Assessment of Offshore Wind Energy in Portuguese Shallow Waters

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Abstract—The increase of electricity consumption in Portugal, together with the energy targets set by the European Union in the wake of that established by the Kyoto Protocol, motivates the search for renewable energy sources capable of satisfying both criteria.

Portugal has an Exclusive Economic Zone about fifteen times its land area and, taking into account the need to increase the national share of energy produced through renewable energy, the installation of offshore wind farms emerges as a viable solution to sustainable energy production.

It is the subject of this work to carry out a feasibility study for an offshore wind farm in Portuguese shallow waters. The evaluation of every viable location was made, taking into account recent legislation and a survey of the state-of-the-art technology used in such projects was carried out. Wind farm prototypes were developed, based on the technology exposed. The financial assessment was performed, grounded on every consideration laid out previously.

The results show that Portugal has the wind potential for the installation of an offshore wind farm in shallow waters and that the feasibility of a project like that, in national waters, depends largely on the area of implementation, the technical characteristics of the wind farm (specially the models of the turbines utilized), as well as the system of incentives and support for offshore wind energy, including the tariffs to be applied to the produced energy.

Index Terms—offshore wind farm, site selection methodology, technical considerations, financial evaluation

I. INTRODUCTION

A. Historical Overview

The utilization of wind energy by Mankind dates back to the origins of History itself. The ancient Egyptians used it to propel their boats; the Persians rely on it to grind their grain; and the ancient Chinese used it to pump water. Centuries later, in Europe, wind power was important not only for the production of food but also for the drainage of lakes and marshes.

In the 18th century, with the Industrial Revolution, the energy demands relied on machines based on thermodynamic processes, due to their greater output and dependability, when compared with wind energy. Nevertheless, the research in wind energy never stopped and in 1887, in the UK, the first windmill developed solely to produce electrical energy was built. With the 1970’s oil crisis, the interest and research in wind energy increased and in 1980 the first onshore wind farm was built, in the USA.

The development of offshore wind started in Sweden with the installation of a single wind turbine and in 1991, the first commercial offshore wind farm was built in Vindeby, Denmark. Nowadays there are 45 offshore wind farms in nine European countries with a total installed power of 2946 MW, producing 11.5 TWh annually [21].

In Portugal, the first wind farm was installed in 1986, in Madeira, and by the end of 2010, national onshore wind farms had produced 9025 GWh. Also, the Project WindFloat was established and it stands as the first national attempt to produce electricity through offshore wind.

B. Motivations and Objectives

In order to fulfill both its national energetic consumption and the European Energy targets, Portugal has to find new sources of renewable energy, and, due to its geographic characteristics, a viable solution could be the installations of offshore wind farms.

The purpose of this work is to assess the feasibility of an offshore wind farm in Portuguese shallow waters. For that, several fundamental aspects are addressed such as the methodology for the selection of the implementation site, the technical aspects concerning the equipment of the wind farm and, finally, the financial evaluation concerning the viability of the scenarios proposed in the case study the is developed along the whole work.

II. WIND TURBINES

A. Wind Generators

A wind turbine generator (WTG) is a rotating mechanical device that converts the kinetic energy from the wind into mechanical energy. When this energy is used to produce electricity, the device is called a wind generator.

Their working principle is the following: as the blades deflect the wind, a lift force is produced, which creates a torque that drives the main shaft. The electro-mechanic conversion happens due to the fact that the main shaft is connected to the generator, through the gearbox.

A WTG is characterized, among other things, by its power curve, which expresses the output power in function of the wind speed (Fig.1).

B. Wind Turbine Models considered for the Case Study

The wind generators considered in this work are manufactured by Vestas and they are of the V90 Offshore and V112 Offshore models. Their respective certified power curves are presented in Fig. 1. The main differences between them are related not only to their rated wind speed, but also to
their swept area, as it affects directly the annual energy production (AEP).

![Power Curves](image)

Fig. 1. Performance Graphs of the Considered Wind Turbines [3], [2].

Table 1 presents the technical aspects of the wind turbine models considered.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>V90 Offshore</th>
<th>V112 Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>3.0 MW</td>
<td>3.3 MW</td>
</tr>
<tr>
<td>Cut-in Wind Speed</td>
<td>5.5 m/s</td>
<td>7.0 m/s</td>
</tr>
<tr>
<td>Rated Wind Speed</td>
<td>16 m/s</td>
<td>18.5 m/s</td>
</tr>
<tr>
<td>Cut-out Wind Speed</td>
<td>25 m/s</td>
<td>25 m/s</td>
</tr>
<tr>
<td>Rotor Height</td>
<td>80m</td>
<td>80m</td>
</tr>
<tr>
<td>Rotor Diameter</td>
<td>90m</td>
<td>112m</td>
</tr>
<tr>
<td>Swept Area</td>
<td>6362 m²</td>
<td>9852 m²</td>
</tr>
<tr>
<td>Orientation</td>
<td>Upwind</td>
<td>Upwind</td>
</tr>
<tr>
<td>Generator Type</td>
<td>DFIG</td>
<td>Synchronous with permanent magnets</td>
</tr>
<tr>
<td>Rated Apparent Power</td>
<td>3125 kVA</td>
<td>3880 kVA</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
<td>145 Hz</td>
</tr>
<tr>
<td>Rated Efficiency</td>
<td>&gt;97.5%</td>
<td>98%</td>
</tr>
<tr>
<td>Rated RPM</td>
<td>1680 RPM</td>
<td>1450 RPM</td>
</tr>
<tr>
<td>Poles</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Cos (φ)</td>
<td>0.98 ind./ 0.96 cap.</td>
<td>0.85</td>
</tr>
</tbody>
</table>

For the case study developed, the wind farm prototypes created are composed of only one of these models. The installed power of each wind farm is 162 MW, totaling 54 wind turbines per wind farm. The reasons for choosing 162 MW are related to the existence of other wind farms with similar capacities, such as Horns Rev, in Denmark.

III. OFFSHORE WIND FARM SITE SELECTION

A. Previous Studies and New Legislation

The assessment of offshore wind energy in Portugal started in 2006, when the areas in the national coast that present the most potential were defined [4], as seen in Fig. 2 (areas A through F). In 2010, the same methodology was applied (with a few different assumptions) and the results indicate the same domains, as seen, partially, in Fig 2.

However, new legislation concerning the territorial management is being developed and it influences the areas exposed above, as it adds several constraints to the ones considered in the previous studies. The new territorial management directives are exposed in the Maritime Spatial Planning, which is also known, in Portuguese, as POEM. Figs. 3 and 4 show the existing situation, respectively for the human activities developing in the Portuguese coast and for the energetic and geological aspects. Figs. 5 and 6 show the potential situation, for the same areas [5].

![Portugal Potential areas for the implementation of offshore wind farms in shallow waters in 2006 (left) and in 2010 (right)](image)

Fig. 2. Portugal Potential areas for the implementation of offshore wind farms in shallow waters, in 2006 (left) [4] and in 2010 (right) [6].

B. Area Analysis, Comparison and Selection

In order to determine the location that yields the best energy production with the lowest set of constraints, the 6 areas considered in [4] and [6], must be confronted with POEM’s determinations, as the following.

Areas E and F, located in Algarve, do not overlap with areas specified in the POEM for the development of offshore wind energy. Furthermore, not only they are located in a very touristic region, but also the existence of an offshore wind farm would interfere significantly with both nature preservation areas and with human activities like aquaculture, fishing and extraction of oil and sand, among areas.

Area D, located in the Tagus Estuary, aside being regulated by a different law, overlaps with areas reserved for nature preservation and important human activities such as fishing and tourism, where the installation of a wind farm would have a high social impact.

Area C, situated in Peniche, despite its superposition with areas designated for the development of offshore wind and being the area with the most wind resource, is near the Berlengas’ Natural Reserve, which is national heritage of Humanity. Therefore, the licensing of the wind farm would be quite troublesome, with an added reason, related to the other activities that develop in the area, such as oil extraction and aquaculture.

Area B, near Figueira da Foz, although being an area designated in POEM for the development of offshore wind in shallow waters, it overlaps with areas reserved for nature protection and for other human activities, like the extraction of oils and sands, fishing and aquaculture. For all those reasons,
Fig. 3. Portuguese Map of the existing situation, for the human activities [5].

Fig. 4. Portuguese map of the existing situation for aspects related to energy and geology [5].

Fig. 5. Portuguese map of the potential situation, for the human activities [5].

Fig. 6. Portuguese map of the potential situation for aspects related to energy and geology [5].
the licensing of an offshore wind farm in this area could prove to be a difficult process.

Area A, situated between Oporto and Espinho, is probably the best site for the development of offshore wind energy in Portugal. Not only is it designated by POEM for that finality, but it also is the area where the impacts on human factors such as oil and sand industries and fishing activities are the smallest. Another important consideration is that Area A does not overlap with nature preservation areas.

For all said above, the following work is devoted to Area A, which is characterized by water depths of 20 to 30m, and a distance to shore of about 5km. In geological terms, the selected domain is composed essentially of undifferentiated metasediments and igneous rocks and sand, clays and silt. (Fig. 7).

![Fig. 7. Seabed Geology for Area A [5].](image)

**C. Further Considerations**

Aside from the evaluation of the implementation area’s constraints, other matters must be equally addressed, such as the environmental and socio-economic impacts.

It is well known that the development of an offshore wind farm has beneficial aspects, such as the reduction of CO₂ emissions and of the country’s dependency on imported fossil fuels. Also, the revitalization of the marine sector, through the creation of local jobs, and the development of the national supply chain are positive implications of the establishment of offshore wind energy.

Nevertheless, the wind farm has a huge environmental impact, especially in the marine life that inhabits the region. The noise emitted by vessels and the vibration produced by the wind turbines affect negatively the wild species, during all the phases of the project. Plus, the electrical cables that connect the wind farm to shore, due to their high functioning temperature, will emit heat that will disturb the surrounding environment.

Concerning the social implications of an offshore wind farm, it is important to assess the level of noise that will reach the local populations and the visual impacts that the wind turbines will cause in the landscape. The obvious solution for both problems is to increase the distance of the wind farm to shore. However, that could put in risk the viability of the project.

### IV. OFFSHORE WIND FARM CONCEPTION AND DESIGN

A wind farm is not only composed by the WTGs (Fig. 8). In order to have a proper functional plant, it is also necessary to install a collection system (responsible for gathering the energy produced by each WTG), a transmission system (whose function is to transmit the gathered energy to shore) and a foundation system (that sustains the wind farm).

![Fig. 8. Components of an Offshore Wind Farm [7].](image)

#### A. Layout Considerations

In order to maximize the wind capture and reduce the wake effect, the disposition of the offshore WTGs is crucial. Usually the WTGs face the preferential wind direction, and, if necessary, then they can adjust their orientation, through their yaw system.

To reduce the wake effect, it is common practice to space the wind turbines 5 to 9 rotor diameters (RD) in the prevailing wind direction, and 3 to 5 RD in the perpendicular direction [8]. When there is more than one preferential wind direction (as it happens in the Nordic countries), the turbines are placed with an equal distance in all directions. [9]

#### B. Foundations

There are several types of foundations that can be used to support offshore wind turbines. Piled structures are the most common ones, the simplest being the monopile, used in water depths up to 40m and not requiring seabed preparation. An alternative are the gravity-based foundations, which are composed of large and heavy masses of material, typically concrete, that rest on the seabed, which requires a previous soil preparation. Finally, for water depths above 50m, the turbine should rely on floating structures, which still need a lot of maturing and are not considered in shallow water projects, such as this one.

#### C. Collection system

The collection system is composed by a series of medium voltage cables (25-40 kV) [10], [11], [12], connecting the WTGs to a collection point, which can be located on an offshore substation or rest on the seabed (Fig. 9).

![Fig. 9. Offshore Wind Farm Scheme [13].](image)

There are several topologies that can be used and the most
The radial topology is the most common one, used, for example, in Horns Rev. Its advantages are related with its control simplicity and low cost. However, it presents poor reliability, due to the fact that a cable fault could prevent the whole array to export power. The single-sided and double-sided designs offer a redundant path for the power flow in case of a cable failure. Nevertheless, this added safety implies higher costs than in the radial design [15]. The final topology, star, is a good way of reducing the cable ratings and still have a great level of security equivalent to the previous ones. However, it also has drawbacks like the need for diagonal cable runs and complex switchgear in the center WTG. Plus, its costs are comparable to the radial design ones.

Considering the collection cables, usually AC ones are utilized, since there is a small amount of power that needs to circulate through small distances. However, due to their intrinsic nature, the generation of reactive power is inevitable (typically, 100-150 kVAR per km, for a 33kV cable [15]) and it must always be compensated, at both end or at a single end of the cable.

XPLE insulation cables are the most optimal solution, when compared to LPOF or LPFF cables, due to their better constitutional characteristics (better bending capability, lower weight and capacitance and higher mechanical resistance) [17]. They have two possible constructive solutions: 1-core (where each cable carries on phase) and 3-core cables (where a single cable carries all the phases). Although 1-core cables have higher ratings than the 3-core ones, they also have higher losses and higher installations costs. Furthermore, for small inter-phase distances, since the 1-core cables are not transposed, they suffer the influence from each other [19].

In order to solve fault situations or to perform maneuvers in the electrical grid, it is essential to install switchgear. Depending on the required selectivity level, one switchgear system or three can be installed in each WTG.

D. Transmission System

The transmission system is responsible for exporting the energy produced by the WTGs and gathered by the collection system, to shore (Fig.9). There are several types of technology that can be used, and the factors that influence their selection are, besides the economic ones, the amount of power to be transmitted and the distance of transmission (Fig. 11.), whose limits vary from each author [17].

The MVAC system merges the collection into the transmission, as the cables that gather energy are the same ones that export it to shore (Fig. 12). For a 33 kV collection voltage, with powers levels up to 200M to be transmitted up to 20km, this option is the most inexpensive one [18].

HVAC (Fig.12) is the most common option, and it is used, for example, in Horns Rev, Lillgrund and Nysted [16]. For transmission distances above 20km, the voltage level must be raised typically in an offshore substation, in order to avoid the massive energy losses that result from the cable’s capacitive current. HVAC is the most economical solution for transmitted distances up to 70-80km [16], [20], [10].

When there is the necessity to transmit an enormous amount of power through very long distances (typically beyond 80-100km), the best option is a HVDC system (Fig. 12), which has two solutions: Line Commutated Converters (LCC or Conventional HVDC) and Voltage Source Converters (VSC). The difference between them, aside from their implementation method, reside in the fact that VSC systems are cheaper, more efficient, require less auxiliary and harmonic filters, offer complete control of reactive power and can be installed in smaller spaces [17], [20]. HVDC presents several advantages over HVAC like, for example, the limit of transmission distance is inexistent and fault currents are not transferred and the connection can be asynchronous, among others [17].
Regarding the substations (offshore and onshore), while the former can be implemented either at the bottom of the sea or in a structure above the sea level, the latter is typically built near the shore. The offshore substation serves to concentrate the energy that comes from the collection system and raise its voltage level. The onshore substation receives the exported power and harmonizes the energy characteristics with the requirements of the central grid.

E. Case Study Options

The layout proposed for the case study can be seen in Fig. 13.

The turbines are oriented in the NW direction (as it is the prevailing winds’ direction for the Area A) and the spacing considered is 4 RD in the prevailing wind direction and 8 RD in the perpendicular direction.

The collection system adopts the radial configuration, due to its intensive usage on other offshore wind farms. The voltage level is 33 kV, as it is a standard procedure that allows the utilization of equipment with competitive prices and the switchgear configuration adopts a low selectivity criterion, with a single switchgear system per WTG. No redundant path is available, following the example of the majority of other offshore wind farms, such as Horns Rev [14].

Since the wind farm prototypes are supposed to be located at less than 20 km from shore, the transmission system chosen is the MVAC, and, as such, the cables selected for collection are the same for the transmission.

The following tables (Tables II to V) illustrate the sizing of the collector and transmission cables, as well as the sizing of the transformer at the onshore substation capable of holding 100% of the load. The cables considered are manufactured by Nexans, a well know submarine cable company. The power losses estimated, considering the model presented in [13], do not exceed the 3% per array.

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**Table II**

<table>
<thead>
<tr>
<th>WTGs in Series</th>
<th>P [MW]</th>
<th>Q [MVar]</th>
<th>S [MVA]</th>
<th>Cable Capacity</th>
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<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>0,9</td>
<td>3,1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
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<td>12</td>
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<td>24</td>
<td>7,0</td>
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**Table III**

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<tr>
<th>WTGs in Series</th>
<th>P [MW]</th>
<th>Q [MVar]</th>
<th>S [MVA]</th>
<th>Cable Capacity</th>
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</thead>
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<tr>
<td>1</td>
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<td>2,0</td>
<td>3,9</td>
<td>20</td>
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<td>2</td>
<td>6,6</td>
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<td>6,1</td>
<td>11,6</td>
<td>20</td>
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<tr>
<td>4</td>
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<td>8,2</td>
<td>15,6</td>
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<tr>
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<td>26,4</td>
<td>16,4</td>
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**Table IV**

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<tr>
<th>Scenarios</th>
<th>W TGs in Series</th>
<th>No. of Arrays</th>
<th>Cable Capacity [MVA]</th>
<th>Cable Section [mm²]</th>
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<tbody>
<tr>
<td>V90 Model</td>
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<td>5</td>
<td>20</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3</td>
<td>28</td>
<td>185</td>
</tr>
<tr>
<td>V112 Model</td>
<td>2</td>
<td>1</td>
<td>20</td>
<td>95</td>
</tr>
<tr>
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<tr>
<td></td>
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<td>6</td>
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<td>150</td>
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**Table V**

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<tr>
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<td>169,4</td>
<td>200</td>
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<tr>
<td>V112 Model</td>
<td>3667,9</td>
<td>209,6</td>
<td>250</td>
</tr>
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V. ENERGY CALCULUS

A. Wind Profiling

In order to properly develop a wind energy project, it is essential to have a good understanding of how the wind behaves in the location reserved for the installation of the WTGs. For that, several approaches can be taken, from the utilization of a wind atlas, which is 40% accurate, until the establishment of a meteorological mast at the site, which
carries only 10% of uncertainty. In a pre-project phase, it is useful to have a mathematical tool that can describe the quasi-stationary wind. The most common are the Weibull Distribution and the Rayleigh Distribution. The former, shown in (1), is a function of the mean wind speed, \( u \), and is characterized by 2 parameters, \( c \) and \( k \), while the latter, only utilized when there is no measurement data available, is equally described by (1), but considering \( k = 2 \).

\[
f(u) = \frac{k}{c} \left(\frac{u}{c}\right)^{k-1} \exp \left\{ -\left(\frac{u}{c}\right)^k \right\}
\]

This probabilistic distribution is fundamental to estimate the annual energy production (AEP) of a wind turbine, as well as the Weibull’s distribution cumulative function, described by (2).

\[
F(u) = \exp \left\{ -\left(\frac{u}{c}\right)^k \right\}
\]

**B. Methodologies**

The estimation of the AEP of a WTG is done by applying the power curve to the wind speed distribution, measured at the WTG’s hub height, and assuming an availability of 100% [22]. There are at least three methods available to do so.

Method A is done through the integration of the product of the Weibull’s probability distribution with the WTG’s power curve, for each wind class between the cut-in and the cut-out wind speeds. This method is a very simplified one and, as so, may present a certain error when confronted with more accurate calculation methods.

Method B relies on the Weibull’s cumulative distribution function, which expresses the probability of the wind speed to be between two values and, together with the mean electric power output value for those wind speeds, obtained from the power curve, it is possible to estimate the AEP, also through integration of the product of the two curves. This method is the one established by the IEC wind energy standard IEC 61400-12 [22].

Method C allows the user to choose the integration step size, making the AEP estimation more or less accurate. An approximation of the power curve is necessary, and it is done by resorting to a sigmoidal function [8], as described by (3).

\[
P_c = \begin{cases} 
0 & , \quad 0 \leq u < u_{\text{cut-in}} \\
\frac{P_n}{1 + \exp \left(-\frac{u-u_{\text{cut-in}}}{b}\right)} & , \quad u_{\text{cut-in}} \leq u \leq u_{\text{rated}} \\
\frac{P_n}{2} & \quad u_{\text{rated}} < u \leq u_{\text{cut-out}}
\end{cases}
\]

**C. Case Study Energy Calculus**

For the area considered, the Weibull Distribution’s parameters obtained were 7.80 m/s for \( c \) and 1.83 for \( k \), after conversion to the appropriated height [10]. The following picture (Fig. 14) shows Area A’s wind profiling.

The approximations considered for the power curves are presented in Fig. 15, where, as it can be seen by the Pearson’s coefficient R, can be regarded as a good ones.

The AEP for each turbine model is presented in Table VI, plus the Capacity Factor and the Annual Equivalent Hours (AEH).

**TABLE VI**

<table>
<thead>
<tr>
<th>WTG Model</th>
<th>Method</th>
<th>AEP [MWh]</th>
<th>Capacity Factor</th>
<th>Annual Equivalent Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>V90</td>
<td>A</td>
<td>7515.87</td>
<td>28.59%</td>
<td>2505.28</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>7554.19</td>
<td>28.74%</td>
<td>2518.06</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>7373.12</td>
<td>28.06%</td>
<td>2457.71</td>
</tr>
<tr>
<td>V112</td>
<td>A</td>
<td>9886.40</td>
<td>37.62%</td>
<td>3295.47</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>9894.95</td>
<td>37.65%</td>
<td>3298.32</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>9715.68</td>
<td>36.97%</td>
<td>3238.56</td>
</tr>
</tbody>
</table>

Two essential conclusions can be drawn from the results
obtained: there are no significant differences between the three methods, as the maximum deviation between the values is in the order of 3%; also, the V112 model yields a greater energy production (by nearly 30%), a bigger capacity factor and more annual equivalent hours than the V90 model. Such was to be expected due to V112’s larger swept area and lower rated wind speed, for the same rated output power.

VI. THE COST OF OFFSHORE WIND ENERGY

The total costs of an offshore wind farm, due to its complexity, depend on several factors, and, amongst the most decisive ones, are the water depth and the distance from shore.

So, in order to ascertain the impact of those two critical factors in the case study, four scenarios were generated (two for each turbine model presented above). The first two depict the implementation of the offshore wind farms proposed in Section 4 between the water depths of 20 and 30m, while the other two scenarios illustrate the same structures, but at a water depth between 30 and 40m. The distance to shore also varies, since in the first two scenarios, it is roughly 8.1 km and, in the last two scenarios, 12.2 km.

### TABLE VII

<table>
<thead>
<tr>
<th>Components</th>
<th>Scenarios</th>
<th>Considered Costs</th>
<th>Range of Costs in other Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Planning and Development</strong></td>
<td>All</td>
<td>€54.48k</td>
<td>€113.132k - €711.132k</td>
</tr>
<tr>
<td><strong>Offshore Wind Turbines</strong></td>
<td>V90 -20m</td>
<td>€20,257k/ MW</td>
<td>-€46,644k/ MW</td>
</tr>
<tr>
<td></td>
<td>V112 -20m</td>
<td>€27,870k/ MW</td>
<td></td>
</tr>
<tr>
<td><strong>Collection Cables</strong></td>
<td>V90 -20m</td>
<td>€5.774k</td>
<td>Transmission system utilizes the same cables as the collection system</td>
</tr>
<tr>
<td></td>
<td>V90 -30m</td>
<td>€8.697k</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V112 -20m</td>
<td>€7.435k</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V112 -30m</td>
<td>€11.199</td>
<td></td>
</tr>
<tr>
<td><strong>Transmission Cables</strong></td>
<td>V90 -20m</td>
<td>€448,200k/ MW</td>
<td>€74,355k/ MW</td>
</tr>
<tr>
<td><strong>Installation</strong></td>
<td>V90 -20m</td>
<td>€32,632k / MW</td>
<td>€46,374k/ MW - €93,288k/ MW</td>
</tr>
<tr>
<td><strong>Foundations</strong></td>
<td>V90 -20m</td>
<td>€672,625k / MW</td>
<td>€371,778k/MW - €457,767k/ MW</td>
</tr>
<tr>
<td></td>
<td>V90 -30m</td>
<td>€896,861k / MW</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V112 -20m</td>
<td>€672,625k / MW</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V112 -30m</td>
<td>€896,861k / MW</td>
<td></td>
</tr>
<tr>
<td><strong>Total Initial Costs</strong></td>
<td>V90 -20m</td>
<td>€3.048k/ MW</td>
<td>€2.350k/ MW - €3.600k/ MW</td>
</tr>
<tr>
<td></td>
<td>V90 -30m</td>
<td>€3.290k/ MW</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V112 -20m</td>
<td>€3.065k/ MW</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V112 -30m</td>
<td>€3.312k/ MW</td>
<td></td>
</tr>
<tr>
<td><strong>Annual Costs</strong></td>
<td>All</td>
<td>€89,816k / MW</td>
<td>€55,305k/ MW - €93,288k/ MW</td>
</tr>
</tbody>
</table>

The first two settings considered were named “V90 – 20m” and “V11 – 20m” and the other two scenarios were named, respectively, “V90 – 30m” and “V112 – 30m”. The name of each scenario reflects the lower limit of the depth at which they were installed and the turbine model used.

The costs presented in Table VII were base in a recent study [23]. Afterwards, they were compared with other values presented in several studies, recent [24], [25], and old ones, properly actualized [26].

A few items present discrepancies, some of them because their price is project specific, others because of their high demand (due to their usage by other industries such as oil and gas, or even by other wind projects) and low availability. Nevertheless, the majority of the costs considered seem to have the same order of magnitude as the costs presented in the other studies consulted.

VII. FINANCIAL EVALUATION

The financial evaluation of the scenarios considered was realized considering the different support schemes for offshore wind energy that exist in EU countries, due to the fact that Portugal does not have an incentive system for the offshore wind, only for onshore, which is 75€/ MWh, for 15 years. The purpose of this analysis is to see if the extension of the Portuguese onshore Feed-In Tariff (FIT) would suffice to support offshore wind, and, if not, to understand which countries’ FIT would suit the Portuguese case better.

A. Assumptions Made

Several considerations had to be made: for all four scenarios, it was assumed that the fuel cost and the electricity export escalation rates equal 3% and that the inflation rate and the clean energy production credit escalation rate equal 1.2%, according to the Portuguese inflation predictions [27].

The discount rate or cost of capital is calculated as the weighted average of the cost of equity (financial investors) and the cost of debt (financial institutions). Assuming, as done similarly in [7], 70% of leverage, with 15% cost of equity and 5% cost of debt, the resultant discount rate equals 8%.

The income taxes must also be accounted for. It was assumed an effective income tax of 25% where the loss is carry forward. The depreciation method considered was a straight-line with a depreciation tax basis of 80%, during 20 years and with no tax holiday.

B. Results and Discussion

The results obtained for each scenario are depicted in the following pictures.

As it can be seen (Fig.16), both V90 scenarios have a negative NPV for the majority of the tariffs considered, with the exception of the UK case, which means that, at the outset, they constitute a bad investment decision. Furthermore, considering the After Tax Equity IRR, none of the support systems tested could provide the investor’s desired rate of return (15%), and that is also true for the case of the UK system, which is the only one that makes both the scenarios viable, from the project’s point of view.
when considering the After Tax Equity IRR, only the UK support system allows the investors to have the return rate above the one demanded, for both of the V112 Scenarios. This means that, despite allowing the viability of the scenarios, some of the tariffs are not enough to make them attractive, from the investor’s point of view.

The importance of the water depth and distance to shore in this type of project’s viability can be verified. With their increase, the feasibility of a project drops, sometimes until the point of turning it into an unviable one.

Another crucial observation is related with the results obtained for the application of the Portuguese FIT to offshore wind. None of the scenarios simulated are feasible, which implies the need to create a new one, or differentiate or modify the existing support system, in order to properly accommodate offshore wind energy.

C. Sensitivity Analysis

Contrary to what happens in the V90 scenarios, the V112 ones, for at least 5 different incentive systems, such as the French one or the German one, present positive and even large values of NPV, meaning that they both are a good opportunity of investment, from the project’s point of view. However,

```latex
\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Initial Costs [k€] & 493.768 & 740.653 & 493.768 & 246.884 \\
FIT [€/MWh] & 75 & 75 & 106 & 106 \\
NPV & -228m & -505m & -5m & 170m \\
Equity IRR & negative & negative & 7.5% & 36.5% \\
\hline
\end{tabular}
\end{table}
```

The parameters tested were the initial costs, which represent the majority of the investment, versus the FIT applied to the energy produced, also known as clean energy production credit rate. Only the value of the FIT was tested, not its duration, as it was assumed to be 15 years.

Tables VII through X present the results obtained for each proposed scenario.

```latex
\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|}
\hline
Initial Costs [k€] & 533.014 & 799.521 & 533.014 & 266.507 \\
FIT [€/MWh] & 75 & 75 & 106 & 106 \\
NPV & -323m & -505m & -34m & 157m \\
Equity IRR & negative & negative & 4.9% & 32.6% \\
\hline
\end{tabular}
\end{table}
```

From the results above, it can be seen that for the scenarios built with the V90 model, regardless of water depth and depth.
distance to shore, the value for the FIT that can make an offshore wind farm viable and attractive is above the 110 €/MWh. That represents an increase of 47% of the actual FIT, for the same years of duration.

For the scenarios with the V112 model, as it can be perceived, the FIT necessary to make a project similar to those presented feasible and attractive is above the €100 per MWh, which represents an augment of almost 34% of the actual FIT, for the same 15 years.

An immediate conclusion can be drawn: the higher the AEP of a wind turbine, the lower the FIT needs to be in order to make viable a similar project. This conclusion is consistent to what has been seen along the financial evaluation of each scenario. Another important observation is that an offshore wind farm, in the Portuguese shallow waters, can only be attractive if the remuneration paid per each produced MWh is well above the €100. Another possible way is to reduce the wind farm’s initial investment, but that does not seem to be happening [7], where the cost per MW of the wind farms keeps increasing through the years.

VIII. CONCLUSIONS

The work developed in this thesis highlights the feasibility of an offshore wind farm in Portuguese shallow waters. It was based on considerations performed over topics like the selection of a proper and sustainable implementation site, the assessment of the optimal technology necessary and the evaluation of each step’s financial cost.

Portugal, despite possessing its wind potential (for shallow water offshore wind farms) scattered throughout the coast, in small areas, presents the possibility of having offshore wind turbines producing electricity with annual equivalent hours that can almost reach the 3300 hours per year, depending of the model of the wind turbine chosen.

The implementation of an offshore wind farm, according to the prototypes developed, would imply a great deal of investment, with costs ranging between €3.047.952 and €3.312.935 per MW, which are comparable to actual values that are seen in real wind farms, both developed and in construction, all over the world.

The development of offshore wind farms in national shallow waters is viable, provided it meets certain conditions. Their economic feasibility is largely dependent not only on some of the factors exposed above, but mainly in the incentive/ support system that will focus on offshore wind energy. Currently, not only Portugal does not have a tariff system developed for offshore wind, but also the extension of the one currently in vigor for onshore wind to it, does not prove to be enough to make these projects feasible. For the scenarios considered, only a FIT around the €100 per MWh can make them viable and even profitable, considering that there is no alteration on the initial costs. Furthermore, in order to ensure the attractiveness of this type of projects for private investors, the FIT will probably have to be higher, or last longer.

The viability of an offshore wind project is highly dependent on the net annual energy production, which in turn, relies on the wind turbines chosen, all else being equal. For the wind farm prototypes with the V90 model, the majority of the European support systems could not make the offshore wind farms viable, but with the V112 model, only a few of them kept the project unfeasible.

REFERENCES