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SCIENCE DIRECT®
Solar Energy 79 (2005) 321–331
SOLAR ENERGY
www.elsevier.com/locate/solener

Feasibility study of off-shore wind farms: an application to Puglia region

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Received 27 August 2002; received in revised form 15 July 2004; accepted 9 August 2004
Available online 30 December 2004

Communicated by: Associate Editor David Simms

Abstract

Recent environmental constraints and new secure technologies have enforced the development of comprehensive programmes for renewable energy. Wind energy is one of the most promising solutions, especially considering its technological advancements and its growth over the last years. In particular, off-shore wind energy is a key element in the EU White Paper target of 10% contribution of Renewable energy by 2010.

In this paper, the technical and economical feasibility of off-shore wind farms is reviewed, in order to evaluate profitability and investment opportunities. In particular, a pre-feasibility study of off-shore wind farms to some selected sites in Puglia Region is provided. The study indicates the best sites in Puglia Region for off-shore plants. For each site, the cost of energy and the profitability of the investment are calculated. Moreover, in the most promising site, different wind turbine generators (WTGs) models are compared in order to evaluate the best performances. In the best site, which presents an average wind speed at 35 m height of 7.66 m/s, the cost of energy ranges between 5.2 and 6.0 c€/kWh. Moreover, the analysis shows that the use of large size WTGs allows reducing the cost of energy and increasing the profitability of the wind farm.

Keywords: Off-shore wind energy; Wind turbines; Micrositing; Cost of electricity

1. Introduction

The application of wind energy throughout the world is growing fast. In particular, off-shore wind farms are different from on-shore installations for several reasons: (i) the wind turbine generators (WTGs) have, on average, larger diameters and rated power, (ii) the plant can be difficult to access in periods with high winds, (iii) the installation and the maintenance are more

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0038-092X/$ - see front matter
doi:10.1016/j.solener.2004.08.030

Nomenclature

A	wind farm area [m^2]	H	WTG hub height [m]
a	annuity factor [years^{-1}]	I	total investment cost [k€]
c	number of columns of the wind farm layout	IRR	internal rate of return (%)
$CF_{i\text{-dis}}$	discounted cash flow at ith year [k€]	L	economic lifetime [years]
C_T	WTG unitary cost [k€/MW]	LPC	levelled cost of energy [c€/kWh]
C_S	WTG support-installation cost [k€/WTG]	NPV	net present value [k€]
C_M	*O&M* facility cost [k€/MW]	η_A	wind farm availability coefficient
C_P	project and development cost [k€/MW]	η_E	electrical transmission losses coefficient
C_G	grid connection costs [k€/MW]	η_L	wind farm array efficiency factor
D	WTG rotor diameter [m]	N	number of WTG in the wind farm
d	average distance to shore of wind farm [km]	O	annual *O&M* cost [k€/year]
d_c	columns spacing of wind farm layout [m]	P_R	WTG rated power [MW]
d_r	rows spacing of wind farm layout [m]	r	number of rows of the wind farm layout
dr	discount rate [years^{-1}]	W	water depth at the wind farm [m]
E	annual wind farm gross energy [GWh/year]	WTG	wind turbine generator
E_G	annual gross energy of a WTG [GWh/year]		

expensive, (iv) the submarine electrical connection to shore increases the investment costs. Despite of the high costs compared with on-shore wind farms, off-shore applications allow an increased energy efficiency, due to the higher average wind speeds and the reduction of the siting and environmental issues, particularly with regards to noise, visual constraints and space limitations, since off-shore wind farm are commonly built some km away from the coast.

Several studies have been carried out on the off-shore wind energy resource for European Countries. By selecting areas which are deemed suitable for wind development, including predictions of public acceptability such as minimum allowed distance to shore, the results indicate a very large resource (Hassan and Lloyd, 1995). Ongoing R & D efforts in the off-shore wind sector are described in (Halliday, 2001). Most of them aim to improve the short term prediction of energy production, while other studies investigate possible cost reduction related to the redesign of off-shore wind turbines (Kuhn et al., 1998).

In Italy, ENEA (Ente Nazionale per l'Energia e l'Ambiente) carried out a preliminary investigation of the best sites on Italian coasts for off-shore applications (Pirazzi, 1998). The most suitable areas seem to be the coasts of Sicily, Lazio, Calabria (Ionian sea), Sardinia, Puglia, and Tuscany, where strong wind and shallow waters are suitable for off-shore wind farms.

In this paper, the technical and economical features of off-shore wind farms are described and a methodology is proposed for evaluating the expected annual energy yield, the cost of produced energy and the profitability of the investment, on the basis of wind farm design parameters and electricity selling price. This methodology is applied to four sites in the Region of Puglia, which offer promising potentials. The investigation is carried out considering different WTGs models suitable for off-shore applications.

The results confirm that: (i) the optimal size for off-shore WTGs is larger than in on-shore applications, mainly because of the larger annual energy production and the lower incidence of the foundation costs; (ii) the water depth and coast distance are the principal factors influencing the investment costs and, consequently, the cost of energy, for a given energy potential.

2. Issues in off-shore wind farm feasibility

A feasibility study for an off-shore wind farm requires an initial investigation of the site characteristics. In particular, the most important elements to consider are

- wind resource;
- natural constraints;
- siting issues.

The wind resource of the site is described by the annual mean wind speed, the Weibull parameters, the air temperature and density. These parameters strongly affect the annual energy yield production of the wind farm. The natural constraints mainly consist on water depth and seabed slope (which should not exceed 5% and 35 m respectively), and wind and wave pattern. These constraints affect the support structure design (including the above water tower and the submerged foundation) and the wind farm availability. Siting issues are given by the presence of shipping traffic zones, military and protected marine areas, visual impact constraints due to the intense coast antropization, and other regulations to obtain planning permissions. In some applications, the grid connection capacity and the network strength at the feeding point can influence the maximum wind farm size. On the basis of the natural constraints and siting issues, the distance to shore and the available area for the wind farm can be evaluated. The first parameter affects the costs of electrical infrastructures, the *O&M* costs and the wind farm availability, while the second one affects the number of WTGs that can be installed and it is also influenced by financing possibilities.

On the basis of these elements, the other technical parameters of the wind farm can be chosen, as the WTG model, the support structure design, the wind farm layout. The electrical system within the wind farm is designed on the basis of optimum level of redundancy vs. costs, while the characteristics of the transmission line to shore are selected on the basis of installed power and distance to coast. The *O&M* strategy, which affects the wind farm availability and the annual costs, is another important factor in off-shore applications.

3. Technical and economical aspects of off-shore wind farms

In the following, the main technical and economical aspects in off-shore wind farm development are reviewed, and the procedure used for the Puglia Region case study is described.

3.1. Annual energy yield assessment

The evaluation of the annual energy E (GWh/y) of an off-shore wind farm requires the steps described in the following.

3.1.1. Off-shore wind flow prediction

A reliable prediction of the wind flow is crucial for off-shore projects planning and siting, since the higher energy production can compensate the additional investment costs. The favourable off-shore wind resource is mainly due to the low surface roughness of water areas, even if this roughness is strongly related to the wave field present. This in turn is governed by the momentum exchange process between wind and waves which depends on wind speed, water depths, distance from shore, atmospheric stability, etc. The sea surface roughness can be described as a function of wind speed, independently from the fetch (Charnock, 1955), or as a function of the length of the upwind sea fetch (Lange and Hojstrup, 2001). A reliable off-shore wind flow prediction must consider that the transition zone between land and sea areas is commonly extended for about 10 km on both sides of the coastal discontinuity. In addition, the difference in atmosphere stability between land and water areas influences the vertical wind speed profile by varying the vertical transport momentum (Garrat, 1994). This variation can be taken into account considering a more uniform wind speed profile in the wind analysis. Moreover, the larger heat capacity of the sea dampens out the wind daily variations to low amplitudes, while marked wind yearly variations occur, because of the water temperature that lags behind the air temperature.

The most used programs for wind resource predictions on land seem to agree well in off-shore conditions, even if recent investigations show that they tend to over-predict the wind speed in case of short sea fetches and under-predict it for long fetches (Lange and Hojstrup, 2001).

3.1.2. Gross energy assessment

The gross energy E_G (GWh/y) produced by each wind turbine can be calculated by using software tools, on the basis of the wind flow and the WTGs power curve. The simplified procedure followed in this study considers the WTG power curve, referred to the meteorological conditions of the site, the prevailing wind direction from north-west and the Weibull distribution with shape and amplitude on the basis of the values of Table 1.

3.1.3. Wind farm design

Since there are no appreciable wind speed variations across an off-shore site, the WTGs layout can have a regular array optimised only for energy capture, as for on-shore wind farms on flat topography, minimizing sheltering effects. However, the water depth and the sea-bed conditions can make preferable not perfectly regular arrays.

Considering a rectangular layout composed by r rows and c columns, the number N of WTGs installed in the wind farm is given by the equation:

$$N = r \cdot c \tag{1}$$

Moreover, the available area for the wind farm A (m^2) can be appreciatively expressed by the equation:

$$A = (r \cdot d_r) \cdot (c \cdot d_c) \tag{2}$$

d_r and d_c being respectively the spacing between rows and columns.

Using the Eqs. (1) and (2), the number of WTGs in the wind farm can be expressed as a function of the available area A by the equation:

$$N = \frac{A}{d_r \cdot d_c} \tag{3}$$

The spacing between WTGs commonly varies from about 10 D (being D the WTG rotor diameter), for a wind farm optimised only for the energy capture and with a relatively uniform wind direction distribution,

Table 1
Main parameters of the selected sites

Site	Air density (kg/m^3)	Weibull k parameter	Average wind speed at 35 m height (m/s)	Exponential coeff. (power law) for wind shear	Available area (km^2)	Mean water dept [m]	Coast distance (Km)
Vieste	1.080	1.5	6.18	0.14	2	20	1.5
Bari	1.080	1.5	6.04	0.14	2.5	20	0.6
Brindisi	1.080	1.5	6.98	0.14	2.5	20	1.5
Otranto	1.080	1.5	7.66	0.14	2	20	1.5

to very small spacing (less than 3 D) in case of restricted available areas (Santjer and Sobek, 2001; Gardner, 2001).

In the proposed feasibility study, the layout is constituted by arrays with distance between columns (d_c) and rows (d_r) respectively of 8 D and 6 D. The utilization of such a tight array is due to the restricted available area for wind farm installations (in a range of 2–2.5 km^2) for the proposed sites. With the previous assumptions, the number N of WTGs that can be installed in the wind farm is given by the expression:

$$N = \frac{A}{48 \cdot D^2} \tag{4}$$

The array efficiency of the wind farm is commonly evaluated with software tools, and takes into account the sheltering effects of the turbines, on the basis of the WTGs layout, the prevailing wind direction, and the wind flow characteristics (Neff and Meroney, 1997; Lubov et al., 1998). In this case, the array efficiency of the wind farm is evaluated considering a rectangular layout with the main side orthogonal to the prevailing wind direction (which is appreciatively double of the small side). The array efficiency factor η_L, which takes in account the energy losses for wake effects among turbines, is evaluated using a commercial software tool. The input parameters for the calculation of the wake effects are both the WTG geometry and power curve and the wind rose in the selected site. The resulting values of η_L, as described in Section 4, range between 0.93 and 0.95.

3.1.4. Wind farm electrical system

The electrical connection within the wind farm can be arranged as a radial system or can result in an open-ring configuration. In the second case, the additional electrical system costs must be balanced by the increase of energy production due to the expected cable failure rate reduction. The cost of the turbine interconnection is also influenced by the spacing of the turbines, which affects the array efficiency η_L. Innovative concepts include clusters of variable-frequency turbines connected to a common AC-bus (Meyl, 1999).

The optimal voltage level within off-shore wind farms is commonly up to 30 kV, due to the costs of cables, switchgear and electrical losses, while, above this level, the costs of switchgear rise steeply. In this study, a 20 kV open-ring configuration is considered.

The electrical transmission system to the shore must be reliable and efficient. In particular, submarine cables should have long continuous non-jointed lengths, high level of reliability, good abrasion and corrosion resistance, and should withstand the mechanical forces of laying and embedment, minimizing water penetration, if punctured (Siepman, 2001). As regards AC/DC transmission strategies, the use of AC cables gives the benefits of low initial cost, but the problem of quickly increasing of the losses when the transmission distance increases. DC technologies present higher initial cost, but the losses are less dependent on distance. The DC interconnection within the wind farm offers the advantages of control and improved power quality (Burges et al., 2001). Available cost and efficiency data show that medium voltage AC systems are preferable for power levels up to 200 MW and distances to shore up to 20 km. For the same maximum power levels and distances to shore up to 30 km and 50 km respectively, high voltage AC and medium voltage DC systems are preferable. In case of power level higher than 200 MW with a cable length higher than 30 km, high voltage DC connections result convenient (Gardner, 2001).

In the proposed case, the expected wind farm size and distance to the coast are 10–20 MW and 0.5–2 km respectively, so that an AC 20 kV transmission line to shore is the best solution. The electrical transmission losses coefficient η_E, considering a feeding point close to the coast, is calculated as a function of the distance to shore d (km) by the following expression (Bauer and De Haan, 2001):

$$\eta_E = 0.98 - \frac{d}{600} \tag{5}$$

3.1.5. Wind farm availability

The wind farm availability η_A is the percentage of time that the plant is available to produce electricity, not including any downtime caused by factors outside the control of the plant operator (e.g. low or high wind speed, requested stops, scheduled maintenance). It is a critical parameter for off-shore applications. In fact, recent studies (Bauer and De Haan, 2001) have proved that wind farm electrical system costs, although a significant part of the total costs, have less effect on the cost of produced energy than the availability of the plant. Therefore, the system should be over designed, by using high quality components and protections against environmental influences. The overall wind farm availability takes into account both the WTG availability and the electrical system availability. The turbine availability is dependent on the typology of aerogenerator, the *O&M* strategy adopted, the site climate and accessibility. In particular, an efficient maintenance strategy allows minimizing the WTGs failure and the time required for machine restoration, while bed site climate can increase the occurrence of failure. For example, in several cases helicopter access might be the most practical solution for wind farm maintenance, providing quick access to the site and increasing the availability of the plant.

On the other hand, the electrical system availability is a function of the complexity and redundancy of the electrical devices, and it is expected to increase with the distance of the plant to the coast, being the restoration of undersea cables more complex and time-consuming than in land applications. A model has been developed by the Institute for Wind Energy (van Bussel and Schontag, 1997), which stochastically simulates the site accessibility and the WTGs failures, in order to determinate the instantaneous and the overall availability and maintenance costs of the wind farm.

Commonly, the wind farm availability is in the range of 94–97% of the total time. Nevertheless, the definition of availability should be based on energy produced instead of time. In this study, considering a range of 0.5–5 km distance to the coast, the availability η_A, has been assumed equal to 95% of the annual energy yield, according to the literature data.

3.1.6. Annual energy yield

On the basis of the previous assumptions, the annual gross energy yield E (GWh/y) is obtained by the following expression:

$$E = E_G \cdot N \cdot \eta_L \cdot \eta_E \cdot \eta_A \tag{6}$$

3.2. Investment and O&M costs

In the following, the general economical aspects in off-shore applications are described and an estimation of investment and *O&M* costs is provided.

3.2.1. Investment cost I

For a conventional on-shore wind farm, the greatest part of the total investment cost is due to the WTGs, which in big farms may account for the 60% of the total investment cost (Hau, 1991). Otherwise, in off-shore applications, the turbine takes a lower part of the total cost, while the support structure and the grid connection assume greater importance. The total investment cost I is composed by the elements described in the following.

(A) *Wind turbine cost* C_T

The WTG cost C_T includes tower, nacelle and WTG electrical devices. It is mainly dependent on the size, typology, rotor diameter and hub height of the aerogenerator. In off-shore applications, the cost increases for the necessity to adapt the WT to the sea conditions.

Many studies show that large turbines are more suitable for off-shore applications, since they allow reducing the cost of produced energy. This is due to the higher energy yield in respect to smaller turbines, and the lower specific investment cost. Despite this, the Opti-OWEC study (Kuhn et al., 1998; Cockerill et al., 2001) which investigates the relationships between the farm design parameters and the related cost of energy, concludes that the use of larger capacity WTGs (4 MW) determinates a significant reduction in energy costs only at sites with low wind, while there is nothing to be gained by using very large turbines at good off-shore sites.

In the present study, a value of C_T in the range of 750–890 k€/MW, respectively for small and large WTG models, is assumed.

(B) *Support and installation costs* C_S

The cost of the support structure is composed by the material cost and the construction and installation cost. The foundation material costs are dependent on the hub height, the water depth and the site climate, while the installation costs are largely dependent on the number of WTGs installed, rather than their size or distance to shore (Gardner, 2001). In the present study, the C_S costs (k€/WTG) are estimated considering the cost trend data of the DWTM Association for monopile foundations in the North sea (Ferguson, 1997) according to the following equation:

$$C_S = \left(\frac{H}{50}\right)^{0.3} \frac{(1700 \cdot W^2 - 9455 \cdot W + 21836)}{1000} \tag{7}$$

W (m) and H (m) being respectively the water depth the WTG hub height.

(C) *Grid connection cost* C_G

The grid connection costs are dependent on the distance to the feeding point on shore, the typology of the transmission system and the electrical system within the wind farm. In this study, a cost of 120 €/m for both the transmission cable to shore and the transmission system within the wind farm, is assumed, including cable laying costs (Burges et al., 2001). The cost of the 20 kV/150 kV transformer is assumed of 8,500 €/MW. The additional cost for the other electrical devices is assumed equal to 100,000 €/MW.

(D) *O&M facility cost* C_M

This cost is highly dependent on the *O&M* strategy adopted which affects the overall wind farm availability. Moreover, the distance from shore, the site climate (in particular annual mean wind speed) and the WTGs reliability are other major features affecting the cost C_M. In this study, a value of 50 k€/MW is considered, on the basis of the data from off-shore plant in operation and the projections for the next years (Junginger and Faaij, 2003; Randemakers, 2003).

(E) *Project and development cost* C_P

The costs of project and development are assumed to be the 4% of the investment cost.

On the basis of the previous assumptions, the total investment cost I (k€) is evaluated with the following expression:

$$I = N \cdot [P_R \cdot (C_T + C_G + C_M + C_P) + C_S] \quad (8)$$

P_R (MW) being the WTG rated power.

3.2.2. O&M annual cost O

The annual maintenance cost in off-shore wind farms is higher than in on-shore applications, since it can represent as much as 30% of the overall energy cost (Cockerill et al., 2001; Milborrow, 2003).

The most important parameters affecting this cost are: (i) distance from shore, (ii) site climate, (iii) size and reliability of the WTG used, (iv) maintenance strategy adopted. In this study, the annual *O&M* cost O is assumed as the 2% of the total investment I.

4. Economical feasibility

This section describes the methodology adopted to calculate the levelized cost of energy and the profitability of off-shore wind farms.

4.1. Cost of energy

On the basis of the assumptions of Section 3, the levelled cost of energy produced by the off-shore wind farm (LPC) (c€kWh) is calculated through a standard discounting calculation as follows:

$$\mathrm{LPC} = \frac{I}{10 \cdot a \cdot E} + \frac{O}{10 \cdot E} \quad (9)$$

a being the annuity factor given by the expression:

$$a = \frac{1 - (1/(1 + \mathrm{dr}))^l}{\mathrm{dr}} \quad (10)$$

where dr is the discount rate and l the economic lifetime (years).

4.2. Profitability analysis

The profitability of the investment is calculated by the net present value (NPV) (k€) and the Internal Rate of Return (IRR), according to the following expressions:

$$\mathrm{NPV} = \sum_{i=1}^{l} (CF_i)_{\mathrm{dis}} - I \quad (11)$$

$$\mathrm{IRR} = 1 + \frac{\mathrm{NPV}}{I} \quad (12)$$

$(CF_i)_{\mathrm{dis}}$ being the discounted cash flow in the ith year. The annual revenues are calculated on the basis of the value of green energy in the Italian electricity market. It is given by the sum of the electricity price in the wholesale electricity market and the value of green certificates. The second ones are available for the first 8 years of wind farm operation, as regulated by the national laws (Legislative Decree no. 79, 1999, Italian Official Journal no. 75, March 31st, 1999).

The depreciation allowance of the investment cost, used for the evaluation of the NPV and the IRR, is considered for the first 8 years of plant operation. The assumed values of green energy and the investment cost I for the selected sites are shown in Tables 2 and 3 of Section 5.

Table 2
Economic parameters

Parameter	Value (unit)
Economic lifetime	20 years
Discount rate	5%
Electricity price	4.40 c€/kWh
Green certificates price	8.50 c€/kWh

5. Selected sites in Puglia region

The selected sites for the feasibility study are described in Table 1. They are close to the Adriatic coast and present a good wind resource. The main obstacle is given by the sea depth, which is, in the South Adriatic

Table 3
Results of the analysis for the examined sites

Site	Power (MW)	*E* (GWh/y)	Total invest *I* (k€)	*O&M* cost *O* (k€/y)	LPC (c€/kWh)	NPV (k€)	IRR (%)
Vieste	14	32.02	22,125	443	6.93	137	0.62
Bari	18	39.78	28,281	566	7.13	−527	−1.86
Brindisi	18	49.09	28,281	566	5.78	5,168	18.27
Otranto	14	42.54	22,125	443	5.21	6,016	27.19

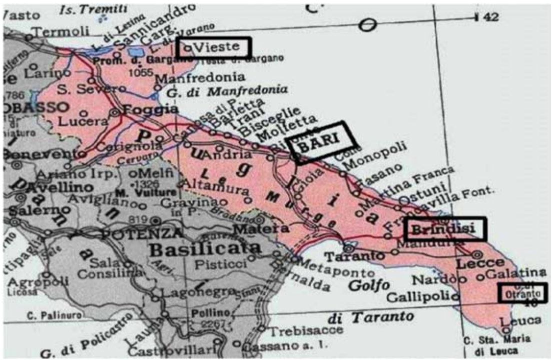

Fig. 1. Selected sites localization.

sea, higher than 35 m for distance to coast greater than 2–3 km.

Fig. 1 shows the localization of the selected sites. The wind flow is estimated using wind data from anemological measure stations located along the Puglia coasts. The data have been compared to the results from the Study of Off-shore wind energy in EC (Hassan and Lloyd, 1995) and from the Italian Hydrographical Institute of the Navy to have a reliable evaluation of the wind resource. The sea depth has been estimated on the basis of Puglia region nautical charts. For these sites, the maximum sea depth is 20–25 m within a distance of 2–3 km from the coast. The seabed is mostly sandy, with some rocky areas. The wind shear, for the 35 m wind speed calculation, has been estimated according to a power law with exponential coefficient 0.14. The prevailing wind direction is North–North/west, and it is used to evaluate the optimal layout and the array efficiency losses. In the following, the main features and constrains of each site are focused.

(A) *Vieste*. The main environmental constraints are the intensive tourist activity in this area and the presence of the Marine Natural Park of Gargano, where off-shore installations are not allowed. The water depth is in the range of 15–20 m if the distance to the coast is below 2 km.

(B) *Bari*. In the North of the port there is a large area where any activity is forbidden for the presence of unexploded war bombs and an area reserved as a shooting polygon. The consistent naval traffic is another obstacle for off-shore installations. The wind resource is quite low and the water depth is in the range of 40–60 m for distance to shore higher than 1.5–2 km, so that an average distance to the coast of 0.6 km is proposed, and an average water depth of 20 m is assumed.

(C) *Brindisi*. In the southern area of the coast there is a large zone forbidden to any activity for unexploded war bomb presence and an area reserved to naval practices. In the north coast, near to Cape Riso, there is a cable of telecommunication and several sand banks. Any activity and installation requires the permission of the Defence Ministry due to the presence of a military harbour. The wind resource is high and the water depth, as in the case of Bari, is in the range of 20 m, for a distance of 0.6 km from the coast.

(D) *Otranto*. This area does not present particular environmental constraints, excepted for an area forbidden for anchoring and fishing due to the presence of submarine cables near Cape Craul (NE coast) and a large sand bank. It presents the highest wind resource and the most favourable seabed conditions, since the water depth is of 15–20 m, for a coast distance of 1.5–2 km.

Other than the environmental constraints, the construction and planning permission requirements are a consistent obstacle in off-shore wind farm development. For example, the off-shore authoritative procedure involves four Ministry (Industry, Environment, Transport, and Defence), Local Authorities and the Independent System Operator (GRTN) for the connection to the national grid. Other obstacles are given by the social acceptance, and in particular visual impact.

6. Case study

6.1. Comparison of selected sites

The economical feasibility analysis described in Sections 3 and 4 is applied to the case studies of Section 5, considering the Vestas V-80 wind turbine model and the economical parameters of Table 2.

The results are shown in Table 3. The lower cost of energy is obtained for the Otranto site, while the low wind resource and the natural constraints of the Bari and Vieste sites determinate the high cost of energy produced and the low values of NPV and IRR.

6.2. Comparison of WT models

For the Otranto site case study, different WTG models have been compared. The results of the energy yield assessment are described in Table 4. It results that large size WTGs allow higher energy output than small sizes. For the same case study, Table 5 shows the investment and *O&M* costs. It results that the unitary investment cost for larger WTGs is lower than in the case of small models, because of the high relevance of C_S cost. Table 6 shows the COE, for the examined WT models, in the high and low scenario respectively. The low scenario considers the value of produced energy and costs of Tables 4 and 5, while the high scenario is obtained considering a decrease in energy yield of 10% and an increase of investment cost of 5%. Fig. 2 shows the NPV and the IRR for Otranto case study, considering the low COE scenario. The results confirm that large size WTs

Table 4
Main wind farm parameters and energy production for the Otranto site

	Enercon E-40	Enercon E-66	NegMicon NM-48	NegMicon NM-64	Vestas V-47	Vestas V-80	Lagerway LW-58	Lagerway LW-72	DeWind D6	DeWind D8
Rated power (kW)	600	1800	750	1500	660	2000	750	2000	1250	2000
Rotor diameter (m)	44	70	48	64	47	80	58	71.2	62	80
Hub height (m)	46	65	60	70	50	78	65	80	65	80
Mean wind speed at hub height (m)	7.96	8.35	8.26	8.44	8.05	8.57	8.35	8.60	8.35	8.60
Number of WTGs	22	9	19	11	19	7	13	9	11	7
Availability	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Array efficiency	0.93	0.95	0.93	0.945	0.93	0.95	0.93	0.95	0.93	0.95
Transmission efficiency	0.978	0.978	0.978	0.978	0.978	0.978	0.978	0.978	v	0.978
Net spec. production (MWh/MW)	2738	2725	2704	2686	2732	3039	3.018	2753	2750	3025
Capacity factor	0.31	0.31	0.31	0.31	0.31	0.35	0.34	0.31	0.31	0.35
Energy (GWh/y)	36.15	44.14	38.54	44.31	34.26	42.54	29.43	49.56	37.81	42.35
Plant size (MW)	13.2	16.2	14.25	16.5	12.54	14	9.75	18	13.75	14

Table 5
Investment and *O&M* costs. Otranto site

	Enercon E-40	Enercon E-66	NegMicon NM-48	NegMicon NM-64	Vestas V-47	Vestas V-80	Lagerway LW-58	Lagerway LW-72	DeWind D6	DeWind D8
Investment cost I (k€)	29,541	25,591	29,763	27,310	27,138	22,125	20,797	28,374	23,831	22,172
C_T (%)	35	55	38	51	36	56	37	56	48	56
C_S (%)	52	27	48	32	50	26	48	26	35	26
C_G (%)	9	10	9	10	9	10	9	10	10	10
C_M (%)	2	3	2	3	2	3	2	3	3	3
C_P (%)	3	5	3	4	3	5	3	5	4	5
Unitary invest. cost (k€/MW)	2238	1580	2089	1655	2164	1580	2133	1576	1733	1584
O&M cost (k€/y)	591	512	595	546	543	443	416	567	477	443

Table 6
Levelized cost of energy. Otranto site

	Enercon E-40	Enercon E-66	NegMicon NM-48	NegMicon NM-64	Vestas V-47	Vestas V-80	Lagerway LW-58	Lagerway LW-72	DeWind D6	DeWind D8
LPC low (c€/kWh)	8.19	5.81	7.74	6.17	7.94	5.21	7.08	5.73	6.31	5.24
LPC high (c€/kWh)	9.46	6.71	8.94	7.13	9.19	6.02	8.18	6.63	7.30	6.06

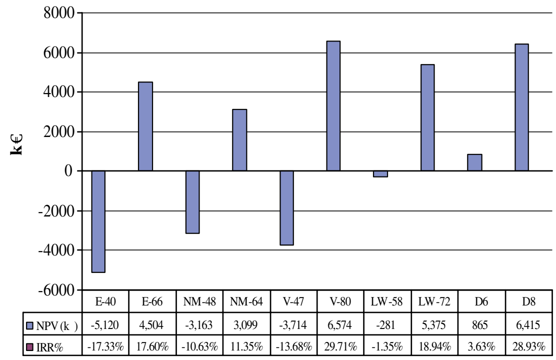

Fig. 2. NPV and IRR for different WTs. Otranto site.

are more competitive in off-shore cases, for their lower unitary investment costs. In particular, the Vestas V-80 and De-Wind D8 models present the highest net specific production, as results form Table 4, and the lowest unitary investment costs, as results form Table 5.

This is the reason of the high differences in the economic profitability using different wind turbine models.

6.3. Sensitivity analysis

The influence of the wind farm parameters in the cost of energy, for the Otranto case study and for the Vestas V-80 turbine model, is described in the sensitivity analysis of Fig. 3. The figure describes the variation in the cost of energy as a function of: (i) the variation of area available for the plant, (ii) the average wind speed, (iii) the water depth, (iv) the distance to shore. The initial values in the sensitivity analysis are those ones considered in Table 1. The analysis shows that the most important parameter in the LPC evaluation is the wind speed at the site. In fact, a decrease of about 10% in wind speed causes a correspondent increase of at least 12% in LPC. Water depth is another influent parameter, since an increase of 10% causes a correspondent increase of more

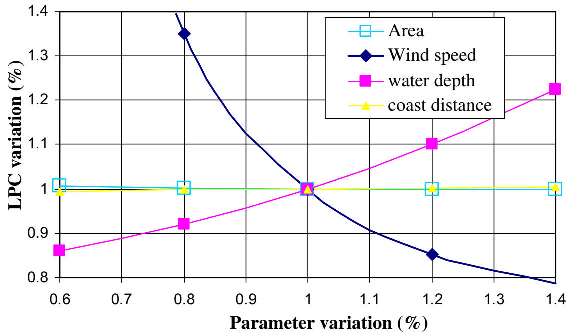

Fig. 3. Sensitivity analysis for V-80 turbine model. Otranto site.

that 5% in the LPC. On the other hand, the incidence of distance to coast variation is negligible, especially for the low values assumed for this parameter (1.5 km for the Otranto site).

7. Conclusions

In this paper, a feasibility study of off-shore wind farms to four selected sites in the Region of Puglia was proposed. The results indicate Otranto as the best localization out of the four selected sites, mainly because of the high wind resource available.

As regard the WTGs, the most suitable solutions are represented by 2 MW rated power wind turbines, which present the lower cost of energy, in the range of 5.2–6.0 c€/kWh for the Otranto site. The profitability analysis shows that, with the considered selling price of energy, larger WTG models present an internal rate of return of the investment in the range of 27%.

The sensitivity analysis confirms that the most important factors in off-shore wind farms feasibility are: (i) the wind resource, (ii) the nature and depth of the sea and (iii) the distance to the shore. Nevertheless, the high uncertainties in the investment and operational costs and in the expected wind farm availability make it difficult to accurately forecast the cost of energy for this kind of applications.

In conclusion, the main technical obstacles in the Puglia off-shore wind resource deployment are given by the high water depth, which determinates the necessity to install WTGs close to the coast. On the other hand, this solution interferes with traffic ships, visual impact and other siting issue constraints. In this case, the burocratic procedures and strictly authoritative constraints to get the construction permissions constitute a consistent non technical obstacle to off-shore installations.

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