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# Economic Feasibility of Floating Offshore Wind Farms in the North of Spain

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**Abstract:** This paper assesses the economic feasibility of offshore wind farms installed in deep waters considering their internal rate of return (IRR), net present value (NPV), and levelized cost of energy (LCOE). The method proposed has three phases: geographic phase, economic phase, and restrictions phase. The purpose of the geographic step is to obtain the input values, which will be used in the economic phase. Then, the economic parameters are calculated considering the inputs provided previously. Finally, the bathymetric restriction is added to the economic maps. The case study focused on the Cantabric and North-Atlantic coasts of Spain, areas that have not been studied previously in economic terms regarding floating offshore wind technology. Moreover, several alternatives have been considered, taking into account the type of floating offshore wind structure and the electric tariff. Results indicate which is the best floating offshore wind structure with respect to LCOE, IRR, and NPV, and where is the best location for the connection of a floating offshore wind farm in the region selected.

**Keywords:** floating offshore wind; feasibility study; internal rate of return; levelized cost of energy (LCOE); net present value

## 1. Introduction

The North of Spain has a great onshore and offshore wind potential. Therefore, it is essential to increase the use of renewable energies in Spain to achieve the objective of the European Union (EU) for 2020 for the electricity production of renewable energies [1], the objectives of its own Renewable Energy Plan 2011–2020 [2], and in order to have an electricity mix [3] and reduce the traditional energy sources [4], which generate greenhouse emissions [5].

Regarding Spain's onshore wind energy potential in Europe, the country ranks second in power installed in the EU during recent years [6]. However, this country is delayed regarding offshore wind energy due to the last national energy laws regarding these issues. In fact, the perspectives of the Wind Europe, for Spain, for 2020 in terms of offshore wind is only 5 MW [7], which is the power of an offshore wind turbine installed in a port in the Canary islands to be tested as offshore wind turbine, but still not deployed at sea. Therefore, it is important to boost the offshore wind sector in the future [8] in order to achieve the success that can be found in the onshore wind sector, including its operational issues such as the safety [9] availability [10,11] and maintenance [12,13], its integration in the grid [14], its offshore wind resource [15–18], its layout optimization [19], or its resource prediction [20].

Although there are studies about increasing the size of wind turbines, the majority of the wind turbines installed have a rated power of 5–6 MW [21] and they have a horizontal axis [22,23]. Due to the increasing size of the wind turbines and the increasing number of onshore wind farms, onshore locations have become more difficult to find because they are occupied by lots of old onshore wind farms or repowering wind farms [24]. In addition, the environmental cost of wind turbines is higher onshore that offshore [24]. Otherwise, the risk of cost overruns for onshore farms is 1.7% and 9.6% for offshore farms—quantities much lower than other types of energies [25].

After years of study, experimental studies, and prototypes [26,27], there are two main sorts of offshore wind structures considering the kind of platform that supports the offshore wind turbine. In this sense, platforms can be fixed (monopiles [28], tripod [29], jackets [30], gravity-based foundations [31]) or floating [32,33] (semisubmersible [34], tensioned leg platforms (TLP) [35,36], spar [37,38]). Regarding the floating concepts, the loads in the semisubmersible platform are the highest for the three floating structures [39]. Nowadays, all the offshore wind farms installed, the majority of which are located in the North Sea, use fixed platforms, of which close to 90% are monopiles. However, considering the characteristics of the Spanish continental waters, the best option is to use floating offshore wind platforms.

In this context, several floating offshore wind platforms have been tested during recent years: a spar platform called Hywind, installed by Statoil in Norway [31], and a semisubmersible platform called WindFloat [40] in Portugal are the most representative devices. The first floating offshore wind farm with five spar Hywind floating platforms, constructed in Navantia Fene, a shipyard located in Fene, A Coruña (Spain), has been installed in Scotland (UK) [41]. The platform Windfloat, which was built in the Portuguese shipyard LISNAVE, was tested during five years in prototype form (2 MW) in Portugal, has now been substituted by a park of three platforms with 8.4 MW turbines in the North of Portugal.

The objective of this work was to carry out a procedure to calculate the economic feasibility of offshore wind farms installed in deep waters, considering their internal rate of return (IRR), net present value (NPV), and levelized cost of energy (LCOE). The method proposed has three phases: geographic phase, economic phase, and restrictions phase. The purpose of the geographic phase is to obtain the input values, later used in the economic phase: the shape parameter of the offshore wind, the scale parameter of the offshore wind, height and period of waves, bathymetry, the distance farm–shore, the distance farm–shipyard, and the distance farm–port. Then, the economic parameters are calculated considering the inputs provided in the previous phase. Finally, the restriction of bathymetry are added to the economic maps, whose value will be different depending on the offshore wind structure selected.

The case study focused on the Cantabric and Atlantic coasts of the North of Spain, areas with high potential of offshore wind [16] and where the wave conditions are also known [42]. Moreover, three floating offshore wind structures were considered—semisubmersible, spar, and tensioned leg platform—and three scenarios for electric tariff were taken into account due to the variability of the offshore wind tariff during recent years in Spain. The best floating offshore wind platform, regarding its main economic parameters, was then identified and the best location at the region of study for its installation was selected. This study will be the first economic analysis of the whole North of Spain regarding floating offshore wind.

## 2. Methodology

### 2.1. Procedure

The method proposed is composed of three main phases:

- Geographic phase.
- Economic phase.
- Restrictions phase.

In the geographic phase, the input values considered, and later used in the economic phase, are: the shape parameter of the offshore wind, the scale parameter of the offshore wind, the height of the waves, the period of the waves, the bathymetry, the distance farm–shore, the distance farm–shipyard, and the distance farm–port. All of these parameters have been considered using input maps, which allow us to generate output maps. It gives more information to users to select the best areas where a floating offshore wind farm can be installed.

In the economic phase, the inputs provided by the previous phase are considered, and the costs of the life cycle of the offshore wind farm installed in deep waters and other economic results are calculated. Its analysis will define the economic feasibility of an offshore wind farm installed in deep waters. These economic issues are: the internal rate of return (IRR), the net present value (NPV), and the levelized cost of energy (LCOE). These are the common economic parameters in this type of study.

Finally, it is important to notice that there can be a great region for exploitation in economic terms, but this is limited by some factors. In this paper, only one restriction has been considered: the bathymetry. In this context, the type of floating offshore wind platform and its draft restrict the economic maps. Other restrictions, such as environmental protected areas, seismic fault lines, and navigation areas, could have been considered. However, in this work only bathymetry was considered because it is one of the most important limitations to the installation of the farm.

### 2.2. Geographic Phase

In this phase, some parameters later used in the economic phase are defined and calculated:

- The shape and scale parameters of the wind were set after having fitted a Weibull distribution to 10 years of wind data (2000–2010), extracted from the ERA-Interim hindcast database, created by the ECMWF (European Centre For Medium Weather Forecast). Weibull distribution is the most common distribution considered for wind resource modelling. The Weibull distribution obeys the following mathematical expression:

$$f(x|a,b) = \frac{a}{b}\left(\frac{x}{a}\right)^{b-1} e^{-\left(\frac{x}{a}\right)^b} \tag{1}$$

in which $a$ is the shape parameter and $b$ is the scale parameter.

- The significant wave height ($Hs$) and the mean wave period ($Tm$) were calculated using the wave model SWAN, which is a third generation spectral model that simulates the wave transformation nearshore, based on wind data, boundary conditions, and bathymetry information [42]. It is one of the most common models usually considered to obtain wave data. It outputs spectral as well as statistical data about the wave climate. These two parameters, Hs and Tm, are calculated according to the following equations:

$$Hs = 4\sqrt{\int\int E(\omega,\theta)d\omega d\theta} \tag{2}$$

$$Tm = 2\pi\left(\frac{\int\int \omega E(\omega,\theta)d\omega d\theta}{\int\int E(\omega,\theta)d\omega d\theta}\right)^{-1} \tag{3}$$

in which:
- $E(\omega,\theta)$: variance density spectrum.
- $\omega$: absolute radian frequency, calculated considering the doppler shifted dispersion relation.
- The bathymetry was taken from GEBCO (General Bathymetric Chart of the Oceans) with a resolution of $0.0083° \times 0.0083°$. This resolution was afterward interpolated for the simulations with the wave model for computational purposes. The implemented resolution was $0.05° \times 0.1°$.

Afterward, for the feasibility study, the bathymetry was then interpolated to a resolution of 16 km × 33 km.

In addition, the distance farm–shore, the distance farm–shipyard, and the distance farm–port were calculated using the tools provided by a Geographic Information System tool.

Regarding the size of the grid, it is important that an offshore wind farm installed in deep waters can be located inside the cell. The distance between offshore wind turbines is 4 times the diameter (D) of the offshore wind generator and the distance between lines of offshore wind generators is 7 times the diameter (D) of the offshore wind turbine (see Figure 1). Therefore, all the data used for the assessment were interpolated into a resolution of 16 km × 33 km.

**Figure 1.** Distance between offshore wind turbines (4D) and distance between lines of offshore wind turbines (7D).

### 2.3. Economic Phase

In the economic phase, the costs of the life cycle of an offshore wind farm installed in deep waters and other economic results are determined, and the economic feasibility of a floating offshore wind farm is assessed. Given that these inputs (the shape parameter of the offshore wind, the scale parameter of the offshore wind, the height and period of waves, the bathymetry, the distance farm–shore, the distance farm–shipyard, and the distance farm–port) vary depending on the point (k) of the geography considered, the joining of all these points generates a map of the location of study.

In this sense, the calculation of the cost of all the life cycle process of a floating offshore wind farm (FOWF) has been developed in previous studies [43,44] and it is calculated considering several phases [1]: the concept definition (C1), the design and development (C2), the manufacturing (C3), the

installation (C4), the exploitation (C5), and the dismantling (C6). This calculation has been carried out for each point "k" of the geography [44].

$$LCS_{FOWF}(k) = C1(k) + C2 + C3\ (k) + C4(k) + C5(k) + C6(k) \tag{4}$$

The most important costs of these six phases are the cost of manufacturing (C3), the cost of installing (C4), and the cost of exploiting (C5) the floating offshore wind farm.

The cost of manufacturing takes into account the values of developing the wind turbines (C31) and their platforms (C32), the cost of manufacturing the moorings (C33) and anchoring (C34), and, finally, the cost of manufacturing all the electric components of the farm (C35) (electric cables, substation, etc.) [45].

$$C3 = C31 + C32 + C33 + C34 + C35 \tag{5}$$

The cost of installing the farm considers the value of installing the wind turbines (C41) and their platforms (C42), the installation of anchoring and moorings (C43), and, finally, the cost of installing the electric components (mainly electric cables and substation) (C44) [44].

$$C4 = C41 + C42 + C43 + C44 \tag{6}$$

On the other hand, the cost of exploiting the farm, which takes place once the farm is operating, is composed of the cost of insurance (C51), the business and administration cost (C52), and the operation and maintenance cost (C53), which includes the preventive and corrective maintenance cost during the life cycle of the farm.

$$C5 = C51 + C52 + C53 \tag{7}$$

In addition, the levelized cost of energy (*LCOE*) is calculated considering these costs ($LCS_{FOWF_t}$) in €, the energy generated ($E_t$) in MWh/year, and the capital cost of the project (*r*) [45].

$$LCOE = \frac{\sum_{t=0}^{N_{farm}} \frac{LCS_{FOWF_t}}{(1+r)^t}}{\sum_{t=0}^{N_{farm}} \frac{E_t}{(1+r)^t}} \tag{8}$$

Furthermore, if you also add the electric tariff, the other economic parameters can be calculated: net present value and internal rated of return.

NPV is the net value of the cash flows of the farm, considering its discount from the beginning of the investment [46,47].

$$\mathrm{NPV} = -G_0 + \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} \tag{9}$$

being that [47]:

- $CF_t = R_t - E_t$: cash flow on year t.
- $E_t$: expenses on year t. It considers the exploitation costs (C5) during all the operation years of the project.
- $R_t$: revenues on year t based on the incomes obtained from the sale of electricity and dependent on the country.
- *t*: life cycle years (20 years).
- $G_0$: initial investment. It considers the C1, C2, C3, and C4 during the years of constructing the farm, and C6 during the last year of its life cycle.
- *r*: discount rate (8%)

IRR is calculated when the net present value is equal to zero [46,48].

$$-G_0 + \sum_{t=1}^{n} \frac{CF_t}{(1 + IRR)^t} = 0 \tag{10}$$

The WACC (weighted average cost of capital) has been calculated and taken into account in Equation (11):

$$\text{WACC} = \frac{MV_e{\cdot}R_e + MV_d{\cdot}R_d{\cdot}(1 - T)}{MV_e + MV_d} \tag{11}$$

being that:

- $MV_e$: total equity.
- $R_e$: cost of equity (8%).
- $MV_d$: debt.
- $R_d$: interest rate (5%,24%).
- $T$: tax shield (1–25%).

Finally, it is important to determine if the floating offshore wind farm considered is economically feasible. In this context, the project will be economically viable if the NPV is positive and the IRR is higher than the WACC. Furthermore, the LCOE should be as low as possible.

### 2.4. Restrictions Phase

Once the economic maps have been defined, it is necessary to restrict the area where the farm can be installed. In this sense, it is important to notice that although there is a viable region in economic terms, its use is limited by some factors. In this paper, only one restriction was considered: the bathymetry.

In this work, the bathymetry restriction was from ($D_c + 20$) to 1000 m of depth, with $D_c$ being the draft of the floating offshore wind platform, which is considered such as an enough value to install this type of farms. Therefore, the kind of floating offshore wind platform restricts the economic maps.

In addition, due to the fact that there is no law about the distribution of the offshore territorial space for the particular issue of the offshore wind, it is important to know the limit of the territorial waters, which was established as 12 nautical miles or 22.2 km. The territorial sea was defined by the 1982 United Nations Convention on the Law of the Sea.

## 3. Case of Study

The case study chosen to carry out the methodology focused on the Cantabric and Atlantic regions of the North of Spain, as shown in Figure 2. These areas were selected because they have the best wind resource of the Iberian Peninsula. In addition, they have not been totally studied regarding economic aspects of floating offshore wind.

**Figure 2.** Spanish regions selected.

These areas are characterized by excellent offshore wind resources (Figures 3 and 4), with values of the offshore wind scale parameter up to 8.77 m/s and deep waters (Figure 5).
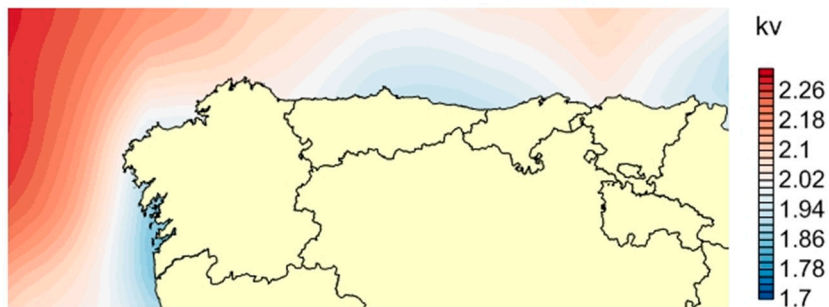


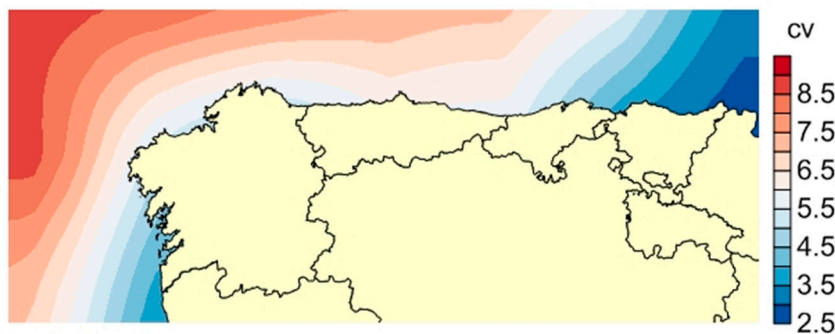**Figure 3.** Shape of the offshore wind parameter for the North of Spain.



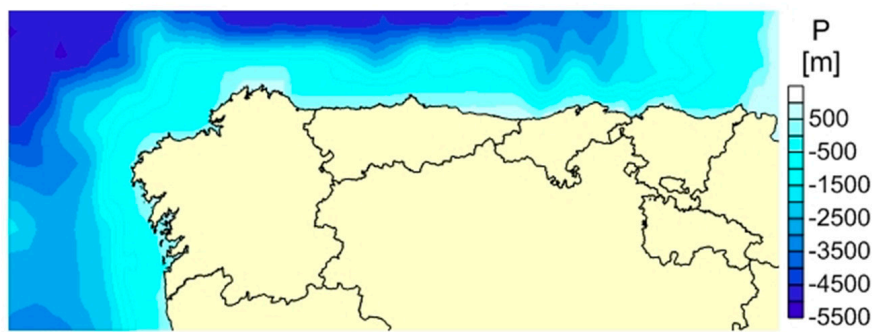**Figure 4.** Scale of the offshore wind parameter for the North of Spain.

**Figure 5.** Bathymetry of the North of Spain.

The farm is composed of twenty-one floating offshore wind generators of 5.075 MW of power, a life cycle of 20 years, and the size of the grid is 16 km × 33 km.

Three different floating offshore wind structures were considered: semisubmersible TriFloater [49], MIT (Massachusetts Institute of Technology) Tensioned Leg Platform (TLP) [50], and spar OC3-Hywind [51], whose dimensions are shown in Table 1 and Figure 6. These structures were selected because they are the most representative of the floating offshore wind and the platforms with the most data available.

**Table 1.** Characteristics of the platforms [47].

| Variable | Semisubmersible | TLP | Spar | Units |
|:---:|:---:|:---:|:---:|:---:|
| $a$ | 8.0 | 18.0 | 9.4 | m |
| $H_f$ | 12.0 | - | - | m |
| $H_w$ | 13.0 | - | - | m |
| $L_w$ | 2.0 | - | - | m |
| $L_d$ | 5.0 | - | - | m |
| $L_s$ | 1.5 | - | - | m |
| $H_d$ | 1.5 | - | - | m |
| $D_c$ | 10.0 | 44.9 | 120.0 | m |
| $H_p$ | 2.0 | 3.0 | - | m |
| $L$ | 76.0 | 54.0 | 9.4 | m |
| $H_{fairlead}$ | 16.8 | 47.9 | 70 | m |



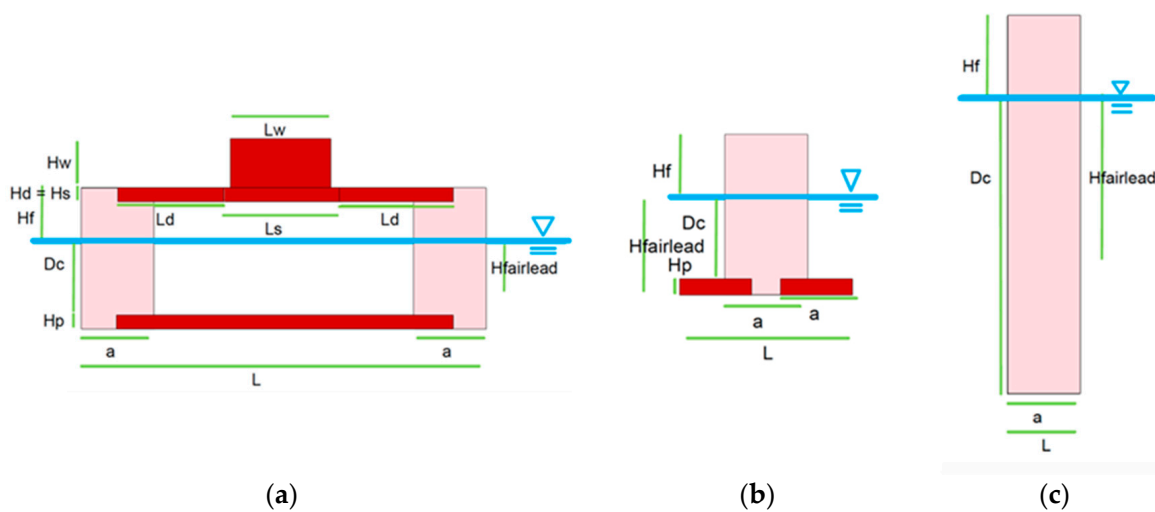(**a**)          (**b**)          (**c**)

**Figure 6.** Dimensions of the semisubmersible platform (**a**), the TLP platform (**b**), and the spar platform (**c**) [47].

Furthermore, the sort of floating offshore wind structure will also determine the type of installation and other aspects such as the mooring material and the disposition of the anchoring and mooring. In this context, the semisubmersible platform will have an onshore installation and wet transport of the offshore wind generator and the floating platform, the TLP and spar platforms will have a dry transport of the offshore wind turbine and dry transport of the floating platform in a barge and floating crane without storage for their offshore installation. Regarding the mooring, the material of the mooring for semisubmersible and spar platforms is a chain and the material of mooring for TLP is cable. Its disposition is determined using nontensioned mooring or catenary in the semisubmersible and spar platform, and a tensioned mooring at 90° with the seabed for the TLP. Finally, the type of anchoring is a drag embedment anchor for the semisubmersible and spar platforms, and a pile for the TLP platform.

The changes in the Spanish electric tariff regulation make an unstable energy situation for investors. In this sense, the Spanish electric tariff for offshore wind has changed from 93.557 €/MWh in 2012, 53.48 €/MWh in 2013, 148.515 €/MWh in 2014 to 45.78 €/MWh in 2015 and 2016 [52]. In addition, in these previous regulations, only offshore wind was considered, but without differentiating between the fixed offshore wind systems and the floating offshore wind systems. Therefore, in the present study three different tariffs were considered, presenting a range of values close to the previous electric tariffs and the minimum electric tariff to become economically feasible: 190.856 €/MWh [53]. These possible electric tariffs are shown in Table 2 and are based on the changes in the Spanish market.

**Table 2.** Electric tariffs considered.

| Scenario | Electric Tariff (€/MWh) |
| --- | --- |
| Scenario 1 | 50 |
| Scenario 2 | 100 |
| Scenario 3 | 200 |

The restriction considered for bathymetry depends on the type of floating platform, as shown in Figures 7–9.
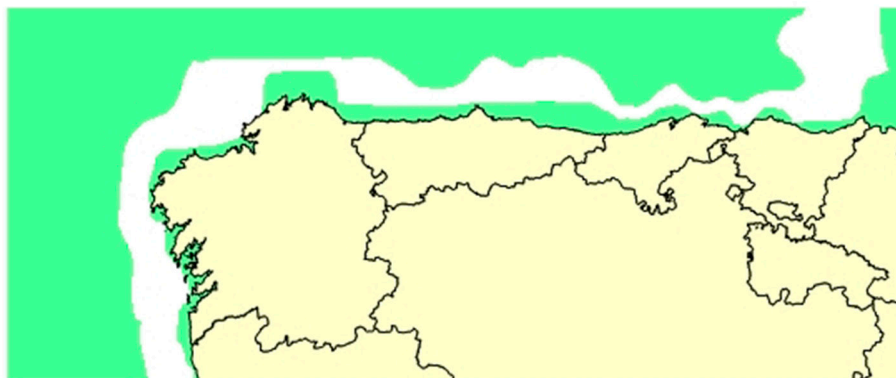


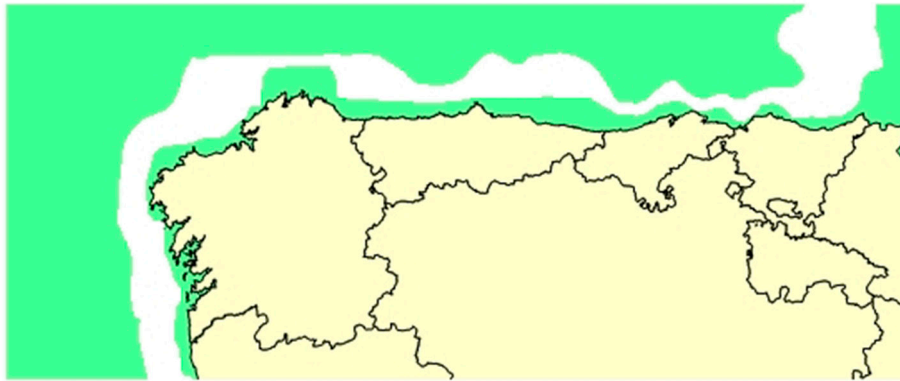**Figure 7.** Bathymetry restriction for the semisubmersible platform.

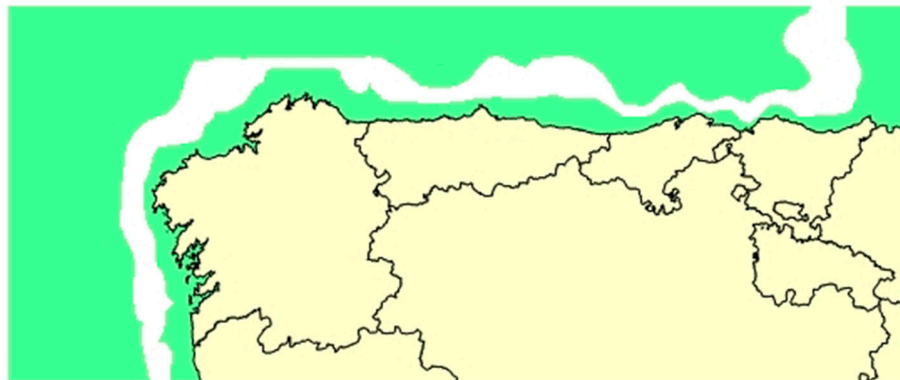**Figure 8.** Bathymetry restriction for the TLP platform.



**Figure 9.** Bathymetry restriction for the spar platform.

## 4. Results

The best LCOE had a value of 172.81 €/MWh for the semisubmersible platform (Figure 10a). It was followed by 184.52 €/MWh for the spar platform, see Figure 10c, and 187.98 €/MWh for the TLP platform (Figure 10b).

However, the map represented by Figure 10. is not applicable in all of the extensions that were calculated, due to the fact that, depending on the type of floating platform, a different restriction of bathymetry appears. It is because the installation of the floating platform depends on the draft and the bathymetry of the region (it is due to the fact that very high bathymetries do not make sense). In this context, three different restrictions for bathymetry were considered depending on the draft of the floating structure. Different maps of LCOE were generated with restrictions for each different floating offshore wind platform. Therefore, one restriction of bathymetry has been taken into account for each platform, considering its particular structural characteristics.

However, in this case, it does not affect to the best values for the LCOE in the three different floating offshore wind platforms, being the best areas located in the area selected considering the bathymetry restrictions, as Figure 11 shows.
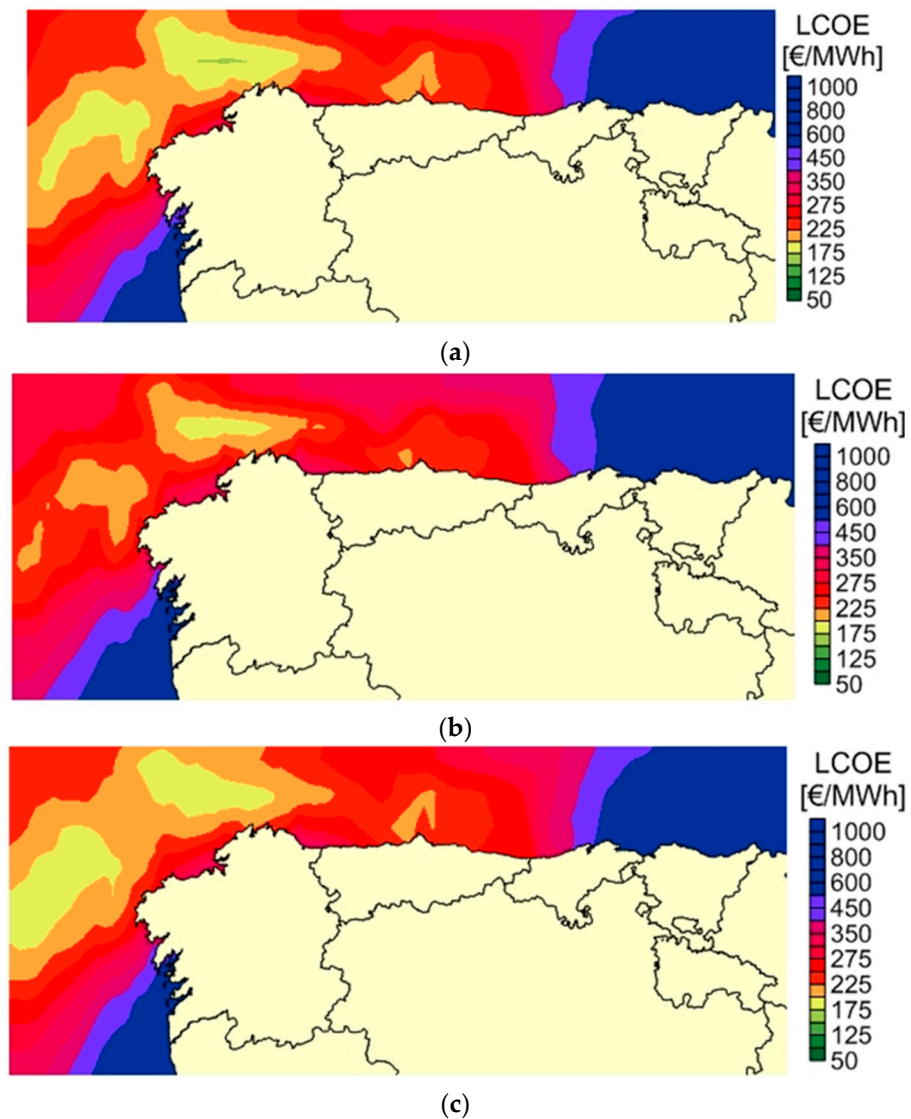
**Figure 10.** Results for LCOE without restrictions for semisubmersible (**a**), tensioned leg platform (**b**), and spar (**c**).

On the other hand, considering Scenario 1 with the 50 €/MWh of electric tariff, all the results are not economically feasible. In this context, the best values for IRR go from −14.5% for the semisubmersible platform, to −15.1% for the spar platform and to −16.2% for the TLP platform, being all of them less than the Weighted Average Cost of Capital. In addition, the best values for NPV go from −222.55 M€ for the semisubmersible platform, to −234.22 M€ for the spar platform and to −233.77 M€ for the TLP platform, all of them being less than zero, which indicates that the project will not economically feasible with this proposed electric tariff (very close to the present Spanish electric tariff).
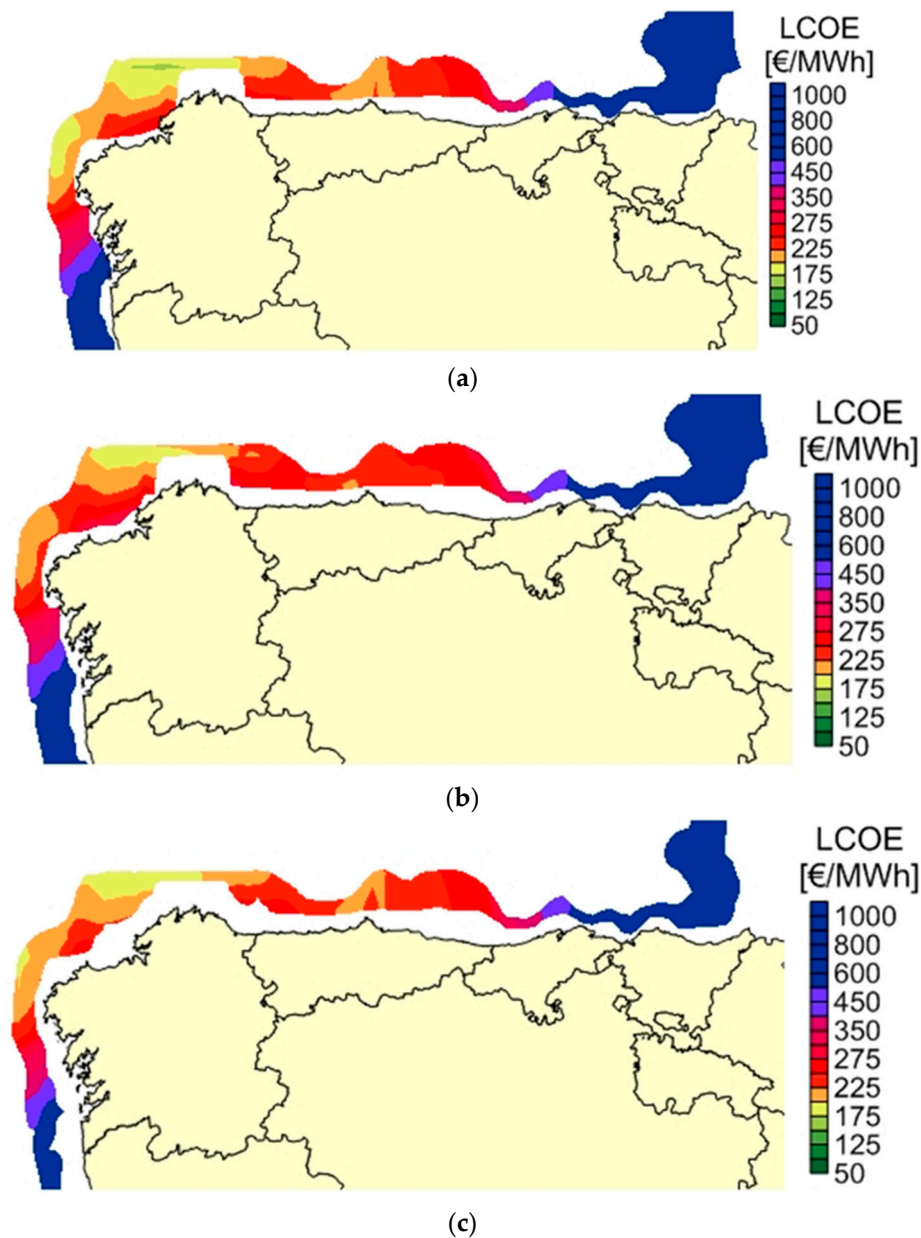
(a)



(b)



(c)

**Figure 11.** Results for levelized cost of energy (LCOE) with restrictions for semisubmersible (**a**), tension leg platform (**b**) and spar (**c**).

Moreover, results for Scenario 2 with the 100 €/MWh of electric tariff have better results than Scenario 1, but they are also not economically feasible. Here, the best values for IRR go from −2.89% for the semisubmersible platform, to −3.67% for the spar platform and to −4.28% for the TLP platform. As it can be seen all the results obtained for the IRR in Scenario 2 are less than the Weighted Average Cost of Capital, therefore, the project will not be economically feasible in these conditions. In addition, the best values for NPV go from −135.18 M€ for the semisubmersible platform, to −151.28 M€ for the spar platform and to −155.22 M€ for the TLP platform, all of them negative, which indicates that this project would not be economically feasible with the electric tariff proposed in Scenario 2.

Scenario 3, which takes into account a 200 €/MWh of electric tariff, presents the best results when compared with the previous ones. In this case, the best values for IRR went from 9.55% for the semisubmersible platform (Figure 12a), to 8.16% for the spar platform (Figure 12c), and to 7.90% for the TLP platform (Figure 12b).
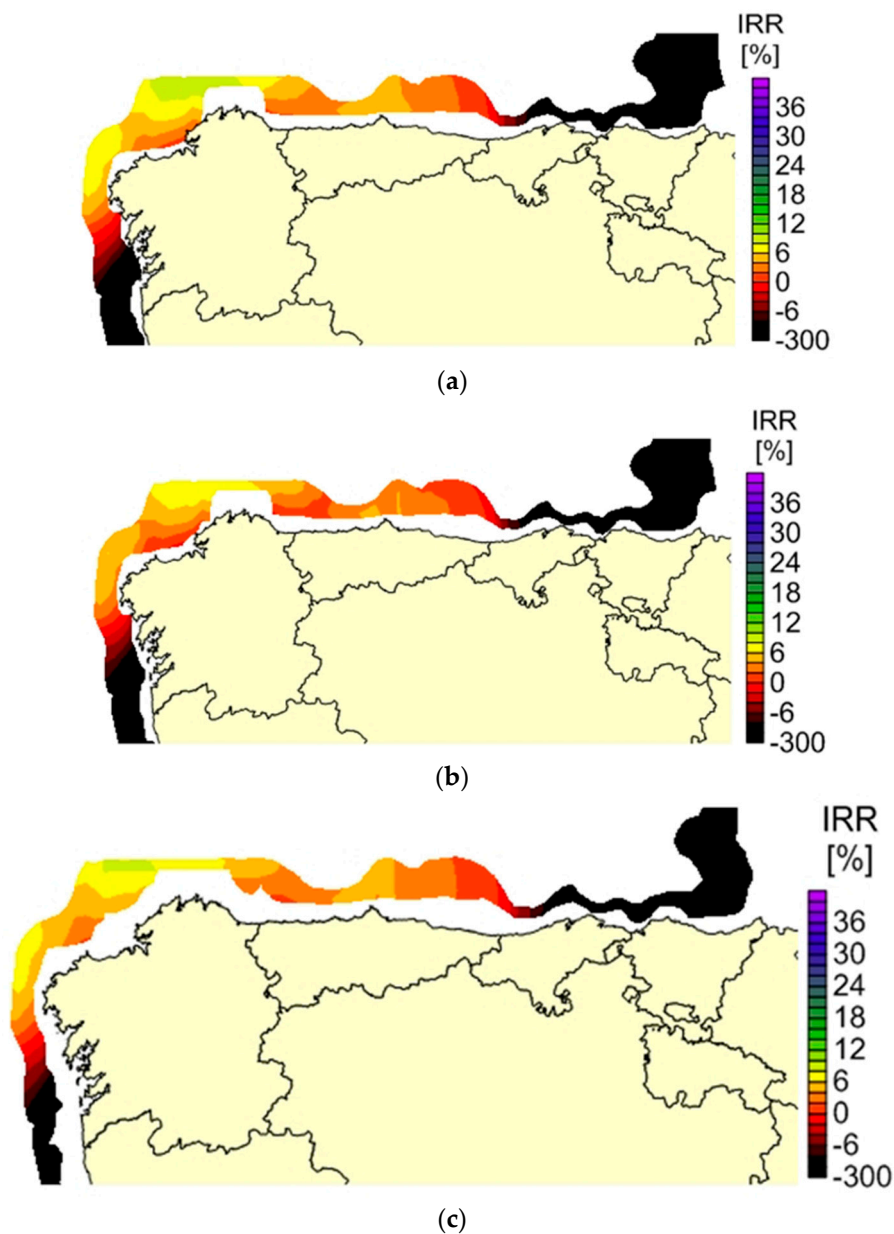
**Figure 12.** Results for internal rate of return (IRR) considering a tariff of 200 €/MWh and the bathymetry restriction for semisubmersible (**a**), tensioned leg platform (**b**), and spar (**c**).

The value for WACC depends on the location, because it changes depending on the total equity ($MV_e$) and the total debt ($MV_d$), which is then dependent on the life cycle costs of each location. In Scenario 3, values of WACC went from 6% to 7%. Therefore, in the last scenario, all the kinds of floating wind structures considered would be economically feasible. Regarding NPV, the best values for Scenario 3 varied from 71.40 M€ for the semisubmersible platform (Figure 13a), to 63.76 M€ for the spar platform (Figure 13c), and to 38.73 M€ for the TLP platform (Figure 13b). All these values have positive values and, so, the project is economically viable.
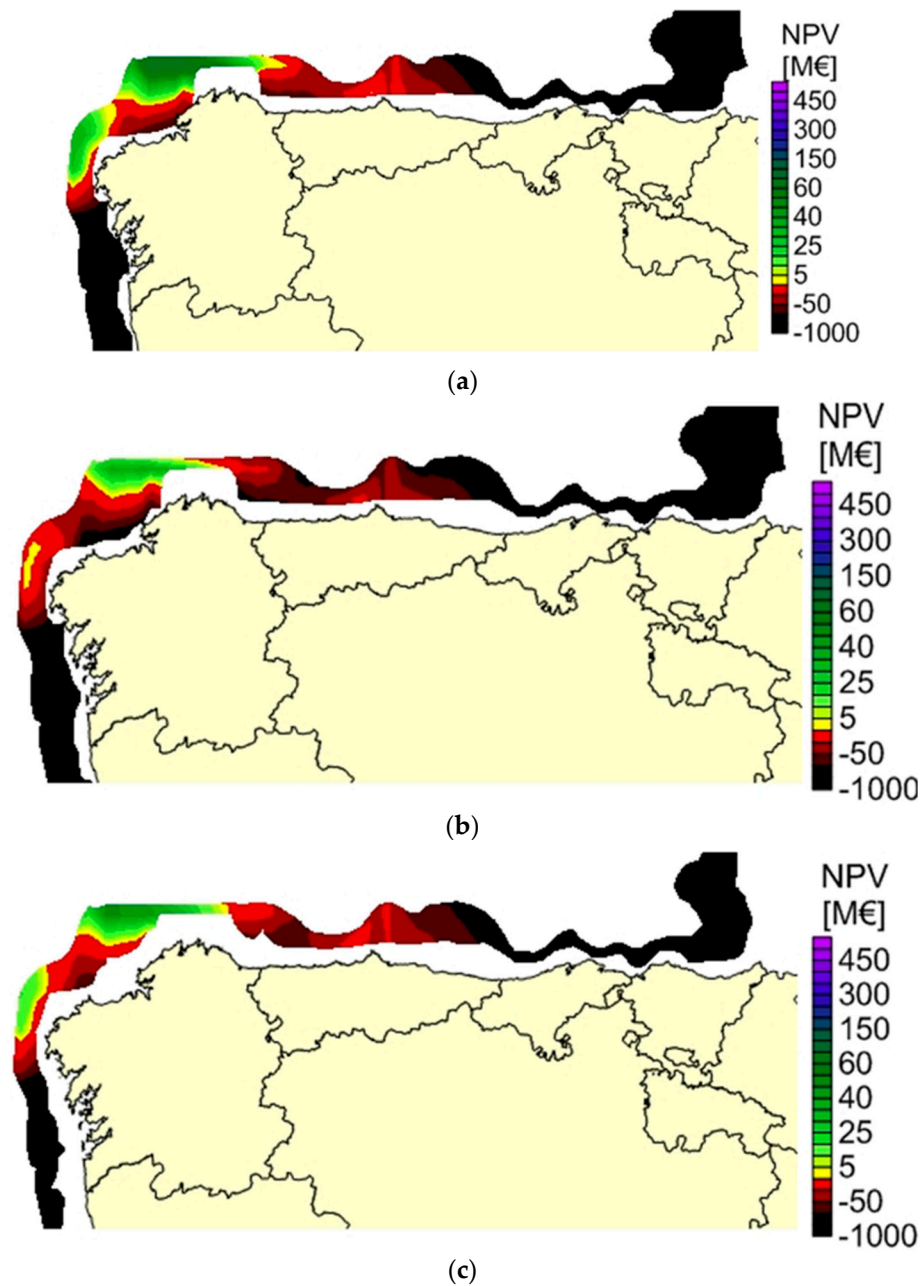
**Figure 13.** Results for net present value (NPV) considering a tariff of 200 €/MWh and the bathymetry restriction for semisubmersible (**a**), tensioned leg platform (**b**), and spar (**c**).

The best area is located close to Ferrol, A Coruña, in the Galicia region of the Northwest of Spain, as it can be seen in all the economic maps with restrictions. In addition, this area has a shipyard with enough technology and technicians to support this important construction. Therefore, it would be a good area to install this type of offshore technology in the future, when the reduction of costs and the stability of the electric tariff guarantee the confidence of investors.

## 5. Conclusions

This paper has established a procedure that allows us to calculate the economic feasibility of offshore wind farms in deep waters based on their economical parameters. In this sense, several economic parameters have been calculated, such as internal rate of return, net present value, and levelized cost of energy. The method proposed has several steps: geographic phase, economic phase,

and restrictions phase. In the geographic phase the input values, afterwards used in the economic phase, were calculated: the shape parameter of the offshore wind, the scale parameter of the offshore wind, the height and period of the waves, the bathymetry, the distance farm–shore, the distance farm–shipyard, and the distance farm–port. Then, the economic parameters were assessed considering the inputs provided in the previous phase. Finally, the restriction of bathymetry was added to the economic maps. In future studies, more restrictions can be added to the method proposed.

The case study focused on the Cantabric and Atlantic coasts of the North of Spain, locations of high wind potential. These regions have not been deeply and completely studied in economic terms regarding floating offshore wind. Therefore, this paper has been an opportunity to have an overview of the best regions for installing floating offshore wind farms in terms of their economic profitability.

Moreover, three floating offshore wind structures were considered: semisubmersible, tension leg, and spar, which are the more representative platforms of the floating offshore wind; and three scenarios for electric tariff were taken into account, due to the variability of the Spanish offshore wind tariff during recent years.

The study showed that the best value for LCOE was 172.81 €/MWh for the semisubmersible platform, followed by the spar platform (184.52 €/MWh), and the TLP platform (187.98 €/MWh). According to the IRR and the NPV, they only have feasible economic values for the case of an electric tariff of 200 €/MWh. Therefore, the present electric tariff in Spain for this type of technology is not enough to support the great investment done in this type of offshore wind farm.

Finally, the best area in economic terms is located close to Ferrol, A Coruña, in the Galicia area (Spain). This area has a shipyard with enough capacity and know-how to support the studied wind farm. Therefore, it would be a good area to install this type of offshore technology in the future, when the reduction of costs and the stability of the electric tariff guarantee the confidence of investors.

This study has a limitation regarding the restrictions considered (only bathymetry). More restrictions should be applied in future works (environmental protected areas, seismic fault lines, navigation areas, etc.) in order to know the detailed areas of where install a floating offshore wind farm.

Obviously, the method applied in this work can be used for other locations around the world in order to analyze the best economical areas where a floating offshore wind farm can be installed.

## References

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