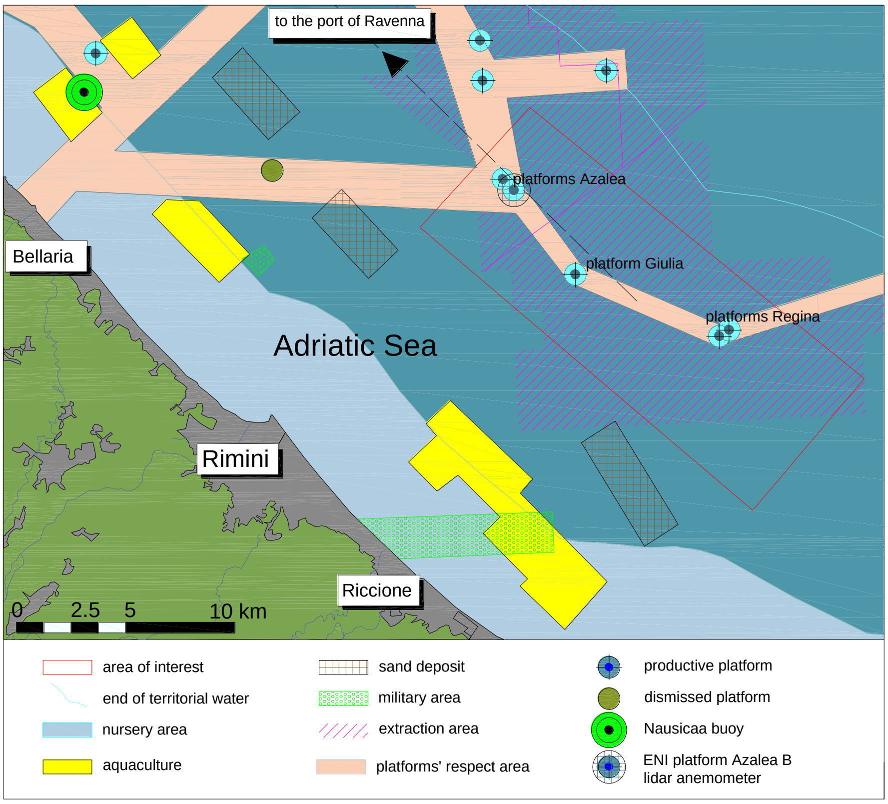


Fig. 1 Area of study on a schematic map illustrating the sea uses off the coast of Rimini (redrawn from [26])

1.2 Geological aspects

Geological details are provided in Fig. 2 [28] where the plan view of the study area, in correspondence of the available section BB', is shown. As mentioned, water is relatively shallow at the section, with depths ranging between 15 m and 20 m, with a gentle slope of the seabed. Three geological units, almost evenly spaced, can be identified below the sea bottom: i) a prodelta and internal platform pelite complex, consisting of clays and clayey silts; ii) a succession of clays and clayey silts with bioclastic sands; iii) the continental deposits, mainly made of overconsolidated clays. Such geological information are crucial for the development of the simplified soil model used for a preliminary design of the wind turbines foundation system.

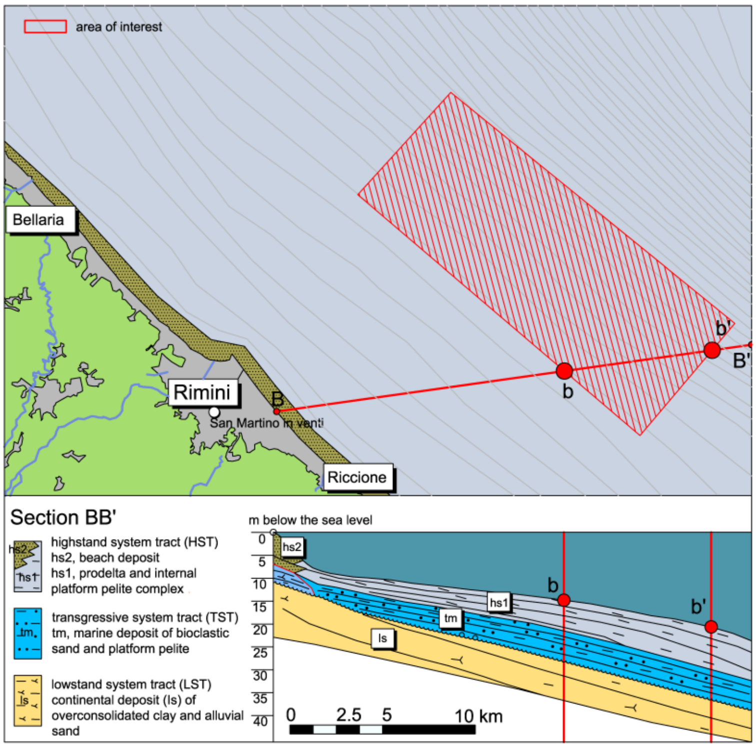


Fig. 2 Extract of the Geological map of the Italian sea at the area of study (redrawn from [28])

1.3 Details of wind conditions

Wind resources have been obtained following an anemometric campaign carried out at the study area between year 2008 and 2013, on the methane platform “Azalea B” (Fig. 1). The area has experienced a regime of mixed wind pattern due to Sirocco (south-east) and Bora (north-east) winds. Bora is a severe, dry, cold and gusty chute wind blowing from the NE quadrant, strongly influenced by local processes and morphology of the eastern Alps; [29] it is more vigorous and frequent in wintertime, when persistent anticyclones over northeastern Europe or cyclones over the Adriatic and Mediterranean ensure the supply of cold continental northeasterly air [30]. Sirocco is a warm and humid southerly wind mainly blowing in spring and autumn along the major axis of the Adriatic basin, channeled by the Apennine and Dynaric Alps, in connection with low pressure systems approaching the basin from W or SW and high pressure areas on the Balkan Peninsula [31]. The data consist of measurements recorded every twenty seconds. For each measurement, the average wind speed of ten minutes has been used, according to the World Meteorological Organization (WMO) instructions. After a preliminary data quality control, the resulting time series is characterized by a total of 295,650 useful wind velocity data against an overall of 394200 possible.

The observed probability density of the wind speed at 80 m above the mean sea level is shown in Fig. 3. The average observed wind speed yields 5.97 m/s with a 95% confidence interval of +/- 0.03 m/s. For verification purposes, the observed probability density curve has been calibrated against a widely used Weibull distribution [32, 33, 34]. A least squares fitting of the observed probability density has been employed to estimate the two Weibull parameters, as proposed by Justus [35]. With a density function at 1 m/s intervals, the best fit has been found for a shape parameter (κ) of 1.72 and a scale parameter (λ) of 6.7 m/s, with a coefficient of determination $R^2 = 0.98$. The resulting Weibull probability density function is also shown in Fig. 3.

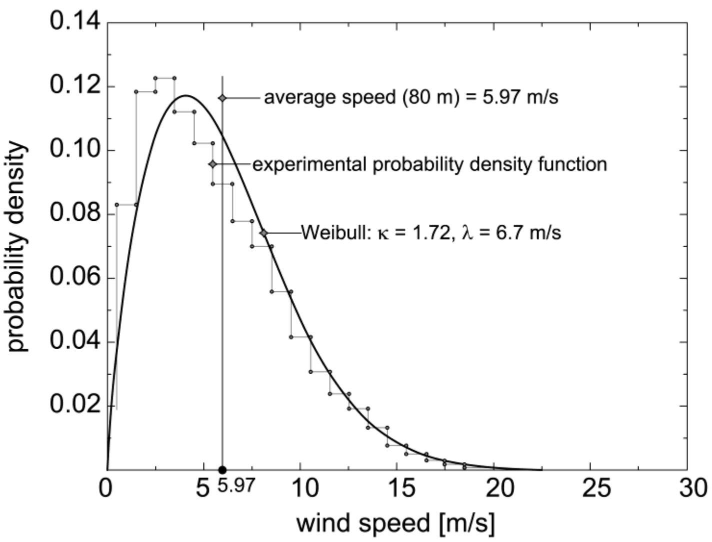


Fig. 3 Data of wind speed at the study area: experimental probability density and Weibull fitted distribution

The data can be further interpreted in terms of extreme events distribution, with the main aim of evaluating the environmental actions at the study area with a return period of 1 year and 100 years. The peak over threshold (POT) method has been used to the scope. The technique is a well-established statistic approach, based on the following steps: i) application of a high threshold and form wind speed clusters above it; ii) selection of homogeneous independent events and peak data exceeding the selected threshold; iii) identifications of a probability model that best represents the exceedances; iv) determination of values within a given return period. The great advantage of POT method is the utilization of an adequate number of independent extreme data, achievable also with a relatively short time series. For this reason, a period of six years turns out to be statistically adequate as suggested by Patlakas et al. [36].

The Maximum Likelihood Method (ML) has been used for the parameter estimation of the distribution fitting, while the goodness-of-fit has been mainly based on the Kolmogorov–

Smirnov test. The POT method has been applied to all wind datasets. The threshold has been selected between 98% and 99% quantile and the Kolmogorov–Smirnov test employed to identify the exact threshold within the mentioned range providing the optimum fit. The resulting value turns out to be equal to 20 m/s, as also found by Patlakas for the quantification of extreme wind events within the Greek Islands [36]. Independency of the events is critical and even high thresholds cannot ensure it. That is why minimum separation time among the events should be ensured. For European climates, the separation time can be set at 48 hours [37, 38]. As an example, in Fig. 4, the technique is illustrated within a time interval of 6 months. Observing that extreme events should have a persistency of 12 consecutive hours, two events are considered separate if peaks are 48 hours distant to each other with values below the threshold lasting for not less than 3 hours. The associated empirical frequency histogram and cumulative distribution function (CDF and pdf) are given in Fig. 5, along with the corresponding exponential distribution and best fit parameter λ equal to 2.2 m/s (95 % lower and upper bound parameter fitting: 1.9 – 2.6 m/s). The approach provides a value of centennial wind speed equal to 37.7 m/s (95% lower and upper bounds values: 35.3 – 40.54 m/s) and an annual wind speed equal to 27.6 m/s (95% lower and upper bounds values: 26.6 – 28.8 m/s).

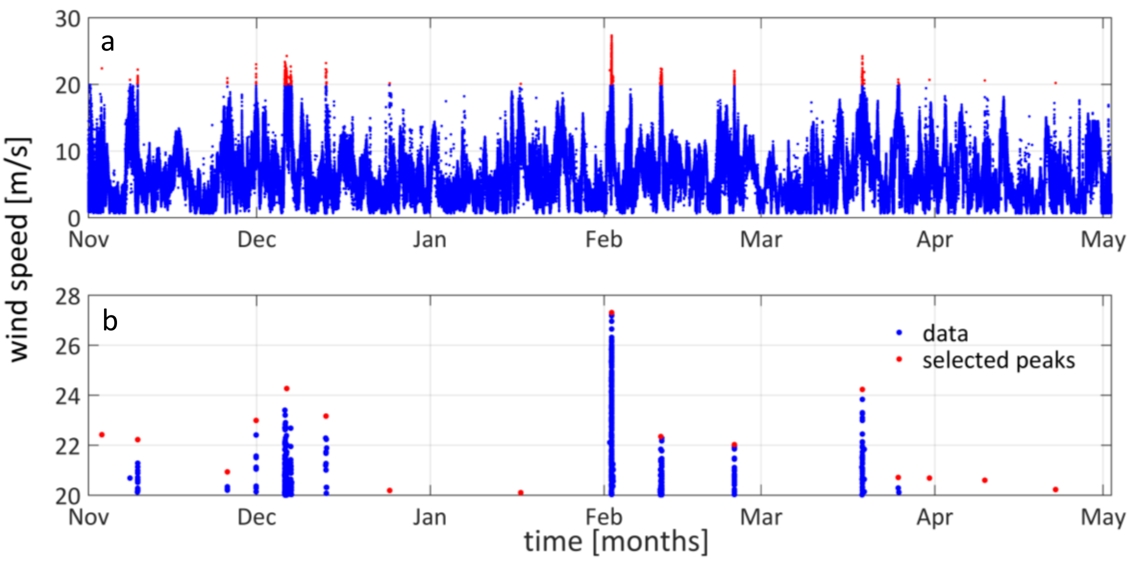


Fig. 4 POT analysis of wind data with a threshold speed value equal to 20 m/s. Red dots indicates a) the selected events and b) the selected peak values, on a 6 months interval

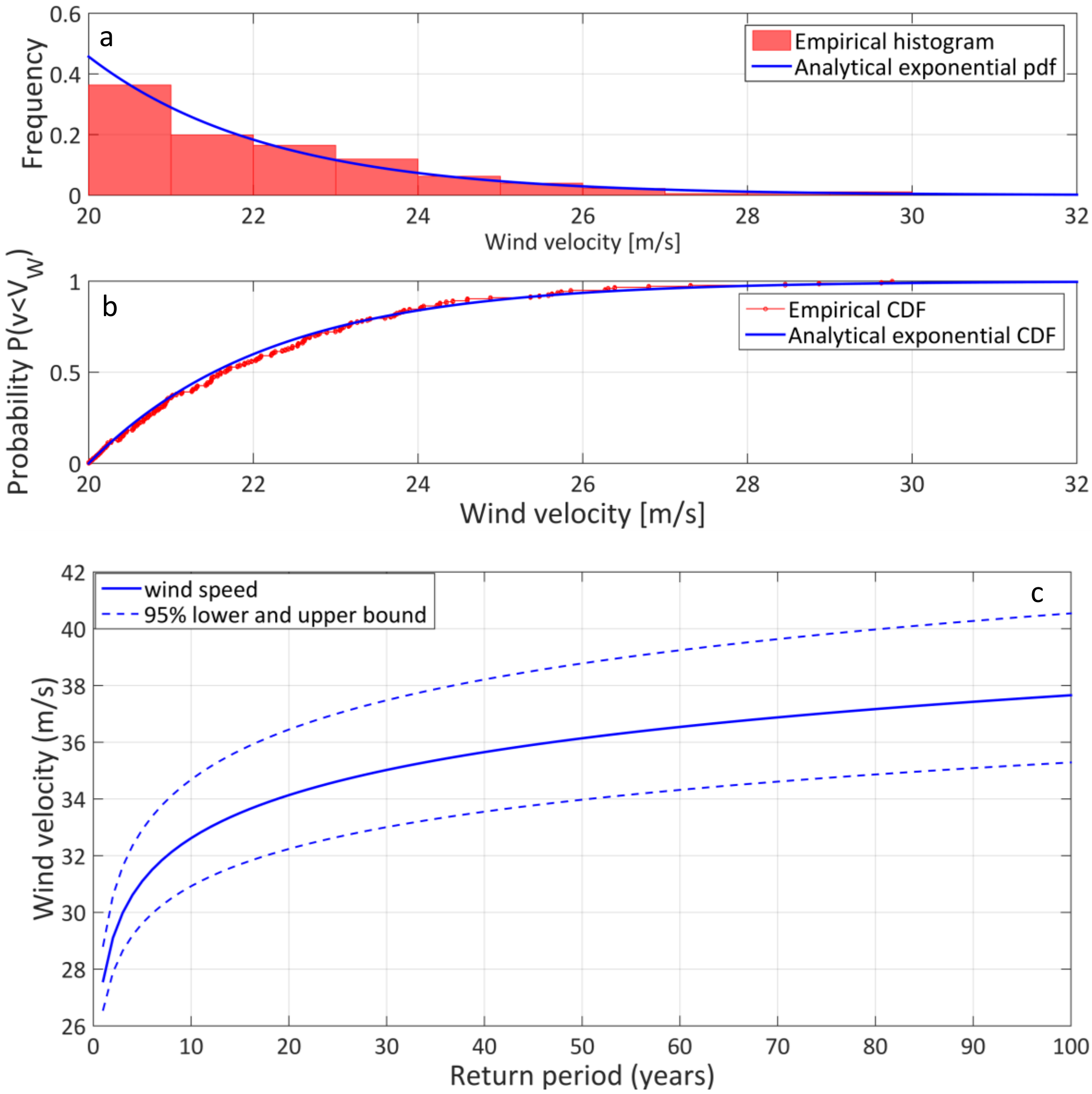


Fig. 5 Interpretation of wind data at the study area: a) empirical and analytical pdf and b) CDF curve distribution function of the peak values of wind speed and c) extreme wind speeds vs the corresponding return periods

1.4 Details of wave conditions

Wave conditions have been established on the basis of the data collected by the “Nausicaa” directional wave buoy installed by the Emilia-Romagna Regional Agency for Environmental Protection (ARPA) at a depth of 10 m below the sea level, about 8 km offshore, north of the study area (see Fig. 1). The data used in the present analysis cover the period from 23 May 2007 to 24 March 2016. The significant wave height (H_S), the peak period (T_P), the mean period (T_m) and the direction of wave propagation (Dir) are provided at 30 min intervals and stored in the meteo-marine database operated by the Hydro-

Meteorological and Climate Service of ARPA [39]. This data collection represents the only wave observation set currently available for the entire coast of Emilia-Romagna. After a preliminary data quality control and interpolation filling of gaps no longer than two consecutive significant wave height observations (1 hr lack of measurements), the resulting time series is characterized by a total of 142748 useful data against an overall of 173836 possible. The wave climate is characterized by low wave energy conditions, with $H_S < 0.5$ m for about 70% of time, and $0.5 \leq H_S < 1$ m for about 20% of observations. The most frequent marine storms are mainly caused by Sirocco (SE) winds while the dominant storms are associated with Bora (NE) winds. The significant wave height rose is given in Fig. 6, with calm referring to values of wave heights below 0.25 m.

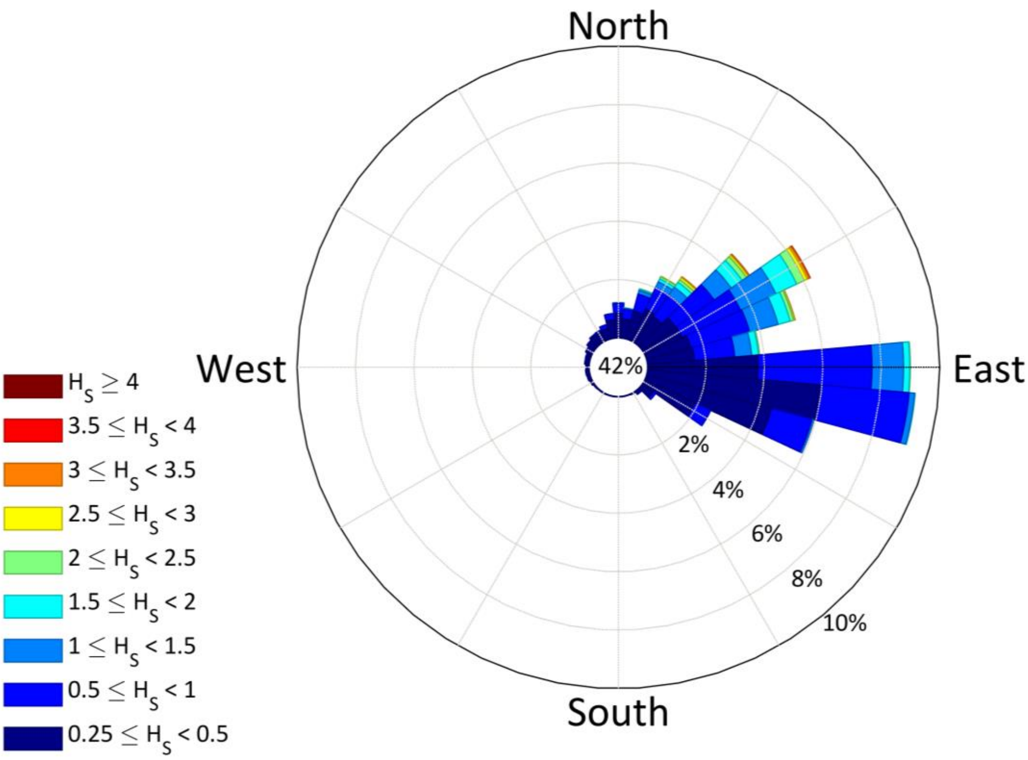


Fig. 6 Rose of the significant wave height, at the “Nausicaa” directional buoy (values in meters).

Since dependence of the extreme waves may vary with the storm direction, the effect of wave directionality has also required further investigation. The “Nausicaa” buoy data are not measured at water depths large enough to consider negligible the refraction effect on the recorded wave directions, as can be deduced from Fig. 6. In the Adriatic basin the offshore wave direction is approximately aligned with the wind direction. Refraction alters the travel path of the waves approaching the northwestern coast and causes the direction of propagation to rotate towards the perpendicular to bathymetric contours, which can be considered ranging approximately between 65 and 70°N in front of Cesenatico, where the buoy is located. Therefore, the following two directional sectors, separated by the aforementioned normal, have been taken into consideration: 22.5–67.5°N, associated with Bora conditions, and 67.5–112.5°N, providing information on Sirocco waves [40]. Notice that waves observed at the "Nausicaa" buoy with directions between 112.5°N and 22.5°N are mostly associated with winds blowing from land to sea and hence corresponding to low wave heights, negligible for the scope of the analysis. According to the two main directions thus identified, a directional analysis of the data has been completed in order to select the most severe conditions and then perform the POT analysis only on this data set. Main results, in terms of annual average significant wave height ($H_{S,y}$) and empirical 50, 98 and 99% encounter probability significant wave heights ($H_{S,50}$, $H_{S,98}$ and $H_{S,99}$), are proposed in Table 1. In agreement to this preliminary analysis, only waves due to Bora wind (22.5–67.5°N) have been subsequently considered to select the design wave heights.

Table 1. Wave data directional analysis results

Dir (°N)	$H_{S,y}$ (m)	$H_{S,50}$ (m)	$H_{S,98}$ (m)	$H_{S,99}$ (m)
0 – 360	0.45	0.31	1.82	2.17
22.5 – 67.5	0.67	0.45	2.50	2.90
67.5 – 112.5	0.42	0.32	1.45	1.68

The POT analysis have been also applied to the wave data providing the results illustrated in Fig. 7, where the empirical frequency histogram and cumulative distribution function (CDF and pdf) are given, along with the corresponding generalized extreme value distribution (GEV), with best fit shape parameter (ξ), scale parameter (σ) and location parameter (μ) equal to -0.042 (95% lower and upper bounds parameter fitting: -0.179 – 0.094), 0.486 (95% lower and upper bounds parameter fitting: 0.422 – 0.549) and 1.820 (95% lower and upper bounds parameter fitting: 1.735 – 1.904), respectively. The same criteria used to define a wind extreme event have been applied for the wave height data, whereas the threshold used to define individual storm has been established according to Boccotti's method [41]. The method is based on a preliminary identification of a wave height threshold, namely 1.5 times the annual average H_{Sy}, that is 0.67 m for the available wave data set described in Table 1: the chosen threshold value is therefore equal to 1.00 m. The analyses have provided the significant wave height (H_s), the mean peak wave period (T_p) and the mean wave direction (θ_m), whose values are given in Table 2 with reference to a return period of 1 year and 100 years. The mean peak periods associated with the predicted extreme significant wave heights have been estimated using a scatter plot of measured peak period versus significant wave height as proposed by Viselli, [42]. A three-parameter power law fit has been selected, based on a comparison of the R^2 value from a three-parameter and a two-parameter fit proposed in [43]. The parameters a, b, and c in eq. 1

$$T_p = a \cdot H_s^b + c \qquad \text{(Eq. 1)}$$

turn out to be equal to 1.923 (-0.9515, 4.798), 0.703 (0.03535, 1.371) and 3.723 (0.5424, 6.904), respectively. The values in parentheses indicate the parameters that define the lower and upper bounds of the 95% confidence interval.

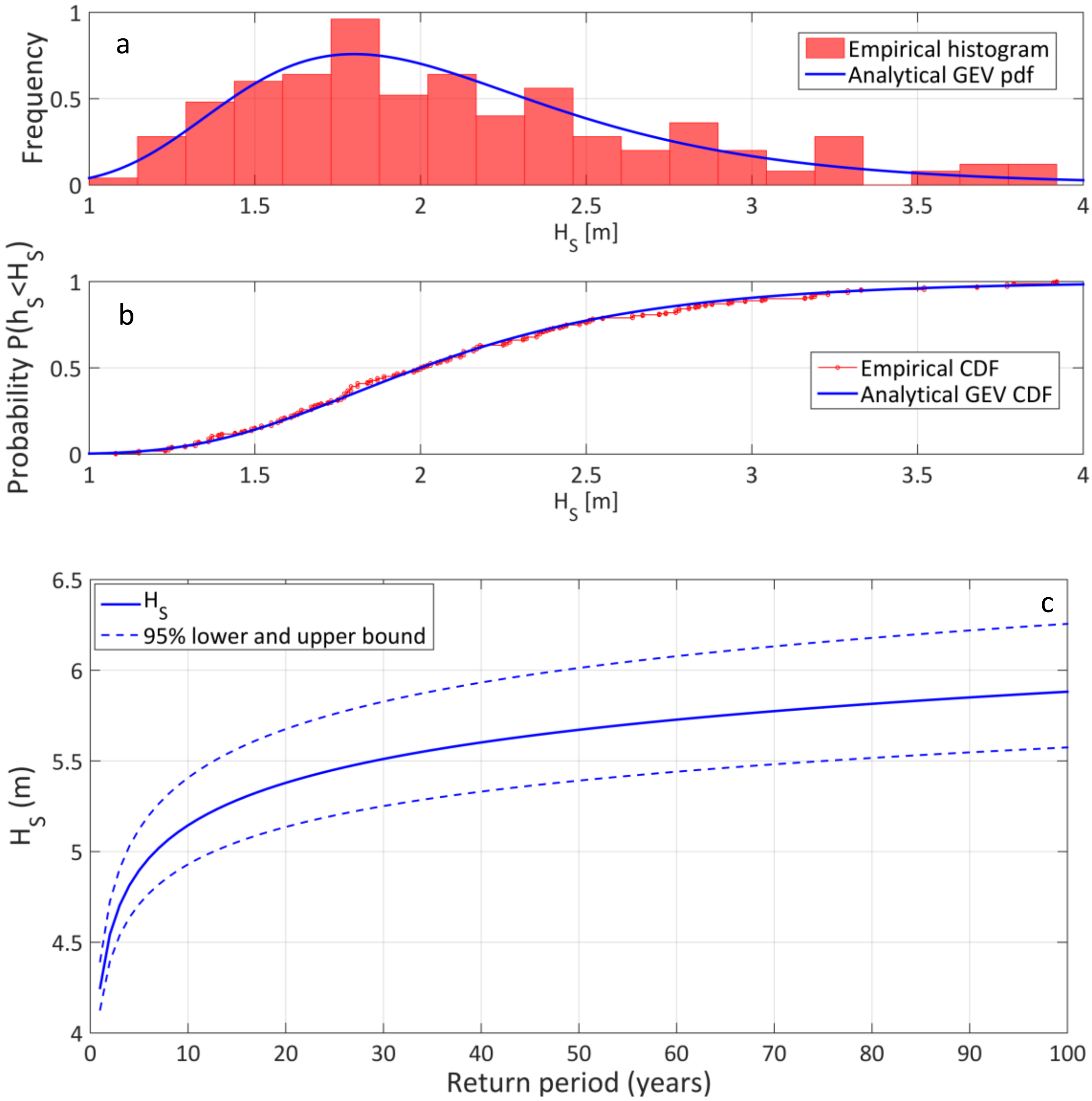


Fig. 7 Interpretation of the wave data at the “Nausicaa” buoy: empirical and analytical a) pdf and b) CDF curve distribution function of the peak values of significant wave height and c) extreme H_S vs the corresponding return periods

The wave conditions at the area of interest, whose water depth is about 20 m (Fig. 2), have been finally estimated by propagating, iteratively, several wave states from such depth to the “Nausicaa” buoy water depth, ie 10 m. To the scope, the wave propagation software MIKE 21-SW [44] has been used to identify the wave conditions at the area of study (Table 3), which generate annual and centennial significant wave heights at the buoy location,

(Table 2). The procedure has been iterated and the solution found when the error between the reconstructed (from the measurements) and extrapolated (from the model) wave height results lower than 0.05 m. More in details, MIKE 21 (version 2011), through the module SW (fully Spectral Waves formulation) with a flexible mesh, has been used. The fully spectral formulation is based on the wave action conservation equation as described in [45, 46]. The main physical phenomena considered in the simulations are: wave growth by action of wind; dissipations due to bottom friction, to depth-induced wave breaking and to white capping as well as refraction and shoaling due to depth variations.

Table 2 Extreme events interpretation of the northern-easterly wave data collected by the “Nausicaa” directional buoy

Return period	H_s [m]	T_p [s]	θ_m [°]
1 year	4.25	9.0	50
100 years	5.90	10.4	50

1.5 Summary of the environmental conditions at the study area

The results of the analyses enable to evaluate the forces acting on an OWT under extreme and service conditions, crucial for the design of site-specific components of the wind turbine, such as the support structure which includes the transition piece and the foundation.

Results are collected in Table 3, where the design environmental conditions at the study area are summarized. Data relevant to the study are: the significant wave height (H_s), the maximum wave height calculated according to the statistical distributions proposed by Battjes and Groenendijk [47] (H_{max} is the height with probabilities of exceedance equal to 0.1 %), the peak period (T_p) and the wind speed (v_w) evaluated for a return period of 1 year and 100 years. The data relevant to the extreme conditions are consistent with previous measurements carried out north to the area of study [48, 49].

Table 3 Design environmental conditions at the area of study

Return period [years]	H_s [m]	$H_{max(0.1\%)}$ [m]	T_p [s]	v_w [m/s]
1	4.60	7.90	9.0	12.5
100	7.60	11.15	10.4	38

2 DETAILS OF THE OWF

2.1 Details of the OWT

A commercially available OWT has been considered in this study. The structure features a 120 m diameter rotor and a hub height of 100 m above the sea level. The weight of the nacelle is 1,226 kN and of the rotor 981 kN. Further technical data are given in [50].

The rated power is 3.6 MW and the power curve, which provides an indicator of the power as a function of the average wind speed at the level of the rotor hub, is given in Fig. 8. As it can be observed, the cut-in wind speed is between 3 and 5 m/s, the rated power at 12-13 m/s and the cut-out wind speed at 25 m/s.

The capacity factor of the OWT at the study area has been calculated from such power curve and from the experimental probability distribution of wind speed, as measured at the platform “Azalea B”, 80 m above the sea level, resulting equal to 25% and an average power of 0.9 MW. A comparatively higher capacity factor was the main reason for choosing this model of turbine, selected among all those currently suitable for the European market.

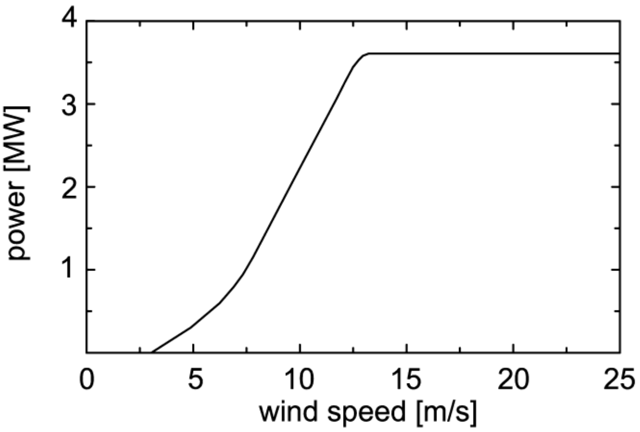


Fig. 8 Power curve for the OWT selected for this study

2.2 Design of the wind farm

In order to estimate the investment costs and revenues of an OWF to be installed at the area of study, two different scenarios have been considered: an arrangement featuring 15 turbines for a total installed capacity of 54 MW, hereinafter called layout A, and an arrangement featuring 60 turbines for a total installed capacity of 216 MW, hereinafter called layout B. A schematic drawing of the layouts is given in Fig. 9: layout A has been designed in a way that can be extended to layout B. In order to maintain the shear losses, due to the interaction between turbines, below 9.75% in the favourable case and 11% in the unfavourable case [51], the distance between the structures has been maintained equal to 625 m. Locating the offshore transformer station at the platform “Azalea B”, the distance to the onshore grid-connection point (San Martino in Venti, within the city of Rimini) could be kept within 15 km.

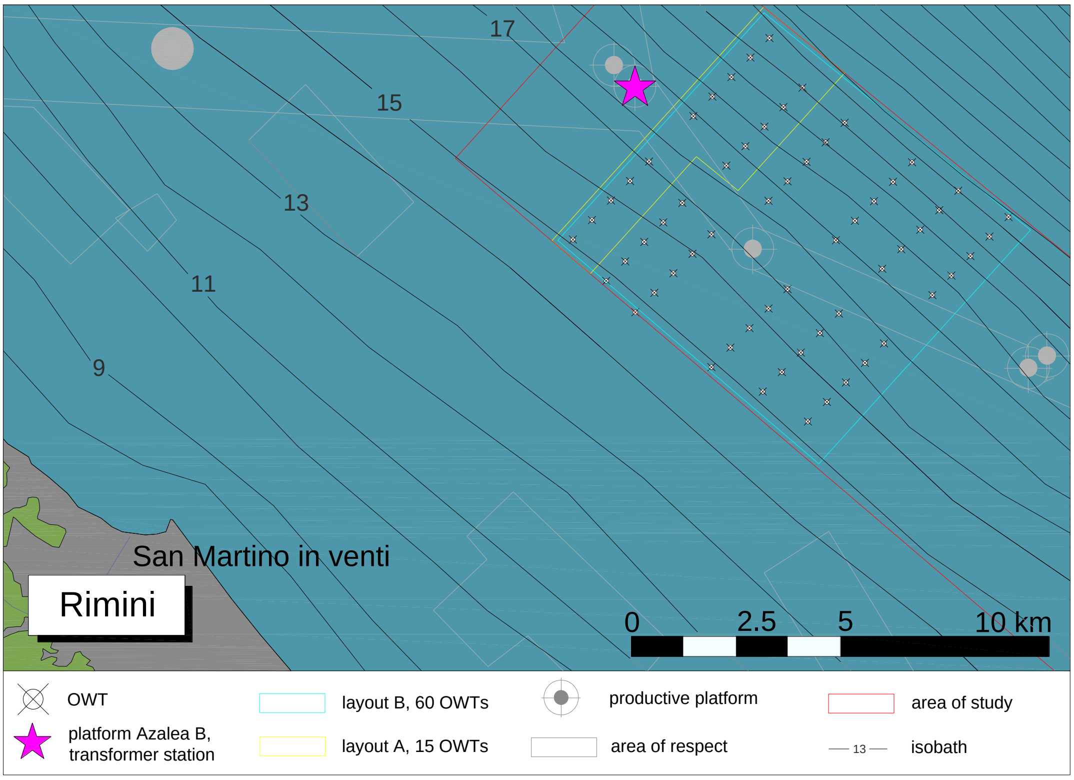


Fig. 9 Schematic drawing of the OWF: layout A and layout B

2.3 Preliminary design of the structural components

2.3.1 Actions on the OWT

A preliminary structural design follows the evaluation of the forces acting on the structure, whose qualitative distribution is shown in Fig. 10: the forces acting on the rotor (F_{rotor}), the drag force, per unit length, exerted by the wind on the tower above the sea level (f_{wind}) and the force, per unit length, exerted by the waves on the tower below the sea level (f_{wave}).

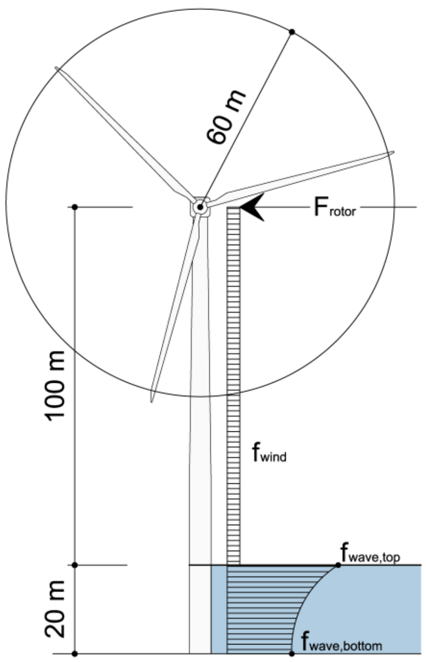


Fig. 10 Schematic drawing of the environmental actions on the OWT

Evaluation of forces in extreme and service conditions makes use of the data presented in Table 3 of Section 1.3. In particular, under extreme conditions, the wind and waves considered correspond to a 100 years return period, while under service conditions to a 1 year return period. Exception has been made for the wind, whose service condition value has been taken as the one at which the turbine reaches the rated power, i.e. 12.5 m/s according to the power curve of Fig. 8, Section 2.2.

In service conditions, the force acting on the rotor has been conservatively evaluated, using the approach presented by Betz [52]. The calculation of the force acting on the structure above the sea level considers a wind speed again equal to 12.5 m/s, with Reynolds number 3.8×10^6 and C_d equal to 0.6. The evaluation of the forces on the submerged part of the tower has been carried out according to the Det Norske Veritas (DNV) standard [43, 53, 54], which makes use of Morison's equation, forced with the annual maximum individual wave height (7.90 m).

In extreme conditions, it has been assumed that the turbine is kept still and the generated force is only due to the drag force exerted by the wind on the blades. The evaluation of the hydrodynamic wave loads has been based on the linear wave theory. Following Natarajan [55], a safety factor of 2 has been applied to the wave loads distribution, due to the importance of the higher order nonlinear wave model on the identification of the wave loads acting on the wind turbine tower. The linear approach can, in fact, lead to underestimate the induced stresses on the wind tower. The calculation of the drag force on the tower and the estimate of the force, per unit length, exerted by the wind on the tower above the sea level, has made use of the centennial wind value (38 m/s), with Reynolds number equal to 1.25×10^7 and C_d equal to 0.8; the force, per unit length, exerted by the waves on the tower below the sea level of the centennial maximum wave height (11.15 m).

Results of the analyses, carried out under service and extreme conditions, are given in Table 4, according to the notation introduced in Fig. 10.

Table 4 Environmental forces on the OWT

conditions	F_{rotor} [kN]	F_{wind} [kN/m]	$F_{wave,top}$ [kN/m]	$F_{wave,bottom}$ [kN/m]
extreme	105	3.6	190	111
service	963	1.1	90	42

2.3.2 Transition piece and foundations for the OWT

Turbine and tower are typically provided as single item, while the support structure made of foundation and transition piece – with the function of connecting the tower to the foundation - is separately sold and specifically designed. All these components are made of steel NV-32 (density 7.8 ton/m^3 and yield strength 315 MPa). Due to the uncertainties introduced in this phase of calculations and the qualitative nature of the study, a reduction equal to the 30% of the steel yield strength has been applied. A tower featuring a diameter of 4.5 m and a transition piece with a diameter of 5 m and thickness 0.05 m, have been shown to be able to safely carry the design loads.

A preliminary design of the foundations has been also carried out, following the evaluation of the combined loads acting at the tower base in both service and extreme conditions.

Actions on the foundations include the weight of the structure and the environmental loading as estimated in Section 2.3.1. According to the notation introduced in Fig. 11, values of vertical load (V), static horizontal load (H) and static overturning moment (M) are included in Table 5. The value of vertical load has been computed as the sum of the weight of single components of the OWT: the rotor, the nacelle, the tower and the support structure. The weight of the tower has been calculated using the design dimensions of Section 2.3.1. These data fall in the lowest side of the common range of static environmental loads on foundations of wind turbines [56], as expected due to the mild weather conditions encountered in the Northern Adriatic Sea.

Two types of foundations have been considered: a monopile (Fig. 11 a), which is the typical foundation solution for OWT, and a caisson (Fig. 11 b), a shallow foundation provided with a steel skirt with an aspect ratio (length to diameter L/D) less than one.

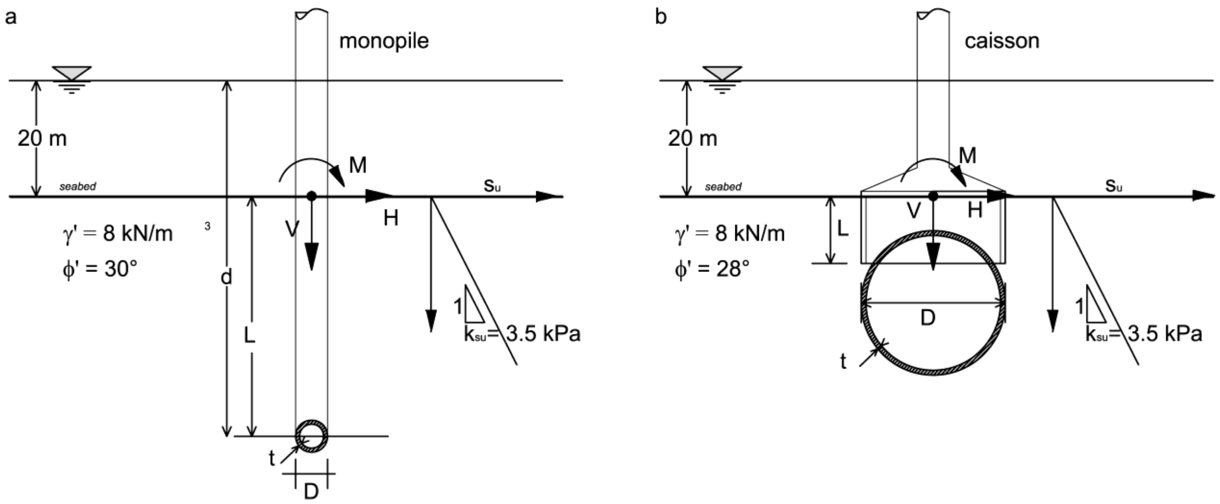


Fig. 11 Simplified geotechnical model of the soil bed and schematic drawing of the foundations for the OWT: a) monopile and b) caisson foundation

Table 5 Combined loading on the foundation of the OWTs

conditions	V [MN]	H [MN]	M [MNm]
extreme	13	3.2	67.5
service	13	2.2	135

At present, a suitable geotechnical characterization of the sea-bed is not available. Following the information provided by the geological section of Fig. 2, two simplified uniform soil profiles have been used in the analyses, carried out in drained and undrained conditions. In particular, drained analyses have been carried with a soil profile of saturated unit weight of 18 kPa and an angle of shearing resistance equal to 30°. As for the undrained conditions, the soil profile can be characterized by an undrained shear strength linearly increasing with depth at a rate of 3.5 kPa, suitable for offshore soft clay deposits and ensuring an undrained shear strength of 80÷200 kPa at the top of the deeper layer of overconsolidated clay.

The lateral bearing capacity analysis of the monopile, subjected to static combined monotonic loading, has been based on the approach proposed in [57], which can be applied in undrained and drained conditions. With reference to the notation introduced in Fig. 11, the analyses has shown that a monopile featuring a diameter (D), thickness (t), embedment length (L) and total length (d) equal to 4.4 m, 0.07 m, and 40 m and 63 m respectively, is able to resist the design loads. The preliminary design of the wind turbine tower and foundation has provided the required amount of steel for the supporting structure of a single wind turbine, including the transition piece and the foundation system as depicted in Fig. 12. Design volumes and masses inserted in Table 6 have been evaluated according to Fig. 12, where an additional 10% of the total volume has been applied to the transition piece to take into account the connecting plates the element is generally provided with.

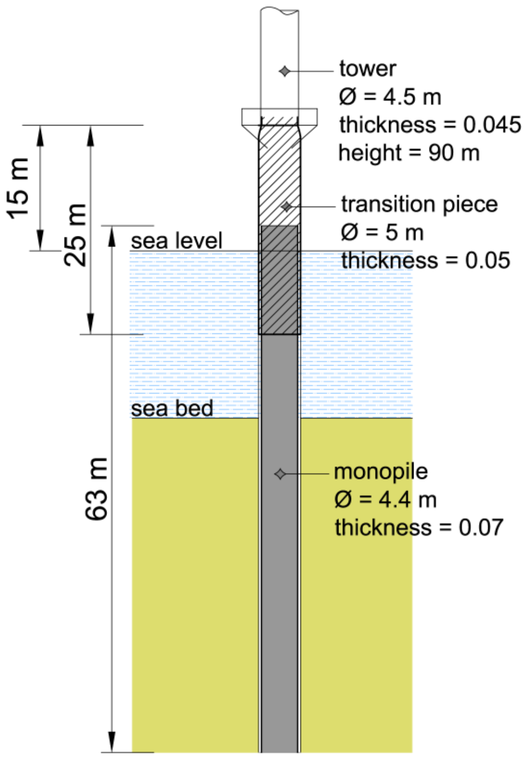


Fig. 12 Schematic drawing of the OWT's support structure

Table 6 Volume and mass of the site of the OWT's support structure

	transition piece	monopile
volume [m^3]	21.37	59.95
mass [ton]	166.709	467.682

The combined loading capacity analysis of the caisson foundation has been based on the novel approach proposed in [58], for the undrained condition case, and on the results from experimental and analytical works presented in [59] and [60] to analyze the combined loading capacity of the caisson foundation in terms of effective stresses. Safe dimensions have been shown to be: diameter (D) embedment depth (L) and thickness (t) equal to 16 m, 8 m and 0.03 m respectively, resulting in a skirt steel volume of only 20 m^3. It is worth noticing that the caisson foundation, whose installation is particularly suitable in a uniform soil bed of soft clay as in the study area up to the skirt depth, requires far less steel than the monopile solution. A single caisson (monopod) foundation would also provide further important advantages, such as a relatively simple and economical installation, resulting in an overall reduction of the entire foundation cost of about 20% [61]. However, the use of caisson foundations for offshore wind application is still in the early stages of development and, therefore, the study has considered only the monopile foundation solution in the following evaluation of the investment costs, due to uncertainties for the estimate of current costs for such new promising technology.

3. REVENUES AND INVESTMENT COSTS

The estimation of revenues and investment costs implies a large number of uncertainties, as there are no preceding experiences of OWFs in Italy and in the Mediterranean Sea; the analysis thus refers to technologies and costs documented in similar studies carried out in the northern European countries according to [51] and [62], where information are given within a specific range. A worst case scenario and a best case scenario have been introduced and applied to layout A (15 wind turbines) and layout B (60 wind turbines). The best case scenario can be considered optimistic and the parameters are set as the most favorable; on the contrary, for the worst case scenario, all parameters have been adjusted to the most unfavorable documented values.

3.1 Energy yield and revenues

The energy yield by a wind farm is a function of the gross energy of the single wind turbine and depends upon the number and configuration of the installed elements. As observed in Section 2.2, the internal loss can be estimated between 9.75% and 11%. For the best case scenario the reduction in the gross energy has been set to its minimum, while for the worst case scenario, to its maximum. According to [10] a wind farm can typically work only a fraction of a year, which may range between 0.94 and 0.97. The availability of the wind farm to evaluate the annual gross energy has been then set to 97% of a year in the best case scenario and to 90% in the worst case scenario.

As for the estimation of the revenues, different hypotheses on fixed feed-in tariffs have been made. For the best case scenario, the current Italian fixed feed-in tariffs [63] have been employed, with an energy price of 0.205 €/kWh. The worst case scenario makes use of the fixed feed-in tariffs for OWFs in the North Sea, as suggested in [51], equal to 0.160 €/kWh. The results for the different scenarios are illustrated in Table 7.

Table 7 Gross energy and total revenues

Layout, scenario	WT number	Farm size [MW]	Capacity factor [%]	OWT availability [%]	Internal losses [%]	Gross energy [GWh/y]	Revenues [M€/y]
A, best A, worst	15	54	25	97 90	9.75 11	103.527 94.726	21.223 15.156

B, best B, worst	60	216	25	97 90	9.75 11	414.108 378.904	84.893 60.625

3.2 Investment and Operation and maintenance costs

In this Section the estimation of investment costs and Operation and Maintenance (O&M) costs for layout A and layout B in the best and worst case scenarios are presented and discussed. As anticipated, as no OWFs are found, at present, on the Italian territory, the study does also refer to technologies and costs from northern Europe [20, 62]. Noting that the costs for the onshore yard have been predicted following the actual costs of these activities at the close port of Ravenna, the investment costs are detailed in Table 8 along with the O&M costs.

3.2.1 Cost of the wind turbine and support structure

The cost of a single wind turbine includes the nacelle, the tower and the electricity generator. The cost of support structure includes the transition piece and the foundation. The wind turbine price, typically sold as a single item, ranges between 4,320 – 5,040 k€. The cost of the transition piece and foundation is site specific and depends on the steel volumes which arise from the structural design as described in Section 2.2. The support structure is made of steel NV-32, whose price ranges between 1,400 and 2,000 €/ton; extreme values of the range have been again used to describe the worst and best case scenario. Results, based on the data of Table 6, are inserted in Table 8. As anticipated in Section 2.2, only the monopile has been considered as possible foundation technology for the OWT. The uppermost and lowermost parameters have been applied to estimate the costs respectively in the best and worst case scenario.

3.2.2 Cost of grid connection

The costs of the grid connection include the cost for submarine electric cables (transmission cables to shore and within the wind farm) and the cost of the transformer station. The lying of high power submarine cables can be particularly expensive and has been computed according to the distance between the OWF and the coast; it does slightly scale with the produced electric power. Assuming that the offshore transformer can be installed on the platform “Azalea B”, as illustrated in Fig. 9, the length of the electric cable to the nearest onshore national grid connection is approximately 15 km. In this study, a cost of 1,300 €/m for the submarine cable has been assumed, independently of the explored scenario, totaling 19,500 k€. The costs for the transformer, including electric cables within the OWF, has been taken equal to 239,46 €/kW.

3.2.3 Installation and decommissioning cost

This item of expenditure is relevant to the installation and removal of the OWT and support structure and depends upon the time necessary to complete the operations. The daily costs, which are typical for offshore operations in the North Sea are 65,000 €/day for the installation and removal of the OWTs and 80,000 €/day for the installation and removal of the support structures. In the best case scenario, 6 days have been assumed a reasonable time for the installation of a single OWT as well as for its foundation. This results in 3 months for the layout A and 12 months for layout B. In the worst case scenario, it has been assumed that the installation can take 3 months longer with respect to the best case. This results in 6 months for the layout A and 15 months for layout B. Time for decommissioning has been estimated equal to 1.5 months for the OWTs and the foundations, independently of the layout and scenario. Cost for mobilisation and demobilisation have been also taken into account and estimated as a function of the rated energy, equal to 11.69 €/kW for the installation and removal of the OWTs and to 20.46 €/kW for the installation and removal of the support structures.

3.2.4 Evaluation of the total investment cost

In Table 8 the cost estimates for the layouts A and B and the respective best case and worst case scenario are presented. The cost of contingency is technically a fund set aside to face extraordinary interventions. For the worst case scenario, it has been taken equal to that used in a similar project planned at the North Sea [62], 489 €/kW. As for the best case, it has been assumed that potential damages to the farm could reach only half of those encountered at the North Sea (244.5 €/kW). The costs for project authorization have been assumed to vary between 317 €/kW and 377 €/kW for layout A and between 158 k€/GW and 377 k€/GW for layout B, with the highest values estimated according to [62] and the lowest values following the recent studies for the development of OWFs in southern Italy [64].

3.2. Operation and maintenance costs

The costs for operation, maintenance and repairs include the staff costs, onshore rental of facilities within the port of Rimini, ships to access the plant, spare parts and other materials necessary to keep the OWT in operation. The operating and maintenance costs have been estimated, based on specific maintenance cost estimates from OWFs in the North Sea, to range between 144.34 €/kW and 224 €/kW. Upper and lower bounds are used to predict the worst case and best case scenario, respectively.

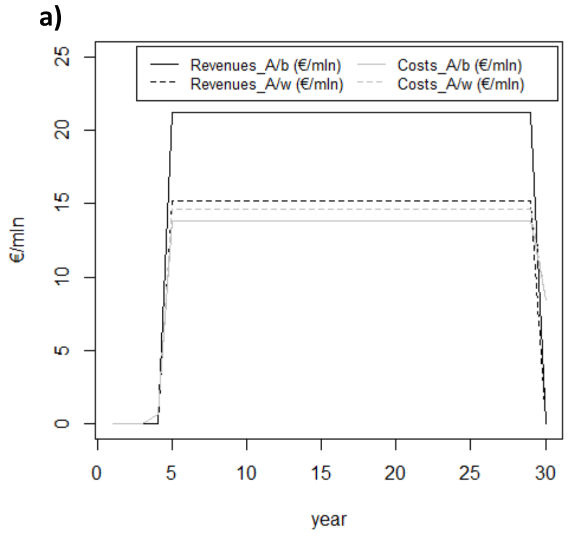
Table 8 Investment costs and O&M costs

cost [k€]	A, best case	A, worst case	B, best case	B, worst case
onshore yard				
	4,592	4,592	4,592	4,592
WTs				

structure	64,800	75,600	259,200	302,400
installation	6,481	12,331	25,926	31,776
removal	3,556	3,556	14,226	14,226
transition piece and monopile foundation				
steel	13,321	19,031	53,289	76,127
installation	8,305	15,505	33,221	40,421
removal	4,705	4,705	18,821	18,821
electrical components				
cable to shore	19,500	19,500	19,500	19,500
transformer/cables	12,931	12,931	51,724	51,724
total				
	138,191	167,751	480,499	559,587
Contingency				
	13,203	26,406	52,812	105,624
planning, project authorization and certification				
	17,117	20,358	17,117	81,432
total investment				
	168,511	214,515	550,428	746,643
O&M				
	3,897	6,048	15,588	24,192

4 ECONOMIC FEASIBILITY

This section provides a preliminary analysis of the economic feasibility of the investment project according to the two layouts and two scenarios considered in the study. The investment is intended to last 30 years. Within the first 3 years, the authorization and the achievement of technical and economic feasibility studies can be obtained and the successive year is taken for the realisation of the farm and its commissioning. Finally, 25 years is the period in which the wind farm will be operating, while the last year is devoted to its disposal and restoration of the status quo. In the analyses it has been assumed that the wind farm will be functioning from the fifth to the twenty-ninth year, during which the Italian State is obliged to pay for the energy produced. Figure 13 shows the revenues and the costs for layout A and layout B in the best and worst case scenario, following the analyses carried out in Section 3. Specifically, Fig. 13a shows revenues and costs for the layout A, in black lines the revenues and in grey ones the costs, while Fig. 13b shows the same financial values for the layout B. Values referring to the best scenario are illustrated by a continuous line and those related to the worst are represented with a dashed line in Fig. 13. In all cases positive net incomes from the fifth to the twenty-ninth period are shown. The layout A in the worst case scenario is characterised by the lowest net income while the layout B in the best case scenario provides the most satisfactory result from a financial perspective. In Table 9 the net incomes for the periods from the fifth to the twenty-ninth year are compared.



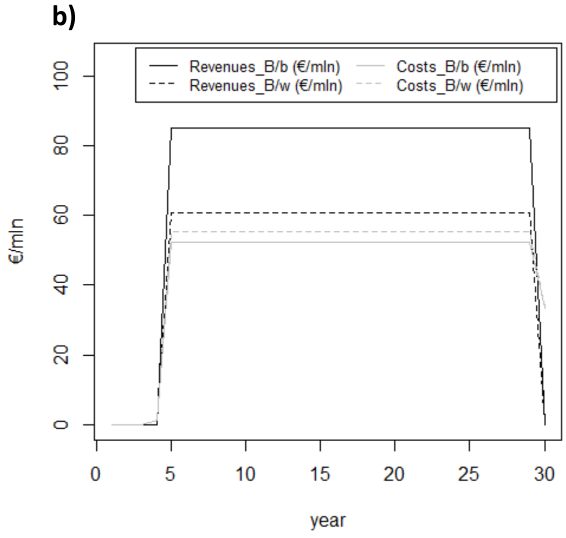


Fig. 13 Revenues and costs for: a) layout A, best and worst case scenarios and b) layout B, best and worst case scenarios

Table 9. Net incomes between year 5 to year 29

Year 5 to 29, net income [€]	
A, worst case	542,683
A, best case	7,382,165
B, worst case	5,283,167
B, best case	32,507,427

In addition, Table 10, highlights the impact of disposal costs that will be incurred during the thirtieth year without any revenues. It has been estimated that disposal costs do not vary for the best and worst case scenarios and they depend only on the number of turbines. Table 11 shows the cost structure for the considered scenarios from the fifth to the twenty-ninth year.

Table 10 Impact of disposal costs for layout A and layout B

Year 30	
A, disposal costs [€]	8,436,502
B, disposal cost [€]	33,047,368

Table 11. Cost structure from the fifth to the twenty-ninth year.

[€]	A, worst	A, best	B, worst	B, best

Costs	14,613,519	13,841,026	55,341,639	52,385,336
Amortisation	8,250,138	6,410,065	28,543,443	21,379,724
Maintenance costs	5,796,840	3,645 840	23,767,940	15,163,940
Consultancy costs	60,000	60,000	120,000	120,000
Personnel costs	251,160	251,160	424,060	424,060
Taxes	255,380	3,473,960	2,486,196	15,297,613

Four financial leverage ratios, as many as the considered scenarios, have been proposed. More specifically, in order to convince banks - given the nature and the riskiness of this investment project – a proposal is formulated that equity is equal to the sum of the minimum required by law for an Italian limited company and the capital covering the fixed investments in the first three years. This would allow all sunk costs generated by the investment project to be covered if it were decided not to realize the OWF. The financial leverage ratio, which is calculated dividing the total asset by the equity, ranges from 9.04 for layout B, worst case to 15.85 layout B, best case.

In order to analyse the economic feasibility for this investment project, two selection criteria have been used: i) Net Present Value (NPV), ii) Internal Rate of Return (IRR).

Both these indicators require the computation of Unlevered Free Cash Flows (UFCF) over the life of the project and the cost of the capital used to finance [65]. UFCFs have been determined using the following formula

$$UFCF = EBITDA - CAPEX - WorkingCapital - Taxes \quad \text{(Eq. 2)}$$

Where EBITDA are the Earnings Before Interest, Taxes, Depreciation and Amortization, CAPEX is the capital expenditures and the WorkingCapital is calculated as the difference between current assets and current liabilities.

Figure 14 deploys the unlevered free cash flows produced by this investment project for the layout A and B in the best and worst case scenarios.

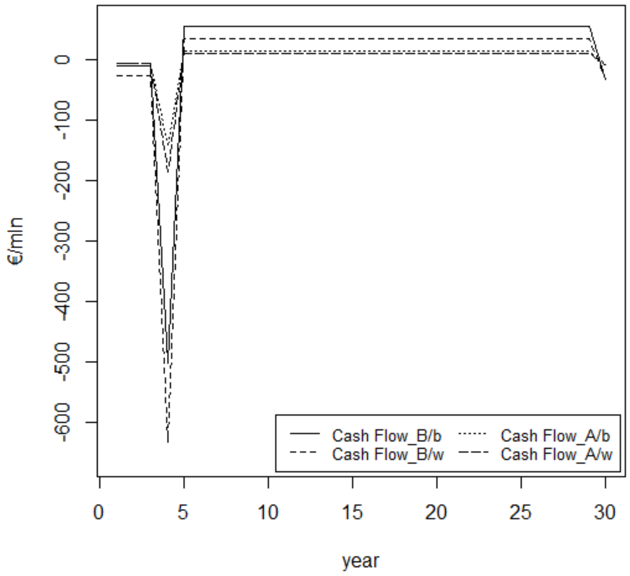


Fig. 14 Unlevered free cash flows produced by this investment

The Weighted Average Cost of Capital (WACC) is the weighted average of debt (D) and equity (E) expected rates of return (r_d and r_e) and it is calculated by the following equation

$$WACC = r_D \frac{D}{D+E}(1-\tau) + r_E \frac{E}{D+E} \qquad \text{(Eq. 3)}$$

where τ is the corporate tax rate in Italy. The Italian legislation does not envisage complete deduction of the passive interests, so the reductive effect on the discount rate has been appropriately neglected. The equity rate of return has been determined by applying the capital asset pricing model (CAPM) [66], which is the most common method applied to similar profitability assessment, [67]. In order to calculate the raw beta of the firm, the daily adjusted returns of five years for five firms operating in the renewable energy industry and listed on the Italian stock exchange have been considered. In applying CAPM, the last average annual rate of return for risk free, thirty-year maturity bonds and the estimate of risk premium provided by Aswath Damodaran [68] have been considered. The debt rate of return has been estimated equal 5% according to the required rate of return for similar investments in the market. The resulting WACC, for the four scenarios proposed, ranges from 8% to 8.15%. The net present value has been calculated using the equation:

$$NPV = \sum_{i=0}^{30} FC_i (1+WACC)^{-i} \qquad \text{(Eq. 4)}$$

while the internal rate of return has been btained solving the equation:

$$0 = \sum_{i=0}^{30} FC_i \left(1 + IRR\right)^{-i} \qquad \text{(Eq. 5)}$$

In Table 12 the NPVs and IRRs, in the four scenarios proposed, are reported.

Table 12. NPVs and IRRs

	NPV (€/mln)	IRR
A, worst	-86.69	< WACC
A, best	-13.67	< WACC
B, worst	-274.42	< WACC
B, best	17.11	8.62% > WACC = 8.12%

Because of the typical timing of cash flows, NPV and IRR give the same answers in order to evaluate the economic feasibility of this investment project. The only scenario presenting a positive NPV, which means IRR is higher than WACC, is that of layout B, best case, with an NPV higher than the value of the investment project and a positive difference between the cost of the capital and the rate of return, as illustrated in Fig. 15.

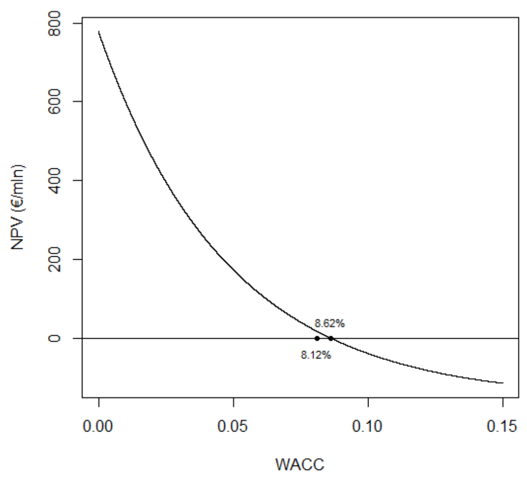


Fig. 15. NPV as a function of WACC

CONCLUDING REMARKS

The paper has presented the first, field data based, feasibility study for the development of an offshore wind farm in the Northern Adriatic Sea, approximately 10 km off the coast of Rimini, Italy. The study responds to the growing need of applied and consistent evidence of the actual feasibility of wind farms in in Italy and, in general, in countries where the exploitation of offshore wind is still being considered only as a possible but not profitable option.

The key aspects of the research work have been:

- a multidisciplinary approach which enables to cover all the essential aspects of the development of wind farms, technical and economic, although at a preliminary stage;
- the availability of the relevant, though essential, environmental data at the site, which provides the necessary reliability to the study;
- the essential interest and collaboration of local authorities, aware of the long-term need of exploiting renewable energies and providing a valuable bridge between research, development and implementation.

The procedure adopted for a preliminary feasibility study has been described in full detail, so that it could be easily repeated and applied on essential data in areas with similar features.

The approach has also provided a new perspective over a suitable choice of the potential location. Among other possible test sites, the area has been selected on the basis of the following promising key features:

- shallow water and flat sea bottom, up to 20 km to shore;
- no significant space restrictions;
- presence of oil and gas platforms (some of which in disuse, which can host the main electrical connection hub);
- availability of favourable environmental impact assessment for offshore productive platforms within the area.

These conditions have provided the base to the investigation of the environmental conditions, while a few technical (e.g. special or advanced support structures) and non - technical (permission process) issues have been kept to a minimum. Data collected at site were:

- wind profiles, measured during the years 2008- 2013 by anemometers mounted on a gas platform within the study area;
- wave conditions, measured by a wave buoy installed in 2007, few kilometers north of the study area.

The environmental data have been thoroughly interpreted to:

- describe the environmental conditions;
- select the most adequate wind turbine, a commercial 3.6 MW turbine with a large, 120 m rotor diameter, able to yield a gross energy equal to 7.88 GWh/y, at a 25% capacity factor;
- provide a site-specific design of the support structure.

As for the economic feasibility, four cost scenarios have been considered:

- a worst case and a best case for a layout with only 15 turbines (with 54 MW rated power);
- a worst case and a best case for a layout with 60 turbines (with 216 MW rated power).

For the best case scenario, realistic, currently valid revenues and costs have been used. For the worst case, a lower wind energy harvest, lower feed-in tariffs, higher internal energy losses, higher insurance and material costs as well as longer construction times, with respect to the best case scenario, have been assumed. Analyzing the net present value (NPV) and internal rate of return (IRR) for the four scenarios, the best case of layout B has finally delivered a positive NPV (17.11 M€) with an IRR of 8.62%, slightly above the average rate of 8.12% expected for this type of investment.

From such detailed and consistent investigation, it can be concluded that the relevant outcome is encouraging and should provide convincing arguments to the decision makers for the development of an advanced and more specific experimental campaign, which would enable a complete and accurate feasibility study to be completed, especially focusing on now possible innovative solutions (different foundation technologies or different assembly methods) that would substantially increase the profitability of such installation.

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