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Wind energy

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1. Introduction to wind energy

The term wind energy is used to describe the kinetic energy of the wind. On a global level, wind is disturbed by the interaction between continental and oceanic masses, but on a smaller scale there's a greater number of factors that affect wind circulation, such as buildings, vegetation and irregular terrain elevation. The power that can be extracted from the wind, which corresponds to the variation of the kinetic energy, increases with the turbine sweep area and is directly proportional to the third power of the wind speed. The wind speed is a way of measuring the quality of the wind resource and it depends on the magnitude of frictional forces, who in turn are affected by the distance to the surface and its roughness. For the former, there's higher wind speeds as the altitude increases as a result of the frictional forces getting progessively weaker. In the latter, an increase in surface roughness (which has it's minimum at the water surface) would be detrimental to the energy production since it would also mean an increase in friction and air flow turbulence. Additionally, still in regard to turbulence, wind turbines should be properly spaced out to reduce the interference between them, also known as wake effect, with the recommended distance being of about 1.5 to 4 rotor diameters to the side and 8 to 10 to the back of the turbine. Therefore, in order the maximize the quality of the wind resource (and the energy production), a turbine should be located either onshore, in places of high elevation like mountains and plateaus, or offshore, at sea, where the low turbulence means the turbines can be shorter (less variation of wind speed with altitude) and they tend to last longer (about 20 years instead of the usual 15 found for turbines on land). However, the costs associated with offshore installation are 2.5 times higher than those for onshore, which, in Portugal, average 1297 €/kW. The costs regarding operation and management (O&M) range between 1 to 2% of the initial investment.

The wind at a given location must be studied for at least a year in order to determine if it would be appropriate for wind energy production. If the wind speed variations are slow, then it can be considered a quasi-stationary wind and represented by statistical distribuitions. These distribuitions are made by counting the number of occurrences of a given hourly average speed and they make it easier to know what is the probability of the wind speed being between two values, conventionally, in an interval of 1 m/s known as wind class. The power curve of a wind turbine is a graph that indicates what the electrical power output will be for different wind classes. The cut-in speed, usually 3 or 4 m/s, is the speed at which the turbine starts producing energy, which means there is no power output between 0 m/s and the cut-in speed. The power output increases until it reaches its maximum value, the so-called nominal power, which happens at the nominal wind speed that ranges from 13 to 16 m/s. The output stays stable at nominal power until the wind reaches its cut-out speed of about 25 m/s, after which the turbine is shut down for safety reasons. The laws of fluid mechanics determine a maximum value of 59.3 % for the conversion of wind kinetic energy into electrical energy. While the Betz limit, as it is known, is never matched due to mechanical imperfections, modern turbines can have an efficiency of up to 50%, which makes wind technology significantly more efficient than other renewable sources of energy.

The electrical grid must always match the energy consumption and the losses that happen during its distribution. However, it is also necessary to have backup energy units to resort to in case the energy demand surpasses the offer. Electrical energy is not the type of energy most suitable to be stored, especially in such large amounts like the ones found in wind energy production. The solution is often reversible hydropower plants when they happen to exist in the vicinity of the wind farm.

The main negative impacts of wind energy production are related to noise, which is why wind farms tend to be located away from populations, although this is becoming less of an issue as the technology evolves. The biggest risk for fauna is for flying animals like birds and bats that can get injured, killed, or have their migratory process affected. There is little information on the impact of offshore installation in marine habitats.

Wind turbines are very large structures and as such will undoubtedly have an impact on the landscape. Its classification as either positive or negative (or neutral) impact is entirely subjective. It is important to note, however, that this matter is only relevant during the lifetime of the turbine, given that once the wind farm is no longer operating all the equipment can be dismantled and removed, leaving the location as it once was.

Due to the wake effect each turbine occupies huge amounts of land, but, since energy production happens dozens of meters from the ground, the land beneath the turbine can be used for other purposes like agriculture or even other forms of energy production such as a photovoltaic power plant, thus making land-use competition a non-issue. Furthermore, besides the obvious contribution to the electrical grid in the form of clean energy production, other positive impacts of the implementation of this technology are related to the creation of jobs and the fact that it could be a source of revenue if the land happens to be owned by public entities.

2. Case study

This chapter details the procedure used and the results obtained regarding the potential for wind technology application on an isolated island with an area of 500 km^2 (the terrain elevation and main watercourses can be found in figure 1). It should also be noted that the provided data corresponds to the recorded hourly average speed of onshore wind for a period of 8424 hours, which is less than the recommended minimum duration of one year for the study of the wind at the site. The turbine considered for installation has a nominal power of 1.8 MW, a sweep area of 3845.5 m^2 and its power curve is represented in figure 2.

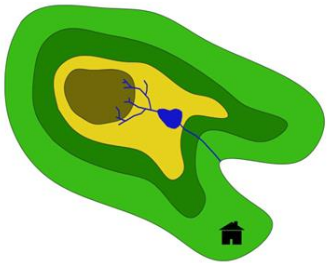

Figure 2 – Case study.

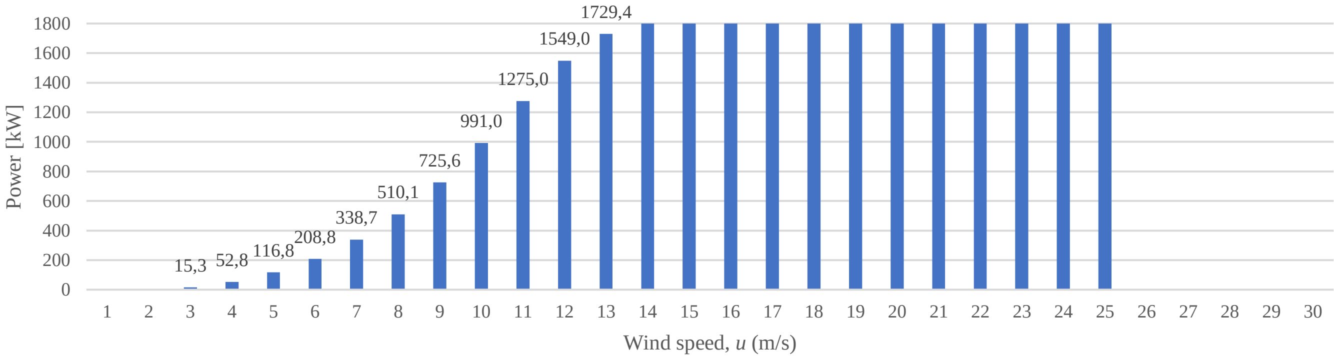

Figure 1 - Turbine power curve. The cut-in, nominal and cut-out speeds are 3, 14 and 26 m/s, respectively.

For calculation purposes, three weeks from different seasons were chosen for analysis, with one belonging to summer, another to winter and a third one representing both spring and autumn. The first step towards determining the dates of said weeks was dividing the data according to the usual start and end dates of all four seasons in the Northern Hemisphere and then calculating the average seasonal wind speed. The proposed week for analysis in a given season corresponds to the week of that season that has the closest average weekly wind speed to the average seasonal speed. For spring and autumn, which were combined into a single week, that week could belong to either of those two seasons and it is the one that as an average weekly speed closest in value to the average of both average seasonal wind speeds.

$$u_{spring/autumn}\left[\frac{m}{s}\right] = \frac{u_{spring} + u_{autumn}}{2} \quad \text{(i.)}$$

Table 1 – Start and end dates for each season, as well as their duration and average seasonal wind speed.

<table>
<tr><th>Season</th><th>Start date</th><th>End date</th><th>Duration [days]</th><th colspan="2">Average seasonal wind speed [m/s]</th></tr>
<tr><td>Summer</td><td>June 21</td><td>September 21</td><td>93</td><td colspan="2">6.701</td></tr>
<tr><td>Winter</td><td>December 21</td><td>March 20</td><td>90</td><td colspan="2">8.418</td></tr>
<tr><td>Spring</td><td>March 21</td><td>July 20</td><td>92</td><td>7.221</td><td rowspan="2">7.099</td></tr>
<tr><td>Autumn</td><td>September 22</td><td>December 20</td><td>90</td><td>6.978</td></tr>
</table>

The average weekly wind speed can only be calculated for uninterrupted weeks (168 consecutive hours), hence why the data was examined to determine if and when there were any missing records. This proved to be true for autumn and winter, with both having 12- and 24-hour gaps, and those days were excluded when outlining the weeks for the average speed calculation. As mentioned before, the proposed week for analysis is the one with a weekly speed closest to the seasonal average.

Table 2 – Missing records, number of uninterrupted weeks per season, proposed week for analysis and its average speed.

Season	Missing records [h]	Uninterrupted weeks	Proposed week for analysis	Average weekly speed [m/s]
Summer	0	13	July 26 – August 1	6.701
Winter	168	11	January 9 – January 15	8.254
Spring	0	13	April 11 – April 17	7.100
Autumn	192	9		

The next step was to count the number of times each wind speed happened in the proposed week for analysis. The wind speeds provided in the hourly time series had, as per convention, been measured with one decimal place. These values were rounded to the nearest unit in order to determine the wind class they belonged to. In the following table, only the wind classes that occur during that particular week of the season are represented, which means that throughout the entire season there could have been stronger or weaker winds, but they are not relevant to these calculations.

Table 3 – Number of occurrences per wind class, in hours, in the proposed week for analysis of each season.

Wind class [m/s]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Summer [h]	0	0	0	10	20	50	47	29	1	3	4	4	0	0	0	0	0
Winter [h]	0	0	12	14	20	18	18	12	17	9	8	13	9	9	3	5	1
Spring/Autumn [h]	8	8	4	10	16	18	32	17	16	18	9	7	3	0	1	1	0

For a given wind class, u, the weekly electricity production (equation ii.) is calculated by its number of weekly occurrences, n, times the turbine operating power at that speed. The total energy produced per week (iii.) is sum of the energy produced for all wind classes. The seasonal energy production (iv.) is equal to the weekly production times the number of weeks per season. A year is 52 weeks long, which means that each of the four seasons has a duration of 13 weeks (this could also be proven by dividing the season duration found in table 1 by the number of days in a week). The annual energy production (v.) results from the sum of the energy produced throughout the four seasons, keeping in mind that the seasonal production for spring/autumn, which had previously been considered a single season, must now be doubled to represent both seasons. The capacity factor, CF (vi.), is the ratio between the real energy production in a certain time interval and the theoretical maximum energy that the turbine would produce in that same period in an ideal situation where it is always operating at nominal power and disregarding any type of losses.

ii. $$E_{week}(u)\left[\frac{kWh}{week}\right] = n(u)\left[\frac{h}{week}\right]\cdot P_{turbine}(u)\,[kW]$$

iii. $$E_{week}\left[\frac{kWh}{week}\right] = \int_{u_{cut-in}}^{u_{cut-out}} E_{week}(u)\left[\frac{kWh}{week}\right]$$

iv. $$E_{season}\left[\frac{kWh}{season}\right] = 13\left[\frac{week}{season}\right]\cdot E_{week}\left[\frac{kWh}{week}\right]$$

v. $$E_{annual}\,[kWh] = E_{summer}\,[kWh] + E_{winter}\,[kWh] + 2\times E_{spring/autumn}\,[kWh]$$

vi. $$FC = \frac{E_{annual}}{E_{annual\ max}}\frac{[MWh/year]}{[MWh/year]} = \frac{E_{annual}\,[MWh/year]}{365\,[day/year]\times 24\,[hour/day]\times P_{nominal}\,[MW]}$$

By observing table 4 it is possible to see the seasonality in wind energy production, with the best weekly results being found in the wintertime and corresponding to double those of the worst season which is summer.

Table 4 – Weekly production per season. Annual energy production and capacity factor.

Weekly energy production [MWh/week]			Annual production [MWh/year]	Capacity factor [%]
Summer	Winter	Spring/Autumn		
59	119	86	4555	29

The levelized cost of energy, $LCOE$, corresponds to the levelized cost of each energy unit produced and it can be determined by the dividing the sum of all costs related to the project (installation, O&M, fuel, and others, respectively, c_{a1}, c_{a2}, c_{a3} and c_{a4}) by the levelized annual energy production, E_L. This calculation can be simplified (rewriting equation vii. as x.) by making the following assumptions:

a) The installation costs, c_{a1} [€] $= I_t$ [€] $= P_{nominal}$ $[kW] \times C_{installation}$ $[€/kW]$ are the only investment;
b) The annual energy production is the same throughout the analysis period (turbine lifetime);
c) O&M costs, d_{om}, are the same throughout the equipment's lifetime;
d) There are no costs related to fuel since wind energy is a clean energy, thus c_{a3} [€] $= 0$;
e) There are no further costs (c_{a4} [€] $= 0$).

vii.	$LCOE\left[\frac{€}{kWh}\right] = \frac{c_{a1}[€] + c_{a2}[€] + c_{a3}[€] + c_{a4}[€]}{E_L\,[kWh]} = \frac{c_{a1}[€] + c_{a2}[€] + c_{a3}[€] + c_{a4}[€]}{k_a \cdot E_{annual}\,[kWh]}$
viii.	$c_{a2}\,[€] = d_{om} I_t k_a$
ix.	$i = \frac{1}{k_a} = \frac{a(1+a)^n}{(1+a)^n - 1}$
x.	$LCOE\left[\frac{€}{kWh}\right] = \frac{I_t(i + d_{om})[€]}{E_{annual}\,[kWh]}$

In the following table are the installation costs, O&M costs and turbine lifetime used in the calculations, all of them having been previously mentioned in chapter 1. A discount rate, a, of 5% was also considered. The results for the total investment and the levelized cost of energy for an onshore wind turbine can be found in the same table.

Table 5 – Installation costs, O&M costs, lifetime and considered for an onshore wind turbine. Total investment and levelized cost of energy.

Installation [€/kW]	Lifetime [years]	O&M [% of investment]	Discount rate [%]	Investment [€]	LCOE [€/kWh]
1297	15	2	5	2 334 600	0.06

The last thing that needed to be determined was the turbine footprint, which corresponds to energy produced per area unit occupied by the equipment throughout its lifetime (equation xi.). To do so, it was necessary to determine the area occupied by a single wind turbine taking into account the wake effect, for which a lateral distance of 3 rotor diameters was considered as well as 8 rotor diameters to the back of the turbine, as seen in equation xii. The rotor diameter was calculated from the sweep area according to equation xiii.

xi.	$footprint\left[\frac{kWh}{m^2}\right] = \frac{n\,[years] \cdot E_{annual}\,[kWh]}{A_{turbine}\,[m^2]}$
xii.	$A_{turbine}[m^2] = 3 \cdot d_{rotor}\,[m] \times 8 \cdot d_{rotor}\,[m] = (3 \times 8) \cdot d_{rotor}^2\,[m^2]$
xiii.	$d_{rotor}\,[m] = \sqrt{\frac{4}{\pi} \cdot A_{sweep}\,[m^2]}$

Table 6 – Rotor diameter, area occupied by a turbine and footprint.

Rotor diameter [m]	Area occupied by a turbine [m^2]	Footprint [kWh/m^2]
70	117510	581

According to the information presented in the first chapter, the best place to install an onshore wind turbine would be a mountainous region like the one painted brown in figure 1. Furthermore, it is relatively close to watercourses, which means that if in one of them there happened to be a reversible hydropower plant it could be used for energy storage.

Given that the case study is an island, it would not make sense not to determine its offshore potential. However, this data was not provided, so it was roughly estimated from the existing onshore wind hourly time series. The wind at sea is stronger, which is another way of saying that it averages higher speeds than on land. For that reason, the first step towards creating an offshore data series was to increase by 10% the maximum speed registered onshore for each season (xiv.). This speed is now the offshore maximum speed. The difference between the seasonal offshore and onshore maximum speeds was then added to the onshore values registered in the proposed week for analysis of each season (xv.), thus creating three weeks of offshore data while maintaining the original statistical distribution.

xiv.	$u_{max,offshore}\left[\frac{m}{s}\right] = 1.1 \times u_{max,onshore}\left[\frac{m}{s}\right]$
xv.	$u_{offshore}\left[\frac{m}{s}\right] = u_{onshore}\left[\frac{m}{s}\right] + \left(u_{max,offshore}\left[\frac{m}{s}\right] - u_{max,onshore}\left[\frac{m}{s}\right]\right)$

Although it was said in the first chapter that offshore turbines could be shorter than their onshore counterparts, the same turbine was considered for the following calculations. The only difference is regarding the installation costs, which are now 2.5 times higher, and its lifetime is extended by 5 years, both facts that were also stated in chapter 1.

The exact same procedure was applied to this new data in terms of determining the energy production potential, the economic analysis, and the footprint. The most relevant results can be found in the following table.

Table 7 – Annual energy production, capacity factor, initial investment, levelized cost of energy and footprint for an offshore wind turbine.

Installation cost [€/kW]	Lifetime [years]	Annual production [MWh/year]	CF [%]	Investment [€]	LCOE [€/kWh]	Footprint [kWh/m^2]
3245.5	20	7279	46	5 836 500	0.08	1239

It is worth mentioning that while the offshore costs and investment are more than double those onshore, its levelized cost of energy is only 2 cents more expensive because there is a 60% increase in annual energy production. Despite the fact that the turbines are identical and occupy the exact same area, the footprint more than doubles for an offshore turbine due to its greater energy production and longer lifetime.

Figure 3 shows that the increase in energy production between onshore and offshore installation is about the same for all seasons and that winter and summer remain, respectively, the best and summer seasons. However, it must also be noted that offshore production in the summer is almost double its onshore production, which is very relevant in terms of grid reliability.

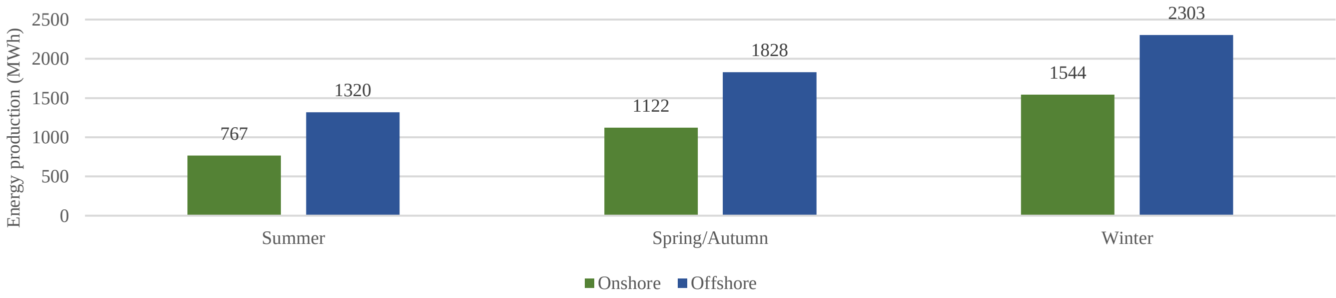

Figure 3 - Seasonal onshore and offshore energy production.

In summary, the case study shows potential for both onshore and offshore wind energy production. These two types of installation are not mutually exclusive, they can co-exist on the island if the energy demand justifies it and there is enough money to afford it.

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