ABSTRACT

The main objective of this project is to analyse the technical and economic feasibility of installing a large offshore wind farm (over 50 MW) on the coastline of Tarragona, taking as a reference the large offshore parks in the Nordic countries, as the *Middelgrunden* in Denmark.

Although being one of the European countries with European countries with the most on-land wind plants installed to date, Spain currently has no offshore wind farm in operation, and this has been one of the main reasons that have led to the undertaking of this project: to determine if installing an offshore wind farm at the Catalan coastline is feasible or not.

To achieve this goal this project has been divided into two parts: the first is the design of the offshore wind farm, taking into account all the existing regulations as well as several technical criteria to make better use of the wind resource.

Actually two power wind plants have been designed for two types of wind turbines to be installed. These two wind farms are compared simultaneously for all the economic aspects.

The second part provides an economic feasibility analysis of the facilities designed. This includes the determination of capital and maintenance costs of the park, as well as the determination of the revenues from the sale of the energy produced by both offshore wind farms. Along with these, a cost benefit analysis of the project is carried out. A sensitivity analysis for different parameters of the profitability analysis is also done at the end of the economic feasibility analysis.

Finally, this project has analysed how the changes in the law concerning economic compensation for the energy produced by the facilities of the special regime affect the profitability of an offshore wind project.

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1. Glossary

1.1. Acronyms and abbreviations

AEE	*Asociación Empresarial Eólica*
AEP	Annual Energy Production
AHT	Anchor Handling Tug
BOS	Balance of Station
CAPEX	Capital Expenditure
COE	Cost of Energy
DCF	Discounted Cash Flow
DFIG	Double Fed Inductor Generation
EBIT	Earnings Before Interest Taxes
EBITDA	Earnings Before Interest Taxes Depreciation and Amortization
EPC	Engineering, Procurement and Construction
EU	European Union
EWEA	European Wind Energy Agency
FPCG	Full Power Converter Generation
GDP	Gross Domestic Product
ICC	Initial Capital Cost
IPC	*Índice de Precios del Consumo*
IRR	Internal Rate of Return
LCOE	Levelised Cost of Energy
LRC	Levelised Replacement Cost
NPV	Net Present Value
OMIE	Operador del Mercado Ibérico de la Energía, Polo Español S. A
O&M	Operation and Maintenance
OWEC	Offshore Wind Energy Converter
PCF	Plant Capacity Factor
PPI	Producer Price Index
REP	Renewable Energy Projects
RET	Renewable Energy Technologies
WACC	Weighted Average Cost of Capital
WCP	Wind Capacity Factor

1.2. Definition of key terms for the understanding of the project

- **Amortization:** The amortization is an accounting term, based on the distribution process at the time of lasting value. The obligation to return a loan from a bank is a liability whose amount is reinstating several payments deferred over time. The amortization allocates a lump sum amount to different time periods, particularly for loans, including related interest or other finance charges.
- **Annual energy production:** Annual average energy production of a particular wind farm. The annual energy production is usually measured in MWh or GWh.
- **Availability:** The percentage of time that the particular wind farm, or wind turbine, is in an operational condition.
- **Betz limit:** The maximum theoretical power that can be captured by a wind turbine from the wind. It is equal to a 59.3% of the wind energy.
- **Depreciation:** There is very few difference between the concepts of amortization and depreciation, since the goal, methods and procedures of calculation are basically the same. The important difference to be noticed is the type of asset on which each concept is applied. While depreciation refers exclusively to fixed assets, amortization refers to intangible assets.
- **Discount rate:** The discount rate is a financial measure that is applied to determine the present value of a future payment. The discount rate takes into account the risk involved when investing. An investment with higher risk have a higher interest rate compared with low-risk investments.
- **Dispatchability:** This term is used in the electricity supply industry to describe how readily power generation is increased or decreased to follow changes in demand.
- **Economies of scale: T**he cost advantages that enterprises obtain due to size, output, or scale of operation, with cost per unit of output generally decreasing with increasing scale as fixed costs are spread out over more units of output.
- **Energetic mix:** The term energetic mix refers to the distribution, within a given geographical area, of the consumption of various energy sources (oil, natural gas, renewables, etc). The composition of the energetic mix of every country depends on the availability of usable resources or the possibility of importing them, the energy needs of the country and the economic, political and geographic context.
- **Energy curve:** is the total amount of energy a wind turbine produces over a range of annual average wind speeds, usually between 3 or 4 to 25 m/s.
- **Energy return on investment:** Defined as the ratio between the useful energy got out of a process against the energy needed for that process.

- **Greenhouse gas savings**: The amount of carbon dioxide that would have been released into the atmosphere by a fossil fuel fired power station had the particular wind farm not been generating power.
- **HVDC:** High voltage direct current is used to transmit large amounts of power over long distances; there are smaller power losses and the construction cost of a HVDC line is less than that of a more conventional high voltage alternating current line.
- **Interest Rate:** the interest rate is the price of money or pay stipulated above the stored value that an investor must receive per unit of time by the debtor as a result of having used their money during that time.
- **Internal Rate of Return (IRR):** The Internal Rate of Return is the discount rate at which the present value of all future cash flow is equal to the initial investment or, in other words the rate at which an investment breaks even.
- **IPC:** The Spanish CPI shows the evolution of the prices of a defined set of products and services purchased by households for consumption in Spain.
- **NPV:** The net present value (NPV) of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values (PVs) of the individual cash flows of the same entity.
- **Supply Chain (SC):** A collection of entities (suppliers of raw materials, production centers, distribution centers, products and consumers) linked by a flow of materials and information in opposite directions.
- **Swept area:** The circle through which the turbine blades rotate and the area of that circle.
- **Wind rose (or compass rose**): The wind rose is a graphic tool used by meteorologists to give a succinct view of how wind speed and direction are typically distributed at a particular location. Historically, wind roses were predecessors of the compass rose. Using a polar coordinate system of gridding, the frequency of winds over a long time period is plotted by wind direction, with color bands showing wind ranges. The directions of the rose with the longest spoke show the wind direction with the greatest frequency.

2. Foreword

2.1. Origin and background of the project

On Saturday July 13th of 2013, the Royal Decree Act 9/2013 was issued, taking urgent measures to ensure the financial stability of the electric power sector. This law substantially affects the remuneration of production facilities eligible economic regime primacy; among which wind power and seaward wind power are found.

Various industry associations and entities advocating for wind energy have since been taking action. Their aim is to make both the public and the government aware that these new regulations will bring negative implications for the sector. The most important impact is that the growth hitherto enjoyed by the industry will probably be reduced by the implementation of these legislation. However, the harshest critics argue that renewable energy projects should be economically competitive by themselves, without relying on bonuses or special rewards.

While other European countries, especially the Nordic, are promoting and investing in this type of sustainable energies, it is surprising that a region leading in wind power such as Spain would take on measures that compromise their development.
It is also baffling how, being one of the European countries with the most on-land wind plants installed to date, Spain currently has no offshore wind farm in operation.
It has to be mentioned, however, the initiation of the Zèfir Project, which expected to install a platform to test offshore wind power in front of Ametlla de Mar, in Tarragona. The rejection of the local population to the project and the lack of economic resources led to its dismissing.
It is for the above reasons that it was decided to study the technical and economic feasibility of installing a wind farm in the Catalan coast and see how these changes in regulation of renewable energy would affect such an offshore wind project.

2.2. Motivation

In recent years, various issues have arisen: sustainable development, the increase in electricity consumption or the goals of saving CO_2 set for 2020 by the Kyoto Protocol -which led more developed countries to invest in renewable energy. All of the previous have made clear the need to take action for the implementation of clean energies and to move towards more sustainable growth.

The close relationship the student has had with the company INSTRA Engineers Ltd. -a developer of onshore wind farms in Spain- through an internship, along with the respect for the environment through the use of ecology-friendly technologies, have been the two major motivational factors that have led to the undertaking of this research project.

3. Introduction

3.1. Project targets

The main objective of this project is to analyse the technical and economic feasibility of installing a large offshore wind farm (over 50 MW) on the coastline of Tarragona, taking as a reference the large offshore parks in the Nordic countries, as are the Horns Rev or Middelgrunden in Denmark. To achieve this goal this project has been divided into two parts: the first is the design of the wind farm, taking into account all the existing regulations as well as several technical criteria to make better use of the wind resource.

It is worth mentioning here that actually two power plants have been designed: one considering that the turbines installed are the SIEMENS model with a rated power of 3.6 MW; and the other considering installing Vestas model turbines, with a rated power of 3.3 MW. These two wind farms will be compared simultaneously for all calculations.

The second part will provide an economic feasibility analysis of the facilities designed. This includes the determination of capital and maintenance costs of the park, as well as the determination of the revenues from the sale of the energy produced by both offshore wind farms. Along with these, a cost benefit analysis of the project has been carried out. Finally, a sensitivity analysis for different parameters of profitability has been done.

Thus, it is intended to unite the technical estimations with the economic. Although the latter are often considered independent on the development of such a project, it has been seen in the previous section how they may be decisive for a project to be carried out or not.

Another major target of this project has been to analyse how the changes in the law concerning compensation for energy producers of the special regime affect the profitability of an offshore wind project.

3.1.1. Specific targets

In order to carry out these goals, the order of the steps in the development of a project of these characteristics should come in first. In addition, each of these stages seeks to achieve a number of secondary aims that contribute to the achievement of the main one.

After seeing the broader objectives of the project one can proceed to delve into the secondary targets, which have led to the achievement of the main objective. The points outlined below are the most important of these secondary targets.

In the first part, design and technical feasibility study:

- Determine the ideal location for the wind farm on the Catalan coast, taking into account the regulations and laws that limit certain marine areas
- Study the wind resource at the candidate site
- Determine the type of turbine to be installed.
- Choose the most suitable turbine locations, taking into account the wake factor for each type of park in order to make the most of the wind resource utilization.
- Determine the annual energy production of the wind farm, considering the wake factor losses, power losses and other losses.
- Establish how the energy produced by the wind farm is evacuated.

In the second part, the analysis of economic performance:

- Estimate the investment costs of the project for each component of the wind farm, plus installation and transport costs.
- Estimate the variable costs: operation and maintenance of the park, as well as administrative costs.
- Implement final breakdown of structure costs.
- Study the changes in the law establishing the remuneration for special regime energy, in which offshore wind is included.
- Define scenarios or possible study cases based on changes in the law of retribution of the energy sale.
- Estimate the retribution received by the sale of the energy produced by the wind farm in each of the three scenarios set.
- Determine the breakdown structure indicators, for the most influential variables in determining economic indicators.
- Determine the profitability of the investment to make the project is implemented, analyzing the following economic indicators: NPV (Net Present Value), IRR (Internal Rate of Return).
- Account for the most influential variables on costs and economic indicators, by performing a sensitivity analysis.

3.2. Project scope

Once the targets have been set, it is worth determining the scope of the technical and economic viability studies.
It is worth mentioning here that the study on the electric losses and cabling connections is beyond the scope of this project.
Due to the high number of variables to be considered, some of the decisions and data are

outsourced to an external consultant.

This external consultant is the student Ariadna Esteva, which has actively participated in and contributed to the realization of this project.

Details of work done by the external consultant are presented in ANNEX I. Outsourced work-list in the external consultant, which could be summarized in the provision of information about anything concerning the wind turbines to be installed in the offshore wind farm.

4. Wind power technology

4.1. Introduction

Since early recorded history, people have harnessed the energy of the wind in a number of different applications, such as water pumping with simple windmills in China by 200 B.C., energy propelling boats along the Nile River earlier before or corn grinding with vertical-axis windmills in the Middle East.

More recently, these uses have spread into more technologically advanced purposes, in which electricity obtaining is included.

The progress made in the polymer materials field, combined with a better understanding of aerodynamics has led to the return of electricity extraction from wind in the latter half of the 20th century. As a result of the concern of the global warming effects, most energy policies are being regulated by environmental criteria and renewables are entering the energy market with increasing strength.

The European Council has set the goal of achieving a 20% share of renewable energy in the total energy consumption in the European Union in 2020, in which wind power is expected to play an important role.

4.1.1. Installed capacities and international scenarios

The SBC Energy Institute **[1]** has recently confirmed that, within the past fifteen years the global wind power installed capacity has increased from 1.7 GW in 1990 to pass the 350 GW today. At the end of 2012 a global capacity of 282 GW in wind power was registered with an average increase of 24% a year for the last 10 years.

Europe -especially Spain, Germany and northern European countries- has been leading this potential growth and being the main market for wind until recent dates, but China and the US have overtaken Spain and Germany as the drivers of the market growth, reaching until 29% of capacity additions in 2012 each. Nowadays, China is the world's biggest market with a 26.7% share of cumulative capacity. China installed the most wind turbine towers in 2013, dominating the global market share with 47.4 percent. The USA came in second with 7.5 percent, followed by India and Canada with shares of 6.5 percent and 5.8 percent, respectively.

4.1.1.1. <u>The role of offshore wind power in Europe</u>

According to a report from the European Wind Energy Association (EWEA) **[2]**, in the European Union-28, a total amount of 117 GW (110.7 GW onshore and 6.6 GW offshore) is now installed, which means a growth of 10% on the previous year. The UK, followed by Spain, Germany, Denmark, Italy and France are the countries with the largest installed capacity. Furthermore, 8 countries in the European Union (Denmark, France, Germany, Italy, Portugal, Spain, Sweden and United Kingdom), have more than 4 GW of installed wind energy capacity.

While onshore technology has been the cutting edge of the wind power growth, accounting up to 98.1% of global capacity and has largely proved to be competitive, offshore wind energy has still a large way to improve its benefits, which will basically depend on the investment cost reductions and a secure regulatory framework for the investors.

According to the EWEA annual statistics report, 418 new offshore wind turbines were fully grid connected in 2013, totaling 1567 MW, a share of 34% more than in 2012. The following graph shows the amount of MW installed of new offshore wind power capacity connected to the grid in Europe in 2013.

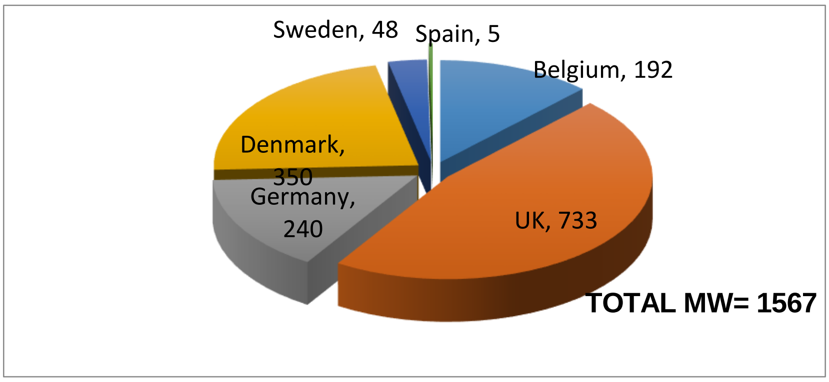


Figure 4.1. MW connected to the grid in Europe per country (in 2013). Source: Author from the European Wind Energy Agency (EWEA)

Of the total 1567 MW installed in Europe waters, 72% were located in the North Sea, 22%in the Baltic Sea and the rest in the Atlantic Ocean.

During 2013, 7 large-scale offshore wind farms were completed in Europe and 3 demonstration projects went online, while in other 8 wind farms work has started but no turbines are yet connected. The following graphs show the number of turbines fully connected to the grid in Europe in 2013 per country **[3].**

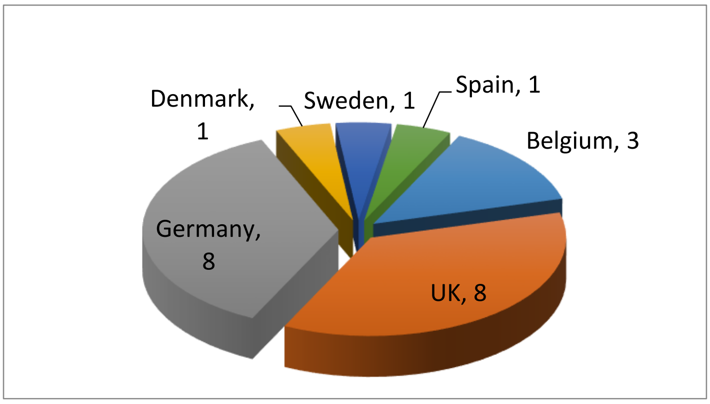


Figure 4.2. No. of offshore wind farms connected to the grid in Europe per country (in 2013). Source: Author with data from the European Wind Energy Agency (EWEA)

Offshore accounted for almost 14% of total EU wind power installations in 2013, further confirming the high level of concentration in annual installations during 2013 **[2]**.

4.1.1.2. A review on the cumulative offshore market

After an insight in terms of global capacity installations in the last year, a resume on the offshore capacity installations done until today in Europe should be done.

Estimations done by EWEA show that in Europe, UK has the largest amount of installed offshore wind capacity (a share of 56% of all installations, which accounts for 3681 MW), only followed by Denmark (19% share and 1271 MW installed). Belgium ranks third with 571 MW (8.7% of total European installations), followed by Germany (520 MW: 8%), the Netherlands (247 MW), Sweden (212 MW), Finland (26 MW), Ireland (25 MW), Norway (2.3 MW), Spain (5 MW) and Portugal (2 MW). All together account the rest (a total of 17% share).

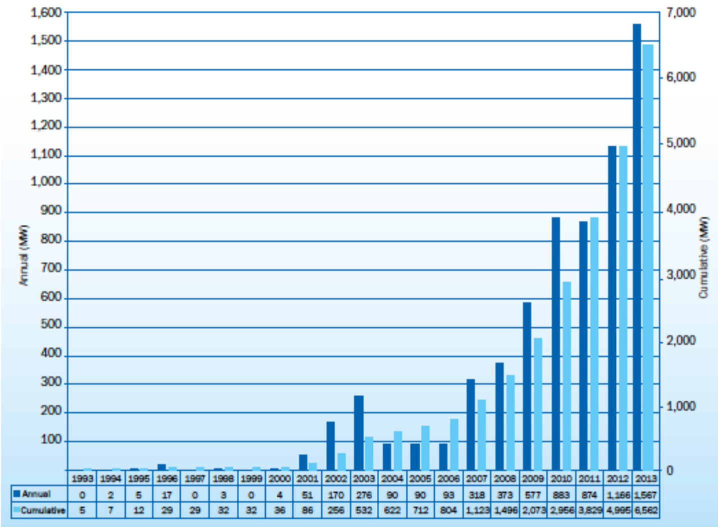


Figure 4.3. Cumulative and annual offshore wind installations (MW). Source: EWEA

Same statistics can be done in terms of number of turbines installed and number of operation offshore farms, as it can be seen in the graph below.

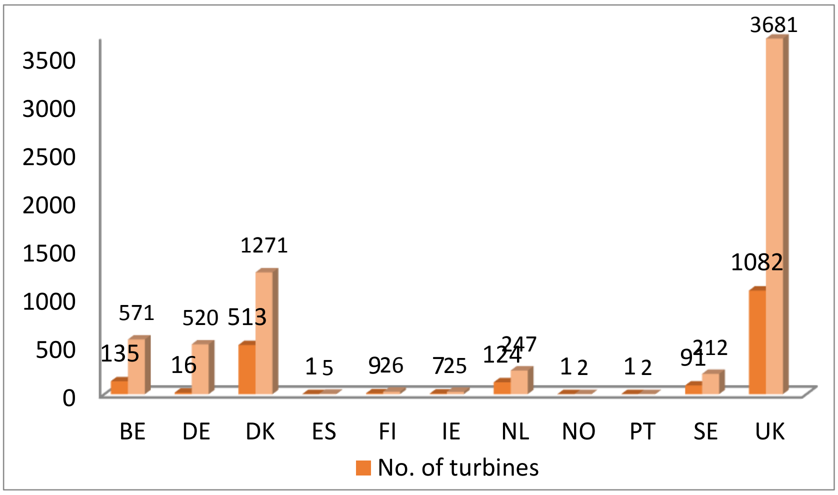


Figure 4.4. Total No. of offshore wind turbines and MW installed per country in Europe (at the end of 2013). Source: Author with data from the EWEA.

Once completed, the 12 offshore projects currently under construction will increase installed capacity by a further 3 GW, bringing cumulative capacity in Europe to more than 11 GW **[4]**. The following graph shows the number of offshore wind farms currently operating in Europe per country (BE: Belgium, DE: Deustchland, DK: Denmark, ES: Spain, FI: Finland, IE: Ireland, NO: Norway, PT: Portugal, SE: Serbia and UK: United Kingdom).

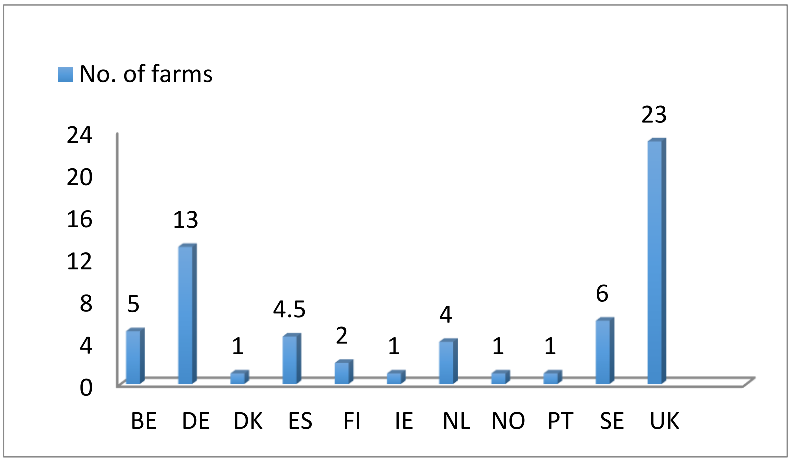


Figure 4.5. Number offshore wind farms operating in Europe (at the end of 2013). Source: Author with data from the EWEA.

4.2. Future growth and trends

Despite the fact that wind capacity has spread worldwide over the last three decades, wind energy is has still a long way to go to reach the installed power of other energy form facilities.

However, if we focus on wind power capacity additions, it can be observed that no other renewables have experienced such an exponential growth.

In terms of annual installations, annual wind power installations in the EU have increased steadily over the past 13 years from 3.2 GW in 2000 to 11 GW in 2013, a compound annual growth rate of over 10% **[2]**.

Thus, this growth is yet expected to continue, reaching a total installed capacity of about 500 GW worldwide by 2017 and more than 688 GW in 2020, according to a report of the EWEA. By 2020, a total amount of more than 180 GW of wind power (including onshore and offshore farms) could be installed only in the European Union. That would stand for up to the 15% of the total EU electricity demand **[3]** and **[5].**

Having seen that, it is easy to deduct that wind energy is called to play a crucial role in the future energy supply of the European Union and of the world **[1]**.

TECHNICAL FEASIBILITY ANALYSIS OF AN OFFSHORE WIND FARM AT THE CATALAN COASTLINE

ETSEIB

5. Standards and regulations

One of the requirements that a wind farm needs to meet in order to be installed on the Catalan coastline is the compliance of the state, autonomic and regional regulations, both financial and environmental regulations.

5.1. Financial regulations

The fundamental rule that has governed and regulated the aspects related to the economic issues of the sale of the energy has been the Law 'Ley del Sector Eléctrico' 54/1997 of 27th November, which included in its title IV a chapter devoted to the *special regime* electricity production, consisting on the settlement of specific rules applied to electricity generated by renewable energy sources. Among this special regime, the offshore wind energy was included.

Later on, the Royal Decree RD 661/2007 of May 25th, on the activity and remuneration of electricity production in the special regime was approved, followed by the RD-Law 1028/2007, which established the administrative procedure of the processing applications for approval of power generation facilities in the territorial sea. These two regulations have been contemplated in Scenario I, as it will be explained in section 11.

This Royal Decrees were lately amended by RD 1614/2010 and RD 1565/2010, which changed and implemented modifications and actualizations for the bonus rates. In 2010, a bonus system or 'feed in tariff' was used, consisting of a grant on the generated electricity by the producing companies to the grid. These two regulations have been implemented with the corresponding actualizations for the bonus rates in 2011 when calculating the revenues of the sale of the electricity in Scenario II.

These actualizations were regulated via the ITC's, the Ministerial Orders which regulated and reviewed the tolls access, tariffs and bonus rates for the technologies of the *special regime*. On example of this could be the ITC 3519/2009.

5.1.1. The energetic reform in 2013: the Law on the Electric Industry 24/2013

The Royal Decrees commented before have been in effect with their corresponding actualizations, until the approval of the Law on the Electric Sector 'Ley del Sector Eléctrico' 24/2013 of July 13th, in which urgent measures are taken to ensure the financial stability of the power system, which substantially affects the remuneration of the production facilities entitled to bonus economic regime. This Law is predicted to have important impact on the development of the renewable energies.

The Electric Industry Law regulates, among others, 'the economic and financial sustainability of the electricity system' and the article Nr. 13 stipulates that the system revenues will be sufficient to meet the full costs of the electricity system.

According to the new Law 24/2013 of the Electric Industry **[6]**, only the Government may only exceptionally approve specific remuneration for production facilities from renewable technologies and this will be based on the necessary participation on the market share of these facilities, supplementing the income of the regulated market remuneration until reaching the minimum level necessary to cover the costs that can not be recovered by the market, to obtain an adequate return with reference to a standard installation, efficient and well managed.
The aim of this new remuneration system is that the renewable energy systems can compete in the market in terms of equal conditions with other technologies. The goal, as the Industry Minister Jose Manuel Soria stated in the press conference after the Council of Ministers on July 6th, is to modify a previous model that "had gone straight to a bankruptcy system."

This new repealing law appeared first in July 13th, 2013. However, in July 2013 the renewables energy producers would not know how this regulation would be carried out and it was not until June 6th, 2014 that the Government published a new Royal Decree stating the basis of these revenues.

In the scope of the standard all renewable, cogeneration and waste facilities are included regardless of their installed capacity. Therefore, it removes the previous separation between the special regime and the ordinary regime.
Only those facilities for which the market price is not sufficient to achieve reasonable return linked to the risk level of the activity and with reference to a well-managed company will receive regulated remuneration, so called 'specific remuneration'. The new compensating measures will apply to both existing facilities and new facilities to be installed in the future.
The main novelty is that the purely variable remuneration that has been used to date (bonus and regulated tariffs) is abandoned, and replaced for a similar scheme for other activities that more accurately reflects the actual cost structure of the activity, as the Government states.
The legislation also establishes the conditions for reviewing the different compensation parameters. These may only be amended, if appropriate, every six years, every three or annually, depending on each case. The standard value of the initial investment and the regulatory life will remain unchanged once recognized each type of installation.

As a summary, the Decree states that facilities may charge for their regulatory useful life, apart from the market price, a specific reward per unit of power to cover their investment costs, but this fact leaves some offshore wind farms without incentives.

Finally, the Law 15/2012, of 27th December on fiscal sustainability for energy, creates "the tax value of production of electrical energy" (IVPEE) as a direct tribute.
Beyond the national legislation, the 2009/28/EC Directive sets the basis for promoting the use of renewable sources and the Directive 2009/72/EC discusses on common rules for the internal

electricity market and other European mandatory standards.

5.2. Geographic and placement regulations

Referring to the geographic standards and permits regulations that have been taken into account while developing this project, the report '*Estudio Estratégico Ambiental del Litoral Español para la instalación de parques eólicos marinos'* **[7]** elaborated by the Ministerio de industria, Turismo y Comercio in 2009 has been taken as a reference when considering possible emplacement locations for the offshore wind farm in the Catalan coastline.

The report outlines the zones that are suitable to install an offshore wind farm and takes into account the coastal fishing areas and the zones which could harm the local fauna.

The report does not considerate the evacuation of the electricity of the offshore wind farm with underwater cables onto the grid, and its effects on the environment would need to be discussed during the environmental assessment procedure for each project due to the fact that multiple alternative paths and local impacts should be considered.

6. Wind turbine election

One of the most important parameters, if not the most, to be set during the design of an offshore wind farm is the choice of the wind turbine. This election has been conducted by an external assessor, who has compared the energy produced by each type of wind turbines considered at a same candidate location.

The study carried out by the external assessor started from 4 turbine models, including those featuring Vestas, Siemens, Gamesa and BART manufacturers. It has to be mentioned that other smaller wind turbine manufacturers would also be considered if a competitive price for their production could be negotiated. However, due to the large investment needed, only expert manufacturers have been taken into account when considering wind turbine models. It should be noticed that, depending on the wind turbine manufacturer, these turbines would need to be transported from the manufacture's origin country. This will be considered in section 10.1.3. Transport and installation costs.

Finally, the wind turbines models chosen are: the wind turbine SWT-3.6-120 from SIEMENS and the model VT105-3.3 from the VESTAS manufacturer.

The most important characteristics for the design of the offshore wind farm are shown in the table below:

Model Manufacturer	MODEL 1 SWT- 3.6-120 Siemens	MODEL 2 V105 - 3.3 MW Vestas
Maximum power output per turbine (MW)	**3.6**	**3.3**
Total power (MW)	64.8	59.4
Cut-in wind speed	3-5 m/s	3 m/s
Cut-out wind speed	25 m/s	25 m/s
Standard operating temperature range		From -20ºC to +45ºC
Hub height	site specific	80 m
Rotor diameter	120 m	105 m
Swept area	11300 m^2	8659 m^2
Blade length	58.5 m	58.5 m
ELECTRICAL		
Frequency	50/60 Hz	50/60 Hz
Density	1.12 kg/m^3	1.12 1.12 kg/m^3
Regulation	PITCH	PITCH
Rotor speed	variable	variable

Table 6.1. Selected wind turbines characteristics. Source: External assessor

7. Wind farm siting

In the context of the Degree Thesis, the feasibility analysis of an offshore wind farm has been taken as the main subject to study. To this end, some mid steps have to be taken into account in order to ensure the accuracy of the calculations.
The first step would include a research on the optimum site where to locate the offshore wind farm. This analysis includes a deep research on the potential wind resources at the sea location. A characterization of the wind conditions has to be made in this section.

Two other main parameters are key factors here: the distance to the shore and the water depth at the supposed location. Both are of vital importance for its influence on the foundations of the turbines, which represent a high percentage on the initial capital costs. E.g if the wind farm is situated too far from the shore, the cost of the installation of the cables are higher and if the water depth is too big, the foundations of the turbines will rise the installation costs dramatically, thus the Project not being viable.

After taking into account the technical aspects, environmental and social issues such as visual and sound impacts need to be also considered when deciding the potential location of an offshore wind farm.

7.1. Determinant factors

Three determinant factors need to be taken economically into account when considering possible locations for an offshore wind farm:

- The water depth at the candidate location
- The amount of energy produced, which is related to the wind resource at the candidate emplacement and,
- The proximity to an onshore sub-station if, as it is our case, the wind farm is close enough to the coastline.

Some of this information has been provided by an external assessor. The first parameter has been taken as an external input in this project and is briefly described. The others are explained in this chapter in a more extensive way.

7.2. Candidate sub-stations to host the *off-take* power of the wind farm

In order to reduce cable installation and electric transport costs, as well as to diminish operation and maintenance costs, the optimum wind farm location is as near to the transformer sub-station as possible. In some cases, when the wind resource is better at a long distance from the shore or where a huge visual impact is not well considered by the population and the wind farm needs to be placed far from the coast, a sub-station is built offshore, near to the wind turbines.

However, due to good wind resources near to the coastline in this project, it has been decided to use an existing onshore sub-station. This decision will thoroughly be explained in section *9.1.3. Electrical Infrastructure Costs*.

With this purpose, some sub-station have been analysed by consulting '*Mapa del transporte ibérico 2014' (see ANNEX II)*, elaborated by '*Red Eléctrica de España'*, a shipping company that values the technical and economic process of connecting new installations to the grid (according to regulatory requirements and plans of development of the electrical system).

In this chapter, special attention has been driven to detect the adequate sub-stations, which is to say, the Catalan sub-stations that are close enough to a good offshore wind resource.

Therefore, the sub-stations selected are necessarily close to the Mediterranean coastline and able to absorb the energy produced for an offshore wind farm with the aforementioned characteristics.

The candidate 220 kV sub-stations are, from North to South: Llançà, Torre del Vent, Bellcaire, Palafrugell, Vall Llòbrega, Castell d'Aro, Lloret, Calella, Iluro, Mataró, Santa Coloma de Gramenet, El Prat, Foix, Altafulla, Tarragona, Cambrils, Plana del Vent I Vandellós.

The company *Red Eléctrica de España* has conducted an analysis on the possible enlargement of the existing sub-stations in the peninsular electric system, detailing where it is not possible to connect new positions. This analysis considers both new installation connections and the planning of new network developments, respecting the safety criteria established by supply and operating procedures.

From the sub-stations mentioned before, none of them is likely to be declared not expandable. Although the list of non-extensible sub-stations can be modified in the next years, it is assumed that all of them can hold and absorb the energy produced by the wind farm.

This information has been supplied to an external assessor, which superimposing this information with optimum water depth and wind resource criteria, has determined the most suitable site for erecting the offshore wind farm. Finally, the onshore substation in Tarragona has been chosen with the wind resource criteria as a crucial factor on this decision. This decision will be explained in the following section. It has to be mentioned here that the Tarragona onshore transformer substation is 4 km far from the coastline according to the information provided by the external assessor, as shown in Figure 7.1.:

Figure 7.1. Location of the Tarragona transformer substation and approximate distance to the coastline. Source: External assessor.

7.3. Water depth at the candidate sea location

The experience of offshore wind farms in Spain is extremely limited as there are only a few experimental stations and projects that have not finally run into operation. Countries experienced in offshore wind technology are the Nordic countries, where the seabed is less profound than the seabed in the Mediterranean Sea.

According to the EWEA, the installation costs of a wind farm increases significantly with the depth of the seabed and the distance to the shore, being the limit for the viability of a project 60 m depth of the seabed. There is a margin for the viability referring the distance to the shore.
This limit is due to the offshore foundations technology, which has improved a lot since recent years but it is still developing as the needs for offshore wind farm installations increase. Meanwhile, in this project marine seabed areas with more than 60 m depth seabed are considered not suitable for installing the offshore wind farm.

The external assessor of this project has analyzed the water depth in front of the Tarragona coastline from marine charts from "*El instituto hidrográfico de la marina*", and has finally determined that the sea depth at the candidate site locations accounts for values between 40 and 60 m.

Thus, thanks to the external assessor, it has been confirmed that the candidate site location is suitable in terms of the depth of the seabed.

7.4. Wind power resource and candidate site wind conditions

Although being one of the most important researches to be hosted in a study of the possible candidate locations for erecting an offshore wind farm, the wind resource assessment is explained after the water depth at the candidate site and the possible substations to host the power parameters. In order to make an accurate characterization of the wind energy resource, companies run heavy investments in prospecting potential wind sites. This includes getting a series of measurements of wind speeds for one or several consecutive years at a certain height and position for different candidate sites.

After performing this analysis, the external consultant responsible for developing this study has determined that the Tarragona coastline is particularly suitable for erecting an offshore wind farm due to good wind resource at this area.

Specifically, this external assessor has provided the main area in which the offshore wind farm should be hosted, with the UTM coordinates that enclose this area, which is shown below:

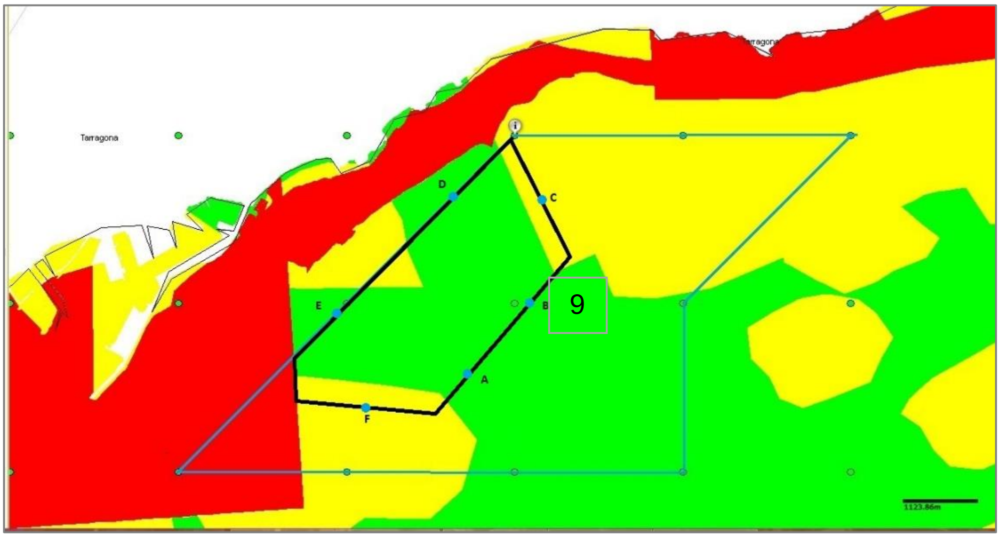


Figure 7.2. Area in which the wind farm will be installed. Source: External assessor

Table 7.1. UTM coordinates for the nodes that comprise the area in which the offshore wind farm will be installed at the sea. Source: External assessor

NODE	UTM X	UTM Y
A	860449	4557166
B	861549	4558466
C	859749	4559666
D	859849	4560166
E	857749	4557866
F	858549	4557166
9	860950	4558266

ETSEIB

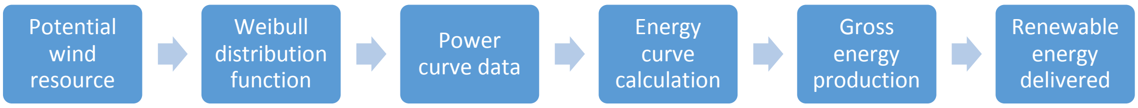
The development method to study the wind resource at the selected location is described in the following sections.

7.4.1. Wind energy produced. Development of the calculation method and analysis of the results

Once the two possible turbine models have been chosen by our external assessor, a summary of the methodology used to calculate an approximation of the energy produced by a single wind turbine to be installed at the candidate site location is done in this chapter. This section also aims to explain the calculation methodology that has been followed until the achievement of the results.

7.4.1.1. Algorithms and calculations

The following flowcharts shows the steps that have been followed in order to calculate the approximate energy production of node Nr. 9, which has been taken as a reference.



Scheme 7.1. Flowchart representing the methodology used to calculate the energy delivered to the grid by the offshore wind farm. Source: Author.

The **energy curve** is the total amount of energy a wind turbine produces over a range of annual average wind speeds, usually between 3 or 4 to 25 m/s.
With the energy curve provided by the power curve and the wind resource data the total annual energy produced by the wind energy equipment, before any losses at atmospheric conditions has to be calculated. This is called **Gross energy production**.
Finally, the **renewable energy delivered** to the grid can be estimated taking into account the losses that the wind system has. This last calculation will be done with more accuracy in Section 8, in which wake and electric losses are considered.

7.4.1.2. Potential wind resource

7.4.1.2.1 *Resource assessment & Site reference conditions*

Before evaluating the energy performance of a wind energy system, some values are taken as input parameters to help characterizing a wind energy system.
The following parameters represent the summary conditions needed to be taken into account, and can be analyzed by doing extensive measurements on the potential site. Note that these values are taken at node Nr. 9 (see Figure 7.2.), which has been taken as a reference for the wind farm location.

Input parameters	Value	Units
Node number	9	
Latitude (UTM X)	860950	
Longitude (UTM Y)	4558266	
Elevation	80	m

Table 7.2. Location parameters for node Nr. 9 at the candidate site. Source: Author.

Input parameters	Value	Units
Air temperature	18.5	ºC
Wind speed	5,52	m/s
Measured at	80	m
Weibull k	1.659	
Weibull C	6.23	m/s

Table 7.3. Wind resource parameters for node Nr.9 at the candidate site. Source: Author.

Having analysed the main parameters needed for the wind resource assessment, one can proceed on calculating the weibull distribution function; which, with the power output curve of the wind turbines, will allow to determine the amount of energy produced by the wind system.

7.4.1.2.2 *Wind speed distribution: the Weibull function*

When calculating the wind-power potential of a certain location, it is important to take into account not only the average wind speed of that region but also the wind-speed frequency distribution.
The wind speed distribution is commonly calculated as a Weibull probability density function, which is the distribution of the proportion of time (usually measured in hours) spent by the wind within narrow bands of wind speed. This statistic tool enables Project Managers and investors observe the long-term distribution of mean wind speeds for a range of sites, thus selecting the ones that have the best wind speed performance.

It is very important for the wind industry to be able to make a model on the variation of the wind speed, given that wind turbine manufacturers can calculate with a highest degree of accuracy the energy produced by the turbines and consequently, the estimated retribution for the sale of the energy, in addition to be able to design turbines that better adapt to the disposal wind resource.
A good wind resource contemplates that the wind speed during a year should be soft and constant during the year, and that strong gales are punctual and rare.
The following expression, the Weibull probability function, express the probability $p(v)$ to have a wind speed v during the year:

$$p(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \cdot e^{-\left(\frac{v}{c}\right)^{k}} \qquad (1)$$

Where each parameter is defined as follows:

$p(v)$ Weibull density probability function

v Vector of wind speeds, usually at 1 m/s intervals

c Scale factor (m/s), indicates how windily strong is the potential site

k Shape factor, typically ranging from 1 to 3. It characterizes the asymmetry or bias of the probability function.

The Rayleigh wind speed distribution, which is a case of the Weibull distribution function with a shape factor *k=2*, is also used in some cases.

Figure 7.3. shows the wind speed distribution at Node Nr. 9 (k=1.659 and c=6.23 m/s):

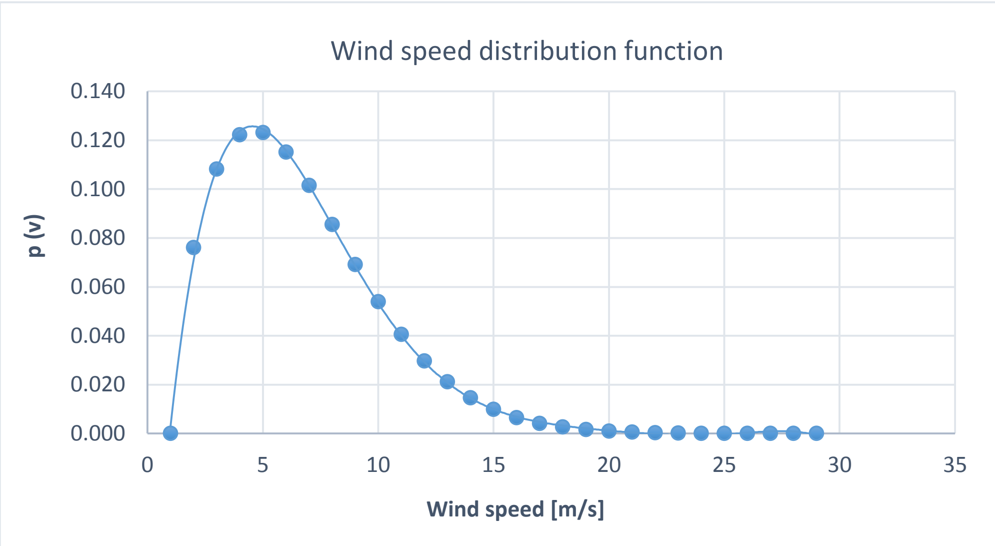


Figure 7.3. Weibull probability function of the wind speed distrbution at node Nr. 9. Source: Author.

The Weibull probability function can be used to calculate the number of hours at which the wind will be blowing at each wind speed in a year, by doing the product between the total number of hours of a year with the probability at each wind speed, as shown below:

$$Number\ of\ hours = 8760 \cdot \sum_{v=0}^{25} p(v) \qquad (2)$$

This can also be represented with an histogram at node Nr. 9, as it can be seen in Figure 7.4.:

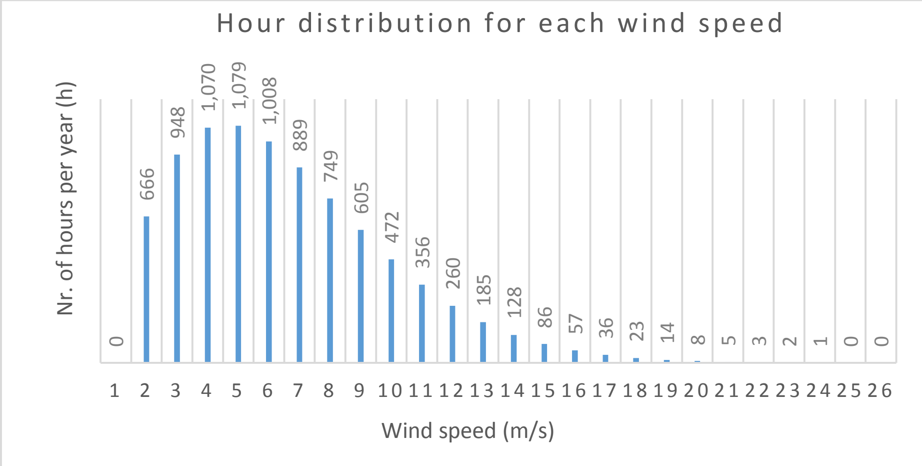


Figure 7.4. Hours distribution at each wind speed for node Nr. 9. Source: author

The Weibull distribution function is valid for the two selected wind turbines, VESTAS 3.3 MW and SIEMENS 3.6 MW given that it only depends on the wind resource and not on the wind turbine characteristics.

Another aspect to be considered in this chapter is the wind speed at hub height. As the wind speed at hub height is usually higher than wind speed measured at the anemometer height, there is an empirical expression that relates the average wind speed with different measurement heights. This expression uses the shear exponent and a power law equation to calculate the average wind speed at hub height:

$$\frac{v'}{v_0} = \left(\frac{\mathrm{H}'}{H_0}\right)^{\alpha} \qquad (3)$$

Where,

v' is the average wind speed at hub height H

v_0 is the average wind speed at anemometer height H_0 and,

$\propto$ is the wind shear exponent. The shear exponent is the rate of increase of wind strength with unit increase in height above ground level **[8].**

In our case, as the wind speed data has been measured at 80 m height -the height at which the rotor will be situated- there is no need to use the conversion of the wind speed with the shear exponent.

7.4.1.3. <u>Average energy produced per year</u>

The energy curve data is the total amount of energy a wind turbine produces over a range of annual average wind speeds. Usually this curve is specified over the range of 3 or 4 m/s to 24 m/s annual average wind speeds and it directly depends on the wind turbine power curve data as a function of wind speed in usually increments of 1 m/s, from 0 m/s to 25 m/s.

To obtain the energy curve data, it is essential that wind farm designers specify the characteristics of the wind turbines, specifically, the power curve data.

7.4.1.3.1 *The power output curve*

The power curve data depends on the wind speed density distribution in usually increments of 1 m/s from 0 to 25 m/s. It is usually provided by wind turbines manufacturers, although the theoretic power delivered by the turbines can be calculated by using the expression below:

$$P_v = \frac{1}{2}\,\rho\, C_p\, A\, v^3 \qquad (4)$$

Where each parameter is described below:

P_v Power output data, in kW

ρ Air density at hub height, in kg/m^3

C_p Capacity factor

A Rotor swept area and, in m^2

v Wind speed at hub height (80 m), in m/s

It can be seen here the importance of the right choice of the wind turbine that the wind farm will employ. A bigger rotor diameter implies a major swept area, thus being the power output higher. However, it also means that the investment costs rise and investors and Project developers always seek balance between the two concepts.

7.4.1.3.2 *The energy curve*

What it has been seek with the previous calculations is to reach the amount of energy produced by a single wind turbine at the candidate site in a year. This is determined by the energy curve, which is the product between the Weibull distribution function, p(v) -which gives the probability that a certain wind speed blows-, the power that each turbine delivers when the wind blows at a certain speed and the 8760 hours there are in a year. This provides the MWh/year a wind turbine generates.

The energy curve is calculated through:

$$E_{\bar{\upsilon}} = 8760 \sum_{v=0}^{25} P_v\, p(v) \qquad (5)$$

Where,

$E_{\bar{\upsilon}}$ Represents each point on the energy curve [kWh or MWh]

P_v Turbine power at a certain wind speed v [kW or MW]

$p(v)$ Weibull probability density function for wind speed v, calculated for an average wind speed $\bar{\upsilon}$.

Table 7.4. attached below, shows the power curve data, the wind distribution in hours/year ant the energy curve data at node Nr. 9 for the two pre-selected wind turbines: VESTAS 3.3 MW and SIEMENS 3.6 MW.

It must be considered, when looking at the data below, that this energy is only an approximation of what a single wind turbine will really deliver to the grid; no losses have been taken into account.

Wind speed [m/s]	Power curve SIEMENS [kW]	Power curve VESTAS [kW]	Wind distribution with SIEMENS [hr/yr]	Wind distribution with VESTAS [hr/yr]	[MWh/yr] SIEMENS	[MWh/yr] VESTAS
0	0.0	0.0	0	0	0	0
1	0.0	0.0	666	666	0	0
2	0.0	0.0	948	948	0	0
3	80.3	61.5	1,070	1,070	86	66
4	190.3	145.9	1,079	1,079	205	157
5	371.8	284.9	1,008	1,008	375	287
6	642.4	492.3	889	889	571	438
7	1,020.1	781.7	749	749	764	585
8	1,522.8	1,166.9	605	605	921	706
9	2,168.2	1,661.4	472	472	1,023	784
10	2,974.2	2,279.0	356	356	1,058	811
11	3,600.0	3,033.4	260	260	937	789
12	3,600.0	3,300.0	185	185	666	610
13	3,600.0	3,300.0	128	128	460	422
14	3,600.0	3,300.0	86	86	310	285
15	3,600.0	3,300.0	57	57	204	187
16	3,600.0	3,300.0	36	36	131	120
17	3,600.0	3,300.0	23	23	82	75
18	3,600.0	3,300.0	14	14	50	46
19	3,600.0	3,300.0	8	8	30	28
20	3,600.0	3,300.0	5	5	18	16
21	3,600.0	3,300.0	3	3	10	9
22	3,600.0	3,300.0	2	2	6	5
23	3,600.0	3,300.0	1	1	3	3
24	3,600.0	3,300.0	0	0	2	2
25	3,600.0	3,300.0	0	0	1	1
26	0.0	0.0	0	0	0	0
27	0.0	0.0	0	0	0	0
28	0.0	0.0	0	0	0	0
				Wind energy production per turbine (MWh/yr)	**7,914.12**	**6,432.87**

Table 7.4. Average wind energy produced per turbine (before losses) at node Nr. 9. Source: Author

As it can be seen in Table 7.4, the turbine SIEMENS 3.6 produces relatively more energy in a year (7,914.12 MWh) than the turbine manufactured by VESTAS (6,432.87 MWh). This is due to its higher nominal power. In the next chapter, a balance between the energy produced (and sold) and the increment of the price of turbines with its nominal power will have to be done. It has to be taken into account that these values do not consider any kind of losses.

7.4.1.3.3 *Hours of utilization*

The energy produced by a wind turbine can also be converted to the number of hours of utilization, which is the quotient between the energy produced (MWh) and the nominal power of the wind turbine.

In the case of the turbine provided by SIEMENS, this quotient is of 3593.6 hours of utilization, while in the turbine provided by VESTAS, 3278.48 hours of utilization are obtained at node Nr. 9.

	SIEMENS 3.6 MW	**VESTAS 3.3 MW**
Average energy produced per turbine (MWh) before losses	7,914.12	6,432.87
Nominal Power (MW)	3.6	3.3
Hours of utilization (h)	2,198.37	1,949.36

Table 7.5. Summary on the average energy produced (before losses), the nominal power and the hours of utilisation for SIEMENS and VESTAS wind turbines. Source: Author

8. Wind turbines location

After determining the perimeter of the wind farm location, this section aims to determine the number of turbines to be installed as well as the exact location in UTM coordinates of each wind turbine. To this end, parameters as the wake effect (which will have a considerable impact on the distance between the turbines) and the prevailing wind direction (which will affect the orientation of the rotor and blades) will be considered.

Having the complete data from the external consultant about the chosen turbines, the water depth at the selected area and considering the minimum capacity that a wind park should have in order to be economically viable the number of turbines that should be installed is finally estimated.

8.1. Predominant wind direction

The most important phase when designing a viable and technically successful wind farm project is proper and thorough site assessment. Even though some of this research work has been relinquished by external assessment, as it has been seen in the previous section, it has been considered essential to study the wind regime in the immediate area around where the park could be erected.

For the furtherance of this project, it is important that understandable categorization of local air flows and combination of computational fluid dynamics modeling and measurements are taken into account. These measurements are conducted with anemometers and wind roses (or compass roses).

First and foremost, before the wind turbines placement is done, the overbearing wind direction needs to be found. The *Atlas Eólico de España* from *IDAE* is used with this purpose given that it presents a compass rose through some of its nodes.

In the wind farm location provided by the external assessor it has been decided to minimize the distance to the shore taking into account the water depth and the required minimum distance between turbines. It has also been taken into account that the wind turbines cannot be placed in the red areas and, if the occupation of yellow areas is needed, special permissions have to be asked to local authorities, as explained in the report made by the external assessor.

The chosen reference node (Nr. 9) has the following UTM coordinates: (860950, 4558266). Assuming that the green nodes are at a distance of 2.5 km from each other, and the diagonal of the square measures 3.53 km; node Nr. 9 is 3.53 km far from Tarragona coastline. This result is appropriate for the location of the wind farm because the transport and installation costs are smaller as the distance to the shore (or a harbour) diminish.

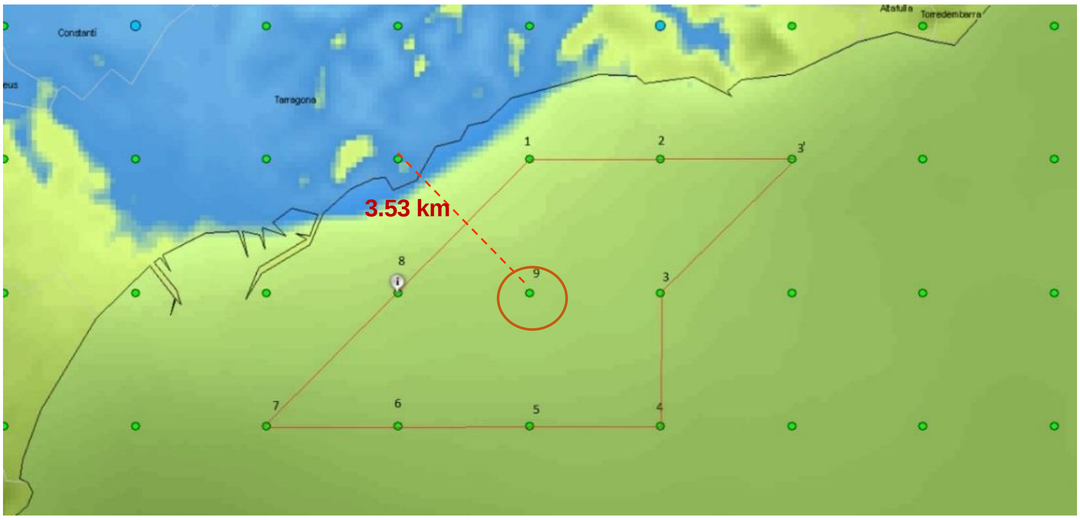


Figure 8.1. Candidate site location for the offshore wind farm and distance to the shore. Source: Author, using the Atlas Eólico de España program

Crossing this information with a deep research in the wind resource at the local surrounding zone and the green, yellow and red zones, the area for the wind turbines siting has been reduced, as it has been seen in the previous section. It has been decided that the furthest to the coastline to be installed turbine will not be further than node Nr.9.

Once selected the final area in which the offshore wind farm will be located, a deeper insight on the main wind directions and blowing frequency needs to be done. The following chart is modeled by *Atlas Eólico* and shows the main directions and frequency of the wind for each direction at node Nr.9, which has been taken as a reference.

Direction	Speed [m/s]	Frequency [%]
N	4.057	5.16%
NNE	4.355	4.94%
NE	5.487	6.90%
ENE	6.729	6.65%
E	5.741	6.03%
ESE	4.344	5.35%
SE	3.892	5.43%
SSE	3.836	4.71%
S	4.046	4.82%
SSW	4.322	5.95%
SW	4.918	5.78%
WSW	4.72	4.39%
W	5.956	5.57%
WNW	7.601	9.10%
NW	7.634	11.17%
NNW	5.956	8.05%

Table 8.1. Main wind speed directions and frequency for each wind direction at node Nr. 9. Source: Atlas Eólico de España

As it can be seen in Table 8.1, the main wind direction is North West (NW).

The design and orientation of wind turbines is a complex task that needs to be thought carefully. According to the book '*Wind energy explained: Theory, designs and applications'* **[9],** wind turbines must be tracked perpendicularly to the predominant wind direction. In our case, as the main wind directions are WNW, **NW** and NNW, the turbines will be placed in parallel lines with the blades orientated perpendicularly to NW direction, in order to harness as much as possible the wind resource. Assuming that the area selected by the external assessor takes into account the water depth at the candidate location, the area compressed between points 1, 8, 7, 9 and 2 can be fully used to install wind turbines.

8.2. Wake factor

Once decided the orientation of the wind turbines, it will be proceeded to determine the distance and relative position between them, considering that the main objective is to minimize the wake factor.

The wake factor phenomenon in a wind turbine which is situated behind another wind turbine can be described as a reduction of the wind resource as a result of the transformation of the kinetic energy of the wind particles into mechanic energy, causing a decrease between the entering wind speed and the wind speed that leaves the blades of the first wind turbine, thus causing that the second wind turbine may not take full advantage of the wind resource.
The wake effect depends on various factors, above all, the distance between the turbines and the layout of the wind farm. Obviously, the greater the distance between the turbines is, the smaller the wake effect will be.

A study conducted by RISØ **[10]** recommends that wake factor losses do not exceed a 5% percentage in large offshore wind farms for an effective use of the wind resource, although in onshore wind farms it is estimated that wake losses can reach 10%.

In order to diminish this factor, the turbines will be situated in a grid of three lines so that turbines in the first line create a shadow on the turbines situated in the second line and the turbines in the third line create a shadow on the turbine in the third line.
According to the RISØ wake factor models **[10]** and 'Wind energy explained. Theory, design and applications' **[9]**, the optimum distance between wind turbines should be of between 3 and 5 diameters in the perpendicular direction to the main wind direction and between 6 and 9 rotor diameters in the main wind direction.
Table 8.2 presents the optimum distances between wind turbines in the directions indicated before that suits both possible options for wind turbines: Siemens 3.6 MW and Vestas 3.3 MW.

	Siemens (3.6 MW)	Vestas (3.3 MW)	Optimum distances
Rotor diameter of the wind turbine	120 m	105 m	
Main wind direction NW: Φ 6-9	720/1080 m	630/945 m	848 m
Perpendicular to the main wind direction: Φ 3-5.	310/600 m	315/525 m	424 m

Table 8.2. Established distances between wind turbines in the design of the offshore wind farm. Source: Author

According to this distances, a general distribution that suits both turbine models has been chosen: a distance of 848 m separation in the main wind directions and 432 m separation in the perpendicular to NW direction, as shown in the following picture (note that every point in the grid is approximately 100 m far from the next node).

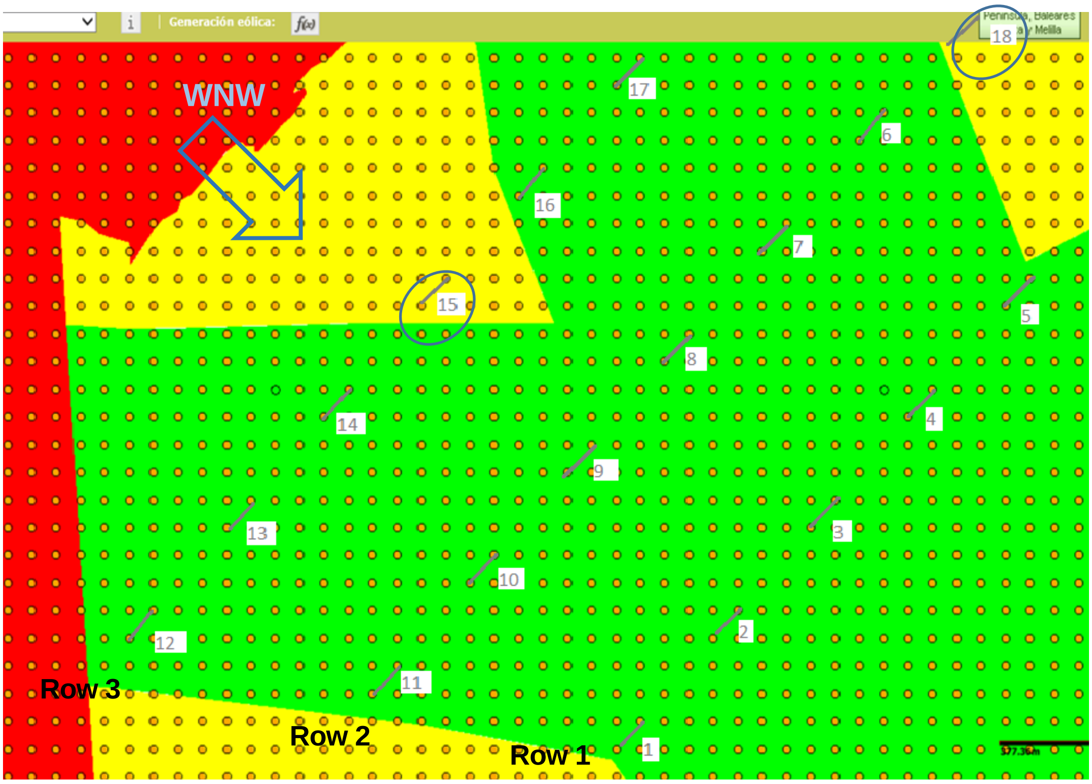


Figure 8.2. Representation of the location of each wind turbine, assigning a numeration to each generator and numerating also the rows of the offshore wind farm layout. Source: Author, with the Atlas Eólico program

The decision to install 18 wind turbines relies on the restriction that the water depth increases overbearing the 60 m from row 1 deeper in the sea. The furthest away from row 1, the deeper the seabed is.

It is for this reason that two turbines (Nr. 15 and 18) are anchored in the yellow area. The installation of these turbines will require a special permission from the local authorities. The goal was to install the largest possible number of turbines within the constraints of seabed depth and geographical

areas established by '*El instituto hidrográfico de la marina'*.
Once the distribution of the wind turbine is made, it will proceeded to calculate the losses created by the wake effect in each turbine, extracting the wind resource data from '*Atlas Eólico'.*

The calculation of wake losses is complex and is usually made by using computational models. However, due to the inability to get access to this kind of programs, a simplified mathematical tool is used. The model created by N.O Jensen and extracted from RISØ **[10]**, assumes that the wake is lineally expanded before the rotor of the wind turbine following a constant (*k*) that depends on the roughness and the hub height at site.

This model allows the calculation of the effective wind speed that the rotor blades of a certain wind turbine receive, being this effective wind speed the difference between the theoretical wind speed for that position and a decrement of the wind speed caused by the shadow that the turbine receives from the other turbines.

The decrement of the wind speed takes into account basically two factors: The shadow area that a wind turbines receives from another and the lineal distance between the positions of the turbines. The following formula shows the calculation of the decrement of the wind speed of turbine Nr. 0, which is affected by the shadow of turbine Nr.1:

$$\delta V_{01} = U_0\left(1-\sqrt{1-C_t}\,\right)\cdot\left(\frac{D_0}{D_0+2kX_{01}}\right)^2\cdot\frac{A_{overlap}}{A_1} \qquad (6)$$

Where,

- U_0 is the average wind speed at hub height for turbine Nr.0
- X_{10} is the lineal distance between the two wind turbines
- D_0 is the rotor diameter of the first wind turbine
- $A_{overlap}$ is the area that the shadow created by turbine Nr.1 leaves on turbine Nr.0 and A_1 is the rotor swept area (the same for both turbines).
- The k constant determines de growth of the wake diameter and considers the hub height and the roughness (z_0) at the surrounding land, which is to say, the wind turbine location as main input parameters. At sea, the roughness value is nearly zero.

$$k = \frac{0.5}{ln\left(\frac{h_{hub}}{z_0}\right)} \qquad (7)$$

- C_t is the thrust coefficient, usually given by the wind turbine manufacturer. The thrust coefficient is a curve that depends on the wind speed, the rotor force, the air density and the swept area of the rotor, as shown in the following formula:

$$C_t = \frac{2\,F_t}{\rho\pi\left(\frac{D}{2}\right)^2 U^2} \qquad (8)$$

The C_t curve provided by the wind turbine manufacturer (see ANNEX III) is shown below. It can be seen that an average wind speed of 6 m/s corresponds to a C_t of 0.8007 for the VESTAS wind turbine.

For the SIEMENS wind turbine, a similar graph can be found in ANNEX III.

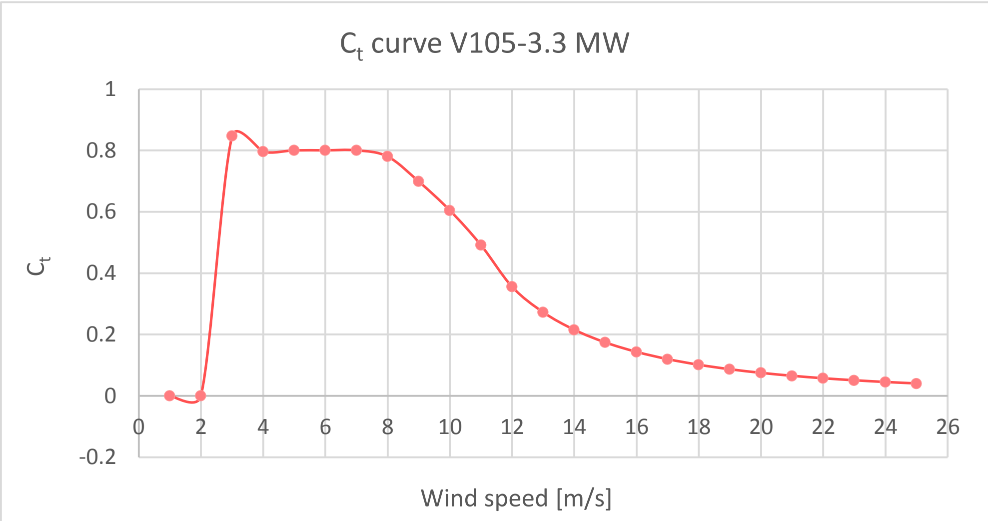


Figure 8.3. Ct curve for the VESTAS wind turbine. Source: VESTAS

Table 8.3, the chart below, outlines the values for each of the parameters described above:

PARAMETER	VALUE SWT-3.6 MW-120	VALUE V105-3.3 MW
C_t	0.866	0.8007
H_{HUB}	80 m	80 m
D_0	120 m	105 m
A_1	11300 m^2	8659 m^2
k	0.075	0.075

Table 8.3. Summary of the parameter needed to calculate the wake factor losses. Source: Author from the wind turbine manufacturers via the external assessor.

The decrement of wind speed and the shadow that wind turbines receive from other turbines is highly affected by the existing area overlaps and the prevailing wind directions. It has to be taken into account that not all wind directions affect the wake factor in the same way. And consequently it has been decided to study the influence of the main directions on the wake factor.

Some of this directions, however, do not have rotor turbine area overlaps and the influence to the wake factor is null. It is the case of N, S, ESE and WNW directions, that, as it can be shown in Table 8.4 the wind speed does not experiment a decrement when wind blows in those directions.

Table 8.4 shows all the possible combinations for area overlaps, the initial wind speed at that direction at node Nr.9 (which has been taken as a reference) and the frequency at which the wind blows for each wind direction, the lineal distance between the overlapped turbines, the % of area overlaps and the wind speed decrement for each direction (calculated with formula (1). Finally, a correction on the decrement associated to each wind direction is calculated in order to determine an average standard depletion coefficient that could be applied to all wind turbines.

For example, for the VESTAS wind turbines, the decrement for NW direction is $\partial V_0 = 0.862\ m/s$ and there are 11 turbines affected by this direction. Thus, the standard decrement for NW direction ($\partial V_{0standard}$) is the product of the decrement (∂V_0) with the ratio of NW direction overlapped wind turbines (11) between the total numbers of installed wind turbines (18), as shown below:

$$\partial V_{0standard\text{-}NW} = \partial V_{0\text{-}NW} * 11/18 = 0.8933*11/18 = 0.527$$

The average standard depletion constant is obtained by relative weighing of the frequency of each wind direction, being the final result of 0.110 m/s.

The same calculations for the SIEMENS wind turbines can be found in ANNEXES IV and V.

Wind direction	Frequency	Overlap combinations	Overlapped turbines	Initial wind speed (U_0)	Separation (X_{01})	% overlap	$A_{overlap}$ (m^2)	∂V_0	$\partial V_{0standard}$
N	5.16%	No overlaps	0	4.06	1414.21	0%	0	0.000	0.000
NNE	4.94%	17-11, 7-1, 6-2, 18-3	4	4.36	2776.69	10%	865.9	0.010	0.002
NE	6.90%	1, 2, 3, 4, 7, 8, 10, 11, 12, 13, 14, 15, 16	14	5.49	424.26	25%	2164.75	0.294	0.229
ENE	6.65%	11-3, 15-18	2	6.73	139.28	5%	432.95	0.130	0.014
E	6.03%	2-12, 3-13, 4-14, 5-15	8	5.74	2000.00	100%	8659	0.213	0.095
ESE	5.35%	No overlaps	0	4.34	130.00	0%	0	0.000	0.000
SE	5.43%	10, 11, 12, 13, 14, 15, 16, 17, 18	9	3.89	848.53	100%	8659	0.440	0.220
SSE	4.71%	4-16, 8-18, 3-15, 7-17, 2-14	5	3.84	984.89	0%	0	0.000	0.000
S	4.82%	No overlaps	0	4.05	1414.21	0%	0	0.000	0.000
SSW	5.95%	17-11, 7-1, 6-2, 18-3	4	4.32	2776.69	10%	865.9	0.010	0.002
SW	5.78%	1, 2, 3, 4, 7, 8, 10, 11, 12, 13, 14, 15, 16	14	4.92	424.26	25%	2164.75	0.264	0.205
WSW	4.39%	11-3, 15-18	2	4.72	139.28	5%	432.95	0.091	0.010
W	5.57%	2-12, 3-13, 4-14, 5-15	8	5.96	2000.00	80%	6927.2	0.177	0.079
WNW	***9.10%***	*No overlaps*	*0*	*7.60*	130.00	0%	0	0.000	0.000
NW	***11.17%***	*1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11*	*11*	*7.63*	848.53	100%	8659	0.862	0.527
NNW	8.05%	4-16, 8-18, 3-15, 7-17, 2-14	5	5.96	984.89	0%	0	0.000	0.000
								0.156	**0.110**

Table 8.4. Wake factor losses table calculation. Source: Author

The calculation for the wake factor losses has been made for the two models of wind turbines and the table for the VESTAS wind turbine has been presented before. The wake factor calculations for the SIEMENS wind turbines are shown in ANNEX IV and V.

On the basis of currently obtained results, one can proceed on calculating the energy obtained by each wind turbine. A table is set out below, containing the energy produced associated at each wind turbine UTM coordinate.

Nº wind turbine	UTM X	UTM Y	Weibull C (m/s)	Weibull K	Average wind speed (without speed decrement)	Average wind speed (with speed decrement)	Energy obtained considering wake factor losses (MWh)	Gross energy production (MWh)
1	859949	4557066	6.32	1.658	5.61	5.50	6,292.79	6,629.525
2	860049	4557366	6.28	1.658	5.58	5.47	6,304.57	6,542.963
3	860449	4557766	6.25	1.659	5.55	5.44	6,237.75	6,476.162
4	860849	4558166	6.23	1.659	5.53	5.42	6,194.50	6,432.872
5	861249	4558566	6.18	1.659	5.48	5.37	6,086.45	6,324.669
6	860649	4559166	6.07	1.661	5.39	5.28	5,845.10	6,082.880
7	860349	4558866	6.12	1.66	5.43	5.32	5,954.93	6,192.941
8	859849	4558366	6.18	1.66	5.49	5.38	6,084.47	6,322.746
9	859449	4557966	6.22	1.658	5.52	5.41	6,174.85	6,413.127
10	859049	4557566	6.25	1.658	5.55	5.44	6,239.70	6,478.042
11	858649	4557166	6.28	1.657	5.58	5.47	6,306.50	6,544.825
12	857749	4557466	6.21	1.657	5.52	5.41	6,155.21	6,393.398
13	858149	4557866	6.19	1.658	5.5	5.39	6,110.04	6,348.224
14	858549	4558266	6.16	1.665	5.47	5.36	6,031.31	6,269.809
15	858949	4558666	6.09	1.664	5.4	5.29	5,882.12	6,120.197
16	859449	4559166	6.01	1.663	5.34	5.23	5,711.82	5,949.281
17	859749	4559466	5.97	1.663	5.48	5.37	5,625.86	5,862.975
18	861049	4559566	6.03	1.662	5.35	5.24	5,756.91	5,994.473
Gross energy production (E_G) (MWh/year)							**108,994.90**	**113,379.11**

Table 8.5. Gross energy production (E_G), and energy production considering wake factor losses. Source: Author

The fourth and fifth columns show the *C* and *K* parameters of the Weibull distribution of their associated wind turbines at a certain location. Following these columns, two average wind speed at 80 m height columns can be found. With the previous information on the table, the energy produced by each wind turbine can be calculated. This energy has been obtained by crossing the Weibull distribution function associated to each installed node with the power curve of the turbines supplied by the manufacturer.

The Weibull distribution function taking into account the wake factor has been obtained by deducting from the C parameter the average standard depletion.
It can be observed that the turbines Nr. 15, 16, 17 and 18 have a worst energy performance rather than the other turbines. This is due to the poor wind resource associated to their location and from this fact, one could deduct that these turbines should be replaced or their location changed. However, it has been decided to leave the configuration that was intended because the length of the cables is shorter than if the turbines would be further from the others.

Finally, it can be determined that the gross energy produced by the 59.4 MW wind farm (VESTAS wind turbines) without considering any losses is 113,379.110 MWh/year; whereas if wake losses are considered the amount of energy produced accounts for 108,994.90 MWh/year.
The same calculations can be made for the SIEMENS wind turbines: the 64.8 MW offshore wind farm annual energy production without considering any losses is 139,664.45 MWh; whereas if wake losses are taken into consideration, the energy production accounts for 133,849.56 MWh/year.

As the main target of this chapter was to obtain a percentage for the wake losses, one can verify that those do not exceed a 5% percentage, as this was recommended by RISØ **[10]**:

$$wake\ losses\ SIEMENS\ \% = \left(\frac{139{,}664.45 - 133{,}849.56}{139{,}664.45}\right) \cdot 100 = 4.16\ \%$$

$$wake\ losses\ VESTAS\ \% = \left(\frac{113{,}379.110 - 108{,}994.90}{113{,}379.110}\right) \cdot 100 = 3.87\ \%$$

This percentage will be used to calculate, by adding this percentage to other kind of losses, the net energy production of the entire wind farm.

8.3. Annual energy production delivered to the grid

The wind energy delivered to the grid can be calculated by estimating the net amount of energy collected (E_C) by the total number of wind turbines, taking into account the losses due to different factors, as shown in the expression below:

$$E_C = E_G - E_G c_L = E_G \cdot (1 - c_L) \qquad (9)$$

Where,

c_L is the losses coefficient, which can be calculated through:

$$c_L = (\lambda_{wake}) + (\lambda_a) + (\lambda_{mis}) \qquad (10)$$

Where λ_{wake} are the wake factor losses, λ_a are the array losses and λ_{mis} are miscellaneous losses. The calculation for this parameters is taken as a percentage on the gross energy produced by the wind turbines.

In order to simplify the calculations and due to the difficulty to estimate array and miscellaneous losses, the c_L coefficient has been estimated as explained below:

- If SIEMENS wind turbines are considered in the analysis, the wake factor losses (λ_{wake}) account for a 4.16% of the gross energy produced, while the array losses (λ_a) account for a 2% and finally, the miscellaneous losses (λ_{mis}) account for a 0.5% of the losses, accounting for a total of 6.5% losses. Consequently, the total amount of energy collected for the SIEMENS offshore wind farm in a year is:

$$E_{C_{SIEMENS}} = E_G \cdot (1 - c_L) = 139{,}664.45 \cdot (1 - 0.065) = 130{,}586.26 \ \frac{MWh}{year}$$

- While if VESTAS wind turbines are considered in the analysis, the wake factor losses (λ_{wake}) account for a 3.87% of the gross energy produced, while the rest losses (λ_a) + (λ_{mis}) account for the rest (approximately 2.13% of the losses), accounting for a total of 6.5% losses. Consequently, the total amount of energy collected by the VESTAS offshore wind farm in a year is:

$$E_{C_{VESTAS}} = E_G \cdot (1 - c_L) = 113.379.110 \cdot (1 - 0.065) = 106{,}009.47 \ \frac{MWh}{year}$$

With the assumption that the amount of energy collected is entirely absorbed by the central grid to which the wind farm is connected, the wind energy delivered to the grid is equal to the energy collected (after considering the losses).

8.4. Wind plant capacity factor (PCF)

The wind plant capacity is the last factor considered, but not less important. It estimates the ratio of the average power produced by the wind farm over an entire year to its power capacity. The formula used for its calculation is shown below:

$$\mathrm{PCF} = \left(\frac{\mathrm{E_C}}{\mathrm{WPC\ h_Y}}\right) \cdot 100 \qquad (11)$$

Where WPC is the wind plant capacity [MW], $\mathrm{h_Y}$ is the number of hours in a year and $\mathrm{E_C}$ is the total amount of energy collected, as described in the previous section.
Accordingly, the PCF for the each designed offshore wind farms is:

$$PCF_{SIEMENS} = \left(\frac{\mathrm{E_C}}{\mathrm{WPC\ h_Y}}\right) \cdot 100 = \left(\frac{130{,}586.26\ \frac{MWh}{year}}{64.8\ \mathrm{MW} \cdot 8760\ \mathrm{h}\frac{h}{year}}\right) \cdot 100 = 23\%$$

$$PCF_{VESTAS} = \left(\frac{\mathrm{E_C}}{\mathrm{WPC\ h_Y}}\right) \cdot 100 = \left(\frac{106{,}009.47\ \frac{MWh}{year}}{59.4\ \mathrm{MW} \cdot 8760\ \mathrm{h}\frac{h}{year}}\right) \cdot 100 = 20{,}37\%$$

8.5. Characteristics summary of the offshore wind farms

After a review on each offshore wind farm characteristics, it has been considered necessary to summarize the most important parameters of each offshore wind farm (considering the installation of SIEMENS or VESTAS wind turbines). Thus, the number of turbines, the nominal power, the Gross energy production, the energy collected (delivered to the grid), the hours of utilisation and the Plant Capacity Factor of the offshore wind farms are summarized below:

	SIEMENS OFFSHORE WIND FARM (SWT-3.6 MW-120)	VESTAS OFFSHORE WIND FARM (V105-3.3 MW)
Nr. of turbines	18	18
Nominal power	64.8 MW	59.4 MW
Gross energy production (E_G)	139,664.45 MWh	113,379.110 MWh
Energy delivered to the grid (E_C)	130,586.26 MWh	106,009.47 MWh
Hours of utilisation	2,015.22 h	1,784.67 h
PCF	23 %	20.37 %

Table 8.6. Key parameters of the SIEMENS and VESTAS designed offshore wind farms. Source: Author

9. Evacuation of the energy produced

The main target of this Project is to analyse the economic feasibility of installing an offshore wind farm in the Catalan coastline, specifically in Tarragona. From here, it has been considered appropriated to comment, although not being part of the main body of the project, how the evacuation of the power generated at the wind farm will be performed.

Mostly, offshore wind farms build transformer offshore substations near the wind turbines as well as onshore wind farms, which are usually erected near transformation centres (onshore transformer substations).

Offshore transformer substations are used when transporting the power generated by the wind turbines to the shore by raising the voltage from medium to high or very high with elevator transformers. The purposes of this transformation are to reduce electrical losses and to inject the electricity to the grid for its transport to high voltage.

The transformer primary voltage is usually 33 kV, the voltage at which wind turbines generate electricity, while the transformers high voltage is determined by the tension of the conveying line or interconnection (usually 66, 110, 220 or 400 kV in Spain).

For economic reasons it has been decided not to install an offshore substation and to use the onshore existing substation in Tarragona. Thus, the energy will have to be transported through three array cables from the three lines of wind turbines onto the shore. The cable selected, with an area of 240 mm^2 in the first and third row of the offshore wind farm can support up to 25 MW, whereas a 630 mm^2 AC cable has been chosen for the second row of the wind farm layout in order to be able to support more power. The wind farm layout designed in section 8.2 presents rows with a maximum of 7 wind turbines of 3.3 MW or 3.6 MW each, yet not accounting the 25 MW allowed in the first and third row. Thus, three array cables will be installed under the seabed at the designed offshore wind farm and the energy evacuated from the park through the array cables will have to be elevated to high voltage for its transportation through the electric grid onshore.

It has been considered interesting to study here the intensity that will circulate through each of the above mentioned cables. The explanation will be made with the example of row 1 (see Figure 8.4) for SIEMENS turbines with a power output of 18 MW.

The power output of row 1 at the end of the last turbine is $P = 18\,MW$. As AC cables are considered, the power factor $\cos(\varphi) = 0.95$ has been taken. Then the reactive power can be determined: $Q = P \cdot \tan(\varphi) = 5.916\,Mvar$.

The line voltage accounts for $U = 33\,kV$. Consequently, $U_{AB} = 33\,kV$ and $V_{AN} = \frac{33}{\sqrt{3}}$.

Using the formula of the power, $P + Qj = 3 \cdot V_{AN}^{*} \cdot I_{A}^{*}$, the intensity can be isolated.

Finally, $I_A^* = 331.49\ (18.49°)$ and the absolute intensity is $I = 331.49\ A$.

The same method can be applied to rows 2 and 3 for both type of offshore wind farms. The following table represents the intensity which would circulate for each cable from the wind farm to onshore.

ROW NUMBER	POWER OUTPUT SIEMENS (P)	INTENSITY THROUGH EACH CABLE	POWER OUTPUT VESTAS (P)	INTENSITY THROUGH EACH CABLE
1	18 MW	331.49 A	16.5 MW	303.87 A
2	25.2 MW	464.09 A	23.1 MW	425.42 A
3	21.6 MW	397.79 A	19.8 MW	364.64 A

Table 9.1. Intensity circulating for each now of the wind farm layout. Source: Author

Power export cables from the different rows should be able to support this intensities from the different rows to the onshore transformer substation. The election of these cables, however, is beyond the scope of this project.

This economic decisions for not installing an offshore transformer substation will thoroughly be explained in section 9.

ECONOMIC FEASIBILITY ANALYSIS OF AN OFFSHORE WIND FARM AT THE CATALAN COASTLINE

ETSEIB

10. Cost analysis of the offshore wind farm

On previous chapter it has been seen that the designed wind park is technically viable; that is to say, that it can produce the minimum required energy to operate. Once this has been demonstrated, the following step should be to determine whether the project is economically viable or not.

To this end, an estimation on the costs of installing and operating the offshore wind farm is done in this section.

According to reference **[9],** the cost components of wind energy systems have to be treated separately. On the one hand, one will find the generating costs (which consider parameters as the wind regime, the energy capture efficiency, etc.). The O&M costs are included in this first group as they depend on the variables mentioned. On the other hand, the fix costs such as the transport, installation and erection of wind turbines have also to be determined.

Some of the variables of the generating costs have already been mentioned in section 6, such as the wind regime, the energy capture efficiency and the availability of the system. The others will thoroughly be explained in this section.

There is also another way of calculating the costs of a wind farm erection, installation and operation project: dividing them in two gropus (CapEx and OpEx).

- The CapEx (or Capital Expenditure) is a business expense incurred to create future benefit i.e. acquisition of assets that will have a useful life beyond the tax year. e.g. expenditure on assets like building, machinery, equipment or upgrading existing facilities so their value as an asset increases.
- On the other hand, OpEx (Operational expenditure) refers to expenses incurred in the course of ordinary business [**11].**

In our case study, buying a wind turbine would be a CapEx, while its operation and maintenance costs would be an OpEx.

It is important to mention that CapEx are usually expressed in euros per Megawatt (€/MW or M€/MW), while OpEx are expressed in euros per Megawatt hour (€/MWh) as they depend on the annual energy production of the offshore wind farm.

The report carried out by Douglas Westwood 'Offshore wind assessment for Norway' **[12]** sets the distribution costs of an example project layout offshore wind farm, as it is shown in the tables below.

At the end of this chapter, it will be discussed if the percentages obtained for the designed wind farm meet the estimations made by the reference mentioned before.

CAPITAL COSTS

Component	% of Cost
Wind Turbines	44 %
Foundations	16 %
Installations	13 %
Electric Infrastructure	17 %
Planning & Development	10 %

INSTALLATION AND TRANSPORTATION TYPE

Component	% of Cost
Turbine installation	20 %
Foundation installation	50 %
Electrical installation	30 %
Turbine transportation	No data
Foundation transportation	No data

ELECTRICAL INFRASTRUCTURE

Component	% of Cost
Small array cable	4 %
Large array cable	11 %
Substation	50 %
Export cable	36 %

O&M COSTS

Component	% of Cost
Grid Maintenance	24 %
Equipment	53 %
Personnel Access	9 %
Labour	8 %
Repair Vessels	6 %

Table 10.1. Capital and O&M costs of an example offshore wind farm layout. Source: Douglas Wstwood Institue

In this Project several sources of information have been consulted in order to estimate the costs of the offshore wind farm, since the scarcity of these parks and the considerable number of parameters to be considered makes the costs extrapolation very difficult. This is the reason why it has been preferred to compare different external references to obtain reliable information. The most important are mentioned below.

The first one is the study carried out by some researchers at Douglas Westwood, '*Offshore wind assessment for Norway',* referred as number **[12].** This article suggests that three main sections need to be covered when carrying a feasibility analysis of this magnitude:

- The current costs of Offshore wind, which includes the O&M costs
- The transmission costs, which take into account the capital and installation costs associated with cabling for the array, substations and export cables to shore, and
- Intermittency costs

It will be driven special attention to the first and second section, and although the third is of equal importance, it has been considered that the investigation on this matter will be left for further studies.

The second one is the European Wind Energy Association (EWEA) on an annual report that is conducted annually and updates the offshore costs as the offshore technology improves. This report is referred as number **[4].**

Finally, an offshore wind farm has been chosen as a model of similar projects: *The Middelgrunden*, a 40 MW offshore wind farm, near to the Danish coastline.

10.1. Capital costs or CapEx

10.1.1. Cost of wind turbines and foundations

According to the EWEA annual report of 2013 **[3],** wind turbines -including the costs associated with the blades and towers- constitute the largest cost component of a wind farm project, typically accounting for around 70% of the total investment cost. However, in offshore projects this percentage is reduced until approximately 50% (44% according to **[12])** because of huge investment costs related to transportation and installation of the foundations and the turbines at the sea.

The input cost of the wind turbines, as well as the foundations costs has been provided by the external assessor, who has chosen the type of wind turbines and foundations that are shown in the table below:

		SIEMENS SWT-120-3.6 MW	VESTAS VT105.3.3 MW
CAPITAL COSTS	Turbine cost	3.340.800 €	3.062.400 €
	Jacket foundation cost	288.000 €	264.000 €

Table 10.2. Costs for each wind turbine model and Jacket foundation cost. Source: External assessor.

10.1.2. Electrical Infrastructure costs

It is not always easy no gauge the cost of a project electrical infrastructure due to the fact that most released projects values encompass all capital costs including the turbines and also due to its dependence on the availability of cables material, the supply capacity of the companies and the demand on cabling at the same time the project is being conducted.

Notwithstanding the difficulty of this research, a sub-division on cabling costs has been made in three groups: array cables and export cables and the transformer substation even though it has been decided not to install these last one, as it will be explained below.

The following scheme shows the three parts in which the electrical infrastructure has been divided: the array cables interconnecting wind turbines (1), the offshore transformer substation (2), which is optional, and the export cables to the grid (3). The three components will thoroughly be explained in the following sections.

The scheme has been extracted from the Douglas Westwood Institute report and has been adapted to the necessities of the author.

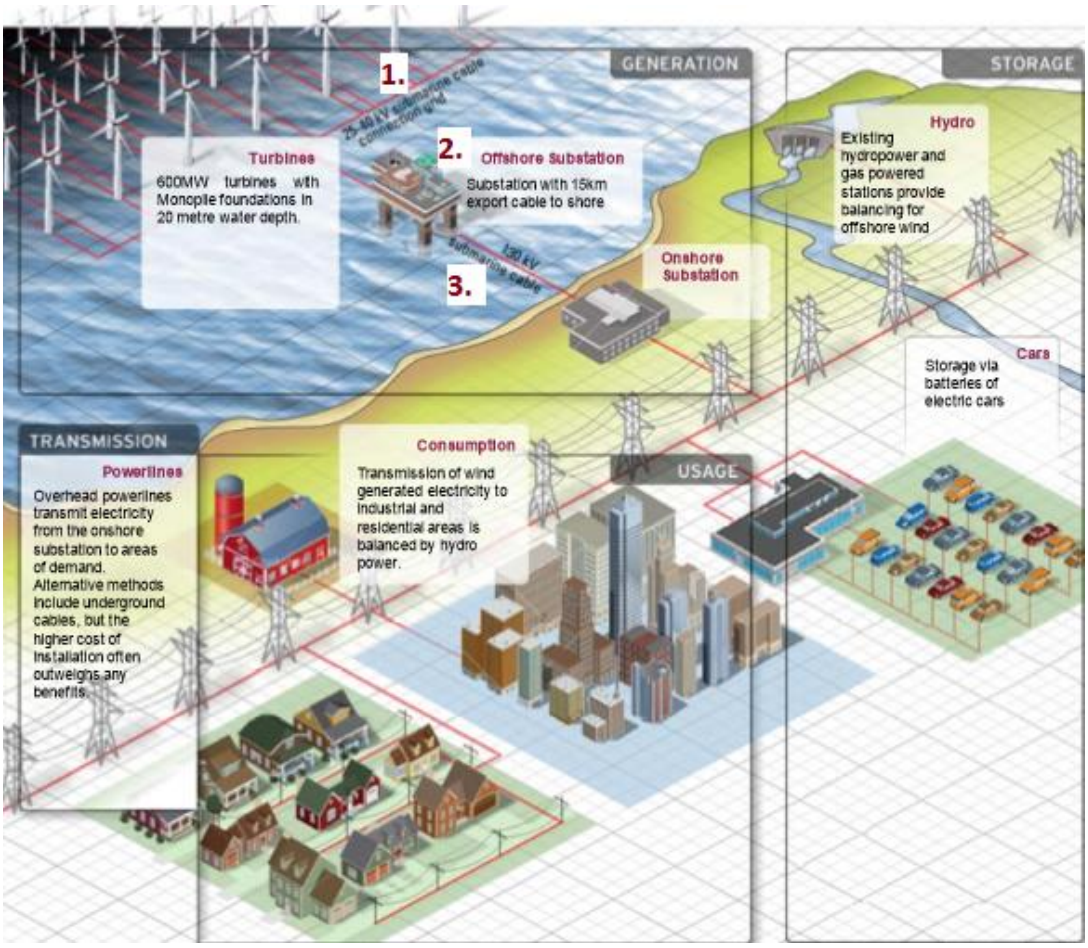


Figure 10.1. Scheme on the main electric infrastructures of an offshore wind farm. 1: Array cables between wind turbines. 2: Offshore transformer (elevator) substation. 3: Export cables to shore. Source: Douglas Westwood.

10.1.2.1. Array cables

The array cables interconnect wind turbines, typically in a grid formation, with turbines arranged in strings and connected back to a substation.

According to reference **[12],** the optimum cable connection method includes alternating current (AC) cables given that most turbines generate 30 or 33 kV AC power and these are usually the cheapest option for mid-sized wind farms which are not more than 20 km far away from the coastline. This is the case of the designed offshore wind farm, where wind turbines produce electricity at a voltage of 33 kV according to the manufacturer's provided parameters.

The report also considers two main diameter sizes for the cables: small (17.48 mm) and large diameter (28.55 mm). The cable selected will be the small (240 mm^2) in the three rows of 59.4 MW offshore wind farm given that this is able to support up to 25 MW capacity and the distribution of the turbines presented in section 8.2 presents rows with a maximum of 7 wind turbines of 3.3 MW, yet not accounting the 25 MW allowed. Thus, three array cables will be installed under the seabed at the 59.4 MW designed offshore wind farm. However, in the 64.8 MW offshore wind farm (with SIEMENS wind turbines), a large array cable AC would be needed in row number 2 to be able to transport the 25.2 MW of the 7 wind turbines.

The costs of the small AC array cable (240 mm^2) have been assumed at 171.836,00 euros per Km, while the costs for large AC array cables (630 mm^2) have been assumed at 456.342,00 euros per Km.

Type of array cable	Price (€/Km)
Small array cable (240 mm^2)	171.836,00
Large array cable (630 mm^2)	456.342,00

*Table 10.3. Cost of small (240 mm^2) and large (630 mm^2) array cables. Source: Douglas Westwood. *Conversion from MNOK to EUROS (15/05/2014)*

The following table shows the km of array cable needed per row on the configuration wind farm layout, considering that these are situated at a distance of 424 m between them in the row direction, thus obtaining the total price for the AC cable:

Row number (park layout)	Nr. connected wind turbines	MW evacuated to onshore substation		Total km per row	Total AC cable price	
		SIEMENS	VESTAS		SIEMENS	VESTAS
1	5	18 MW	16.5 MW	1.697 km	291,605.69 €	291,605.69 €
2	7	25.2 MW	23.1 MW	2.545 km	1,161,390.39 €	437,322.6 €
3	6	21.6 MW	19.8 MW	2.121 km	164,4464.16 €	164,4464.16
				TOTAL (€)	**1,817,460.24 €**	**1,093,392.4 €**

*Table 10.4. Cost of array cables interconnecting wind turbines. Source: Author with data from Douglas Westwood. *Conversion from MNOK to EUROS (15/05/2014)*

The cost of array cables per MW installed can be deducted by dividing the total costs of array cables (in euros) between the total installed capacity of the wind farm (59.4 MW or 64.8 MW): 28,047.23 €/MW if the chosen turbines are SIEMENS or 18,407.27 €/MW installed if the turbines installed are VESTAS.

10.1.2.2. <u>Offshore and onshore transformer substations and evacuation of the energy produced</u>

When considering transformer substation costs, the cost of the platform on which the substation will be mounted constitutes a large amount of them due to the difficulty of its transport and installation. However, the largest investment when constructing the offshore substation is due to the electrical equipment.

The following table is an extrapolation of the total investment cost of an offshore wind substation made by Douglas-Westwood [16]:

COMPONENT	€/MW	TOTAL (€) per 59.4 MW	TOTAL (€) per 64.8 MW
Substation Electrical Equipment	**237.708,20**	**14,192,649.90**	**15,482,890.80**
- Voltage Source Converter (VSC)	202.174,50	12,009,165.30	13,100,907.60
- Power transformers	9.802,40	582,262.56	635,195.52
- Auxiliary transformers, generators and systems	7.351,80	436,696.92	476,396.64
- Switchgear	14.703,60	873,393.84	952,793.28
- Workshop, Accommodation & Fire Protection	4.901,20	291,131.28	317,597.76
Substation Structure and installation	**46.561,40**	**2,970,000.00**	**3,240,000.00**
Nota: transformació de MNOK A M€		**17,162,649.90 €**	**18,722,890.80 €**

*Table 10.5. Cost of an offshore transformer substation. Source: Author from Douglas Westwood. *Conversion from MNOK to EUROS (15/05/2014)*

To avoid this large amount of investment, an alternative could be to transport directly the current to an onshore substation using array cables, given that most probably the cost associated to the electric losses produced by the Joule effect when transporting the electricity will not overbear the costs of installing an offshore substation. Another reason that enhances and reinforces the decision of using the existing onshore substation in Tarragona is its proximity to the wind farm (3.53 km at the most remote turbine (Nr. 9 see Figure 8.1). This is believed that makes it cheaper to transport the electricity generated by the wind turbines directly to the onshore substation rather than building an offshore substation, with the associated investment costs that this would represent.

Having seen the reasons commented before, the option of erecting an offshore transformer substation has been dismissed.

An important aspect needs to be considered here: although using the Tarragona onshore substation implies great savings, Project Managers are not exempted to considerate its adaptation to be able to absorb the expected injectable energy that will receive. The electrical grid in Tarragona is nearly swamped, and probably an enlargement of it should be done. The cost that these works would imply are difficult to estimate, and so who would be responsible for executing it, given that *Red Eléctrica de España* periodically carries out enlargement of its substations. A negotiation with the local authorities and the responsible for *Red Eléctrica* would be needed.

10.1.2.3. <u>Power export cables</u>

The export cables carry the generated electricity from the substations to the shore. Typically, large projects (100 MW or more) require HVDC cables, while smaller and mid-size projects use AC cables.

HVDC cabling needs a transformer substation onshore (DC to AC) and AC to DC transformer substation offshore and could start becoming more cost effective for large wind farms located more than 50 km offshore.

HVDC cabling when the distance from the offshore substation to the shore is larger than 50 km is not advisable given that although losses in HVDC cables are lower than in HVAC cables, the losses in the VSC converters are much higher in both ends and this fact does not compensate the losses of electricity transporting unless the distance to the shore is higher than, at least, 50 km. It can be said that, by now, HVDC cabling may start becoming more cost effective for large wind farms located more than 50 to 100 km offshore.
According to Douglas-Westwood, export HVAC cabling is the most cost efficient cabling method for mid-sized projects (with distances between 20 and 30 km).

Additionally, the costs of cabling from the coastline to the onshore transformer substation need to be considered.
The costs of the cabling from the coastline to the transformer substation have been assumed to be the same as the array cables. Thus, there will be three array cables from the coastline to the onshore substation although in this case, the cables will not be installed under the seabed (the array cables that interconnected the wind turbines are prolonged until the onshore transformer substation). The distance from the coastline to the onshore substation is 4 Km.
Thus, the power export cables cost has been divided in the two options described before: if an offshore substation is considered, the power export cables will connect the onshore substation with the coastline and then to the onshore transformer substation. If no offshore transformer substation is considered, the same array cables that interconnected the wind turbines will be prolonged onto the coastline and then back to the onshore substation. The table below shows the costs for power export cables to shore and to the onshore substation if no offshore substation is built.

Row number (park layout)	**MW evacuated to onshore substation and type of cable**		**Total km per cable**	**Total AC cable price**	
	SIEMENS	**VESTAS**		**SIEMENS**	**VESTAS**
1	18 MW (small)	16.5 MW (small)	7.5	1,288,770 €	1,288,770 €
2	25.2 MW (large)	23.1 MW (small)	7.5	3,422,565 €	1,288,770 €
3	21.6 MW (small)	19.8 MW (small)	7.5	1,288,770 €	1,288,770 €
			TOTAL (€)	**6,000,105.00 €**	**3,866,310.00 €**

*Table 10.6. Costs of export cables to shore. Source: Douglas Westwood. *Conversion from MNOK to EUROS (18/05/2014)*

On the other hand, if an offshore substation is build, the costs of HVAC cables should be considered. According to the Douglas Westwood report, a 132 kV HVAC cable can carry up to 250 MW. Assuming that the onshore substation would be 5.5 km far from the onshore substation in Tarragona and that the price for 1600 mm^2 HVAC cable accounts for 396,363.70 € per km, a total amount of 2,180,000.35 € should be invest for this type of cables for both type of offshore wind farms.

With all this review on the electrical infrastructure costs a comparison between the two possible options (to use the Tarragona onshore substation versus erecting an offshore wind substation) is made.

	OPTION 1. Onshore substation	OPTION 1. Onshore substation	OPTION 2. Offshore substation	OPTION 2. Offshore substation
	SIEMENS	VESTAS	SIEMENS	VESTAS
Array cables interconnecting turbines	1,817,460.24	1,093,392.40 €	1,817,460.24	1,093,392.4 €
Array cables to shore and to the onshore substation	6,000,105.00	3,866,310.00	2,180,000.35 €	2,180,000.35 €
Offshore transformer substation	–	–	18,722,890.80 €	17,162,649.90 €
TOTAL (€)	**7,817,565.24**	**4,959,702.47**	**22,720,351.39**	**20,436,042.72**

Table 10.7. Comparison on the costs between two options: using an existing onshore substation versus erecting an offshore substation. Source: Author

As it can be seen, erecting an offshore substation would represent a large investment cost, much higher than using the existing onshore substation in Tarragona, although it would need remodelling works and these would need to be negotiated. This is the reason why OPTION 1 has been chosen ahead of OPTION 2.

By choosing this option it should be taken into account the Joule effect losses through the electricity-carrying wires from the turbines to the onshore substation. However, this specific calculations are beyond the scope of this project and these losses have been contemplated as a percentage of energy losses, with the economic impact they carry. These results have been thoroughly discussed in section 8.3. Annual energy production delivered to the grid.

It also has to be noticed from this section that cables installation costs have not been considered. This parameter will be studied in the next chapter.

Finally, it can be determined that the electric infrastructure costs without installation labor reach a total amount of SEVEN MILLION EIGHT HUNDRED SEVENTEEN THOUSAND FIVE HUNDRED SIXTY-FIVE EUROS AND TWENTY FOUR CENT for the largest offshore wind farm and FOUR MILLION NINE HUNDRED FIFTY-NINE THOUSAND SEVEN HUNDRED TWO EURO AND FORTY-SEVEN CENT for the VESTAS offshore wind farm.
In €/MW the electric infrastructure costs without installation labor accounts for: 120,641.44 €/MW in the case of using SIEMENS wind turbines or 83,496.67 €/MW of VESTAS wind turbines.

10.1.3. Transport and installation costs

Once the locations and distribution of the wind turbines is done, it has to be taken into account the construction and assembling method, which has an impact on the transport and installation costs. There are many components of the wind turbine to be considered in this phase: the wind turbine rotor, the nacelle, gearbox and main shaft, the tower and finally, the wind turbine foundation. According to reference **[13]** and the indications of the external assessor, these components offer several possible transport and installation alternatives. Additionally, transport and installation can be done simultaneously or in separate phases of the wind farm erection.

The following table shows six possible alternatives when installing and transporting the components of the wind turbines depending on the pre-assembled parts to be transported:

OPTION	Description	Pros and Contras
1	Installation of the four components separately	• Increase in time and storage costs • Mounting nacelles offshore is time consuming • Personnel risk during rotor installation • Several small vessels
2	Installation of the foundation followed by pre-assembled tower and nacelle, rotor separately	• No more than two pre-assembled towers can be transported simultaneously. • Installation can be executed from the barges.
3	Installation of the foundation first, followed by the tower and the assembled rotor and nacelle.	• One transport vessel must be used for each pre-assembly
4	Installation of the pre-assembled foundation and tower, followed by the nacelle and the installation of the rotor.	• For the transport, is no valid for monopod foundation types. • Transport the foundation and tower separately (maybe on the same barge) and connect the parts before installation • Useful for Jacket foundations
5	Installation of the pre-assembled tower and foundation first, followed by the pre-assembled nacelle and rotor.	• Combination between options 3 and 4
6	Installation of the pre-assembled foundation, tower and nacelle, followed by the installation of the rotor.	• The installation time is reduced. • The total mass of the pre-assembled structure will be high.
7	Installation of the foundation, followed by the pre-assembled tower, nacelle and rotor.	• Need for vertical transport • Transportation speed is low
8	Installation of the turbine as a whole	• Need for special vessels • A maximum of two complete pre-assembled wind turbines can be transported simultaneously.

Table 10.8. Possible alternatives when transporting and installing the wind turbines offshore. Source: S.A. Hermann, Transport and installation costs

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The discussion and selection of the transport and assembling method has been carried out by the external assessor, as a part of the total costs the wind turbines comprise, which, after considering the pros and contras for each option, has decided to choose the option Nr. 3: installing the foundations first, followed by the tower and the assembled rotor and nacelle

Figure 10.2 below shows the assembling method described before. The chosen configuration for this project (Nr. 3) for the installation of wind turbines has already been used in a number of offshore wind farms installations when they are close to the coastline, given that the trips of the vessels to the harbor are not as expensive as if they were located further from the coast.

Figure 10.2. A common assembling method that was used in Horn Rev I consisted on erecting the wind turbine tower and nacelle and the assembly of the rotor with the three blades at the end. Source: Danish Energy Authority– Key Environmental Issues.

10.1.3.1. Transport and installation of wind turbines and foundations

The installation of an offshore wind farm project is a complex issue that involves a number of steps and technical, economic and legal issues.

It has to be taken into account that sites close to shore and in shallow water are less expensive and risky than deep-water sites.

While erecting a wind turbine of small to medium size does not present much technical problem if the site is accessible to common transport and hosting equipment, the erection of large offshore wind turbines, as in this case, is another issue. Many varied solutions have been developed in recent years as wind farms and turbines are growing in size and power, but the common steps when installing a wind turbine are usually the same, and are summarized in the following list in execution order:

- Possible adaptation of the vessels for a specific installation procedure
- Prepare port logistics: assembly of turbine components onshore (configuration 3)

- Mobilisation of equipment and personnel
- Installation of the foundations
- Installation of the tower, nacelle and rotor (configuration 3, with the same vessels than the foundations)
- Installation of the substation (if required)
- Application of scour protection
- Cable laying operations at the end, to avoid damages in the electric system when installing the heavy foundations.

A transport and installation and transport cost model developed by S.A Hermann **[13]** is used by the external assessor, although some simplifications have been done and some parameters and time estimations actualised. The model does not include the cables installation costs.
According to this model, the installation costs for the foundation and the assembly of the tower, nacelle and rotor for a smaller than 5 MW wind turbine is given by the following equation:

$$Cost_1 = \left(\frac{t_{work}}{P(work)} + t_{fixed} + t_{delay}\right) \cdot Q + Mob \qquad (12)$$

Where,

- t_{work} is the time (in days) required to install one structure using one vessel, which, according to the external assessor accounts for 4 days in SIEMENS wind turbines and 3.5 days in VESTAS wind turbines.
- *P(work)* is the probability of the vessel to operate due to good weather conditions and has been fixed at 75%.
- t_{fixed} is the extra time needed to load the structure onto the vessel, to position the wind turbine and to mobilise to the next position, which has considered to be half a day.
- t_{delay} has also been set at half a day.
- *Q* is the vessel day rate, which has been set to 120,000 €/day for VESTAS wind turbines and to 125,000 €/day according to the information provided by the external assessor.
- *Mob* represents the costs of mobilising all the construction vessels required for the transport of the wind turbines from their initial expenditure to the harbour in Tarragona and has been estimated to 6 days for the vessel to go from Denmark, where the wind turbines would be built, to Tarragona. The costs for Mob account for 22,136.18 €/SIEMENS turbines and 21,997.55 €/VESTAS turbine.

Thus, the total transport and installation costs could be estimated by the utilisation of the following calculations:

$$Cost_{Siemens} = \left(\frac{t_{work}}{P(work)} + t_{fixed} + t_{delay}\right) \cdot Q + Mob = \left(\frac{4}{0.75} + 0.5 + 0.5\right) \cdot 125{,}000\,€ + \ 22.316{,}18\frac{€}{turbine}$$

$$= 791.666,67 \frac{€}{turbine} + 22.316,18 \frac{€}{turbine} = 813,982.95 \frac{€}{turbine}$$

$$Cost_{Vestas} = \left(\frac{t_{work}}{P(work)} + t_{fixed} + t_{delay}\right) \cdot Q + Mob = \left(\frac{3,5}{0.75} + 0.5 + 0.5\right) \cdot 120,000\,€ + 21.997,55 \frac{€}{turbine}$$

$$= 680.000 \frac{€}{turbine} + 21.997,55 \frac{€}{turbine} = 701,997.55 \frac{€}{turbine}$$

Finally it has been decided to take into account the extrapolation made by our external assessor in order to considerate a margin for the viability analysis of the offshore wind farm and the capital costs will include the information provided in the table below:

		SIEMENS SWT-120-3.6 MW	VESTAS VT105.3.3 MW
TRANSPORT AND INSTALLATION COSTS	Foundation and turbine installation costs (€/turbine)	791,666.67	680,000
	Foundation and turbine transport from Denmark (€/turbine)	22,316.18	21,997.55
	Total transport and installation costs for the offshore wind farm (€)	**14,651,693.10 €**	**12,635,955.9 €**

Table 10.9 Transport and installation costs for each offshore wind farm. Source: Author with the information provided by the external assessor.

10.1.3.1.1 *Cables installation*

An aspect that must be considered when in the installation strategy is the installation of the array cables, the electric cables between the wind farm power collection facility (transformer substation) and the cables between the transformer substations to the shore. In this project, the cables will be connected between the wind turbines directly to the shore, as no offshore substation is needed.

If cables are installed before the turbine foundations are placed, cables are sensible to damage due to the movement of the soil by the installation vessels or the foundation itself during its installation. So, a common cabling method is to install the wires after the foundations have been installed.

Prior to cables installation, some preparatory measures could be necessary to conduct. The clearance of unavoidable obstacles lying along the cable route that could endanger installation operations or flatten the seabed contours along the cabling route are some examples of prior to cables installation works.

The cables are manufactured onshore and spooled onto a carousel on the lay vessel. When the installation vessels reach the desired installation location, the wire line is progressively unwound and paid out in a J-curve while at the same time, the cables are being buried under the seabed by another equipment.

A parameter that can make cables installation costs increase is the burial depth. In some countries, e.g. the USA, the burial depth is fixed to 3 m. The time and costs increase as the burial depth increase given that the burial requires ploughing; while a 1.5 m burial depth can be carried out by high power air jets, which is significantly cheaper.

When the cables are sensible to be damaged due to high levels of vessels activity or busy shipping lines, these need to be protected, usually by a coverage with gravel or rock dumping.

According to reference **[13],** lead times on cable installation are currently around between six and twelve months but it has to be taken into account that this work can be done while the towers are being erected offshore, after the installation of the foundations, thus a period of three or four months overlap exists between the two work-types.

The report also sets the cable installation rates. The installation of the array cables can take one array cable per day, while simultaneous burial can take 1.5 days per cable. There are 15 array cables (between wind turbines) in the offshore wind farm configuration layout.

The following table shows the total amount of array cables installation costs assuming that the vessel rate reaches 73,300 € per day, as it is assumed in the 2013 Douglas Westwood report.

Row number (park layout)	Interconnected wind turbines	Array installation (days)	Burial (days)	Total installation price
1	5	4	6	733,000 €
2	7	6	9	1,095,000 €
3	6	5	7.5	912,500 €
From turbines 5, 17 and 18 to shore	123,320 €/Km	8 km		986,400 €
		TOTAL (€)		**3,726,900 €**

Table 10.10. Cables installation costs. Source: Author

Finally, the total amount of cable laying operations reaches THREE MILLION SEVEN HUNDRED TWENTY-SIX THOUAND NINE HUNDRED EUROS, or which is equivalent: 57,513.89 €/MW if SIEMENS wind turbines are installed (64.8 MW offshore wind farm) or 62,742.42 €/MW if VESTAS wind turbines are installed (59.4 MW offshore wind farm).

10.1.3.2. Entire transport and installation time of the offshore wind farm

In the previous sections an estimation of the time required to transport and install the parts of an offshore wind farm, including foundations and cable laying has been made. For example, it has been seen that the time of installation of turbine foundations and the sailing time to the port was 6.5 days per turbine, which multiplied by the 18 turbines that comprise the wind farm, it results in a total 117 days (approximately four months).

However, it should be noticed that this calculation has been done attempting to optimize the trips made by vessels. The election of the installing vessels (crane barges for the transport and installation of the foundations, jack-up for the installation of the wind turbines and barges equipped with a carousel, tensioners and haulers for cable laying) has been made trying to reduce as much as possible the installation time (and consequently the costs) and it is possible that the results are more optimist than in real projects.

There are also many other factors that can delay these periods and that should be taken into account but are not beyond the scope of this project and have been not considered. This is the reason why the work of planning transportation, assembly and installation of the wind farm needs to be done very carefully and in real projects, it involves high amounts of resources both human and economic.

Finally, reference **[12]** gives a standard time for the installation of an offshore wind farm, which is between 12 and 18 months (including the transformer substation, which has not been considered in this chapter). Obviously this period can be reduced by simply changing the contract strategy and using more vessels for the transport and installation works.

10.1.4. Planning & Development costs

As it has been mentioned in the previous section, planning the design, construction, installation and assembly labours plays a crucial role in the technical and economic feasibility of a project of this magnitude. Good planning and anticipation of possible contingencies that may arise during the construction phase can help saving much time and money to wind farm developers and investors. Thus, the previous works to the development of offshore wind farms can be divided in two phases, according to reference **[14]:**

- Costs of definition and design
- Costs of design and development

10.1.4.1. Phase I. Costs of definition of the offshore wind farm

The first phase involves the cost of the market study, legislative factors and the cost of the design and analysis of the design of the wind farm, and it is the phase that has been developed in this project.
The cost of market research and study involves the prior economic feasibility analysis to determine whether or not the project has an attractive and potential benefit.

Legislative factors are composed of the '*Boletin Oficial del Estado* (BOE)', the cost of released facility permits and the cost of the environmental impact study.
Finally, the design of the wind farm comprises the cost of the study of the wind resource at the sea and the mapping on existing and planned activities in the water and on the seabed, both the geotechnical and soil relief.
This phase has been entirely carried out in this project in a theoretic way, thus the costs of this phase are contain the costs explained in section 14.2. Human resources costs.
Reference **[8]** estimates that the total Planning costs can be broken down as shown in the following table:

PLANNING ACTIVITIES	COSTS
Costs of market study	
Personnel costs (for professional staff)	294,280.0 €
Legislative factors	
Building permit (varies regionally)	73,570.0 €
Ecological compensation measures (if required)	110,355.0 €
Design of the wind farm	
Wind resource assessment	3,000 – 5,000.0 €
Siting assessment	14,714.0 €
Shadow casting assessment (if required)	1,500.0 -3,000.0 €
Geological studies	14,714.0 €

Environmental compatibility study	73,570.0 €
Noise emission assessment	2,943.0 €
TOTAL PLANNING ASSESSMENT COSTS	**592,146.0 €**

*Table 10.11. Costs of the designing of the offshore wind farm. Source: Hau, Wind turbines. *Conversion from USD to EUROS (01/06/2014)*

Finally, it can be estimated that the costs for planning assessment of the offshore wind farm account for FIVE HUNDRED NINETY-TWO THOUSAND ONE HUNDRED FOURTY-SIX EUROS. In €/MW: 9,138.06 €/MW if SIEMENS wind turbines are installed, or 9,968.78 €/MW for the VESTAS wind turbine.

10.1.4.2. Phase II. Costs of design and development

The main costs of phase 2 are related to the management of the draft and the wind farm engineering, including foundations, substation, anchor and mooring structures design and calculations. These are usually carried out by an external engineering company.

In this phase, the Facultative Management of the erection of the wind farm is usually also subcontracted or externalized.

There are finally two activities or measures which are of vital importance when developing the wind farm construction phase: the Safety and Health measures, which must be supervised by a specialized company and the Quality and Control. Both activities will provide control and monitoring of the construction labours that will enable the right development of the project, complying with the legislative rules established in Phase I and all the security measures implemented. There is also a very important documentation work to be done in this phase. These costs, however, are considered in the installation section.

10.1.5. Decommissioning

At present, very few turbines have been operating offshore by more than 15 years (as it is the case of the Middelgrunden, which started operating in 2000) and therefore anticipated life expectancy is yet to be validated by experience.
As decommissioning for offshore wind farms is usually defined by regulatory requirements, each dismantling project is unique in terms of requirements of the operations, site characteristics, contract terms, conditions of the installations, etc.

A fact that can happen is that the operating company decides to replace the park turbines or parts of the facility that will ceasing to be operational, or decides at the end of the project life, to replace certain parts of the wind farm facilities. This would mean no dismantling costs, but instead a start of a new remodeling project.

Governments usually see decommissioning activities as an uncertain financial risk, due to its dependence on the financial strength of operating companies. However, from the operator's and investor's point of view, dismantling activities is a cost to be incurred in the future and, although they are obligated to remove all the structures, clear the site and verify the clearance upon lease termination, not very much attention is driven to these costs at the earliest stages of offshore wind farms design **[15].** Thus, these costs are difficult to estimate for two reasons: the inexistence of projects in that stage and the low industry experience and the inability to access to operating companies data for dismantling activities.

Despite the fact that the industry has very few experience at this point for the moment, according to the Douglas Westwood report, as a rule of thumb, decommissioning or dismantling can be estimated at half a year's revenues of the offshore wind farm. As a reference value, a total amount of SIX MILLION EUROS cost has been estimated for the dismantling process for both types of offshore wind farms, given that it is possible that some of the materials of the dismantled offshore wind farm could be sold and some extra income obtained. This value reflects a standard residual value for these projects.

10.2. Operation and Maintenance costs or *OpEx*

The OpEx (Operational expenditure) refers to expenses incurred in the course of the entire lifetime of the project, such as sales, general and administrative expenses, maintenance, etc. The operation and Maintenance costs of the wind farms are included in this section. '*8 years O&M experience at the Middelgrunden Offshore Wind Farm'* **[16],** renames this costs as 'Current costs of Offshore Wind'.

The actions of Operation and Maintenance contain a wealth of activities that can be easily confused and mixed between them. This is the reason why a meeting has been carried out with the Manager of the company *GdES*, an operator and owner of wind farms in Spain property of *COMSAEMTE*.

The meeting has been really successful in terms of obtaining Operation and Maintenance costs data, and although this data cannot be attached in this project due to the privacy policy of the company, some information can be extracted from the meeting.

During the interview, special emphasis has been driven through the difference between Maintenance costs of onshore wind farms versus offshore, where these are up to three times higher.

The company GdES owns a method that helps monitoring the costs of the operation of wind farms. This is called Balance of Plant and is distributed according the following chart:

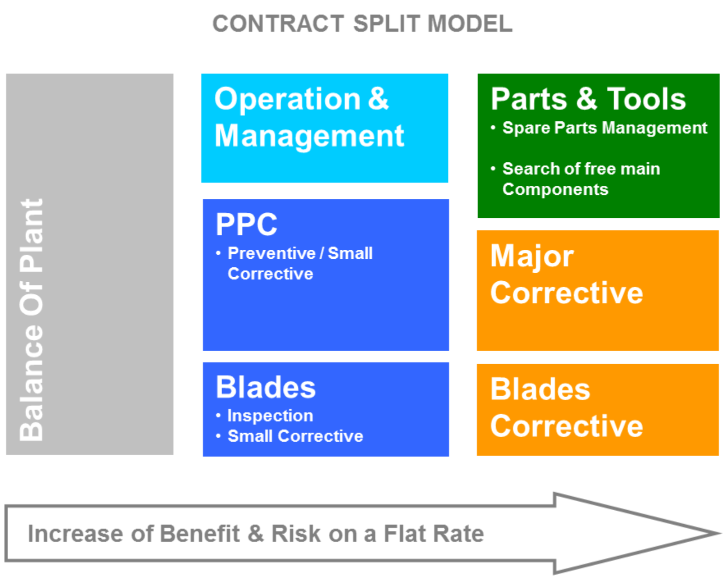


Figure 10.3. Contract split model of the Balance of plant. Source: GdES, COMSAEMTE

10.2.1. Management and administrative expenses of the offshore wind farm

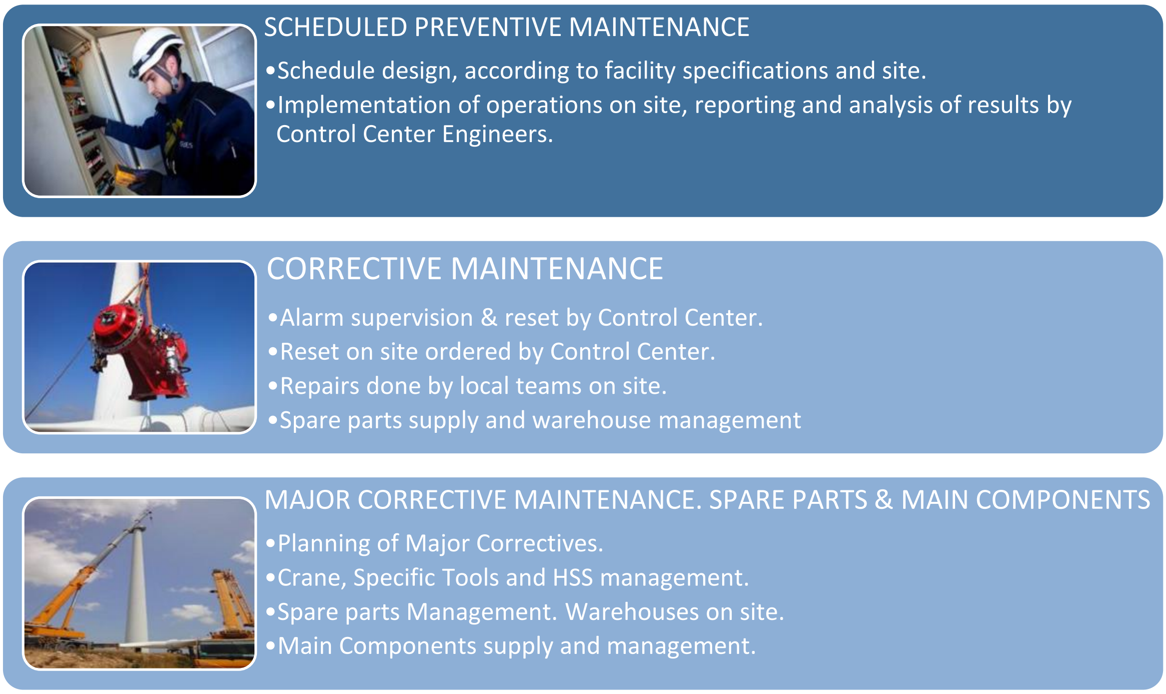
According to the information provided by GdES, the administrative expenses account for a 0.4% of the annual revenues of the operating wind farm.

For the cost model under study, which is presented in the next chapter, the profits (revenues) take into account an inflation rate of 2.5%. Therefore, the administrative expenses of the operation of the offshore wind farm have also been referenced to the same inflation rate.

10.2.2. Maintenance costs of the offshore wind farm

The costs for repairs and maintenance of the offshore wind farm will decisively depend on the rate of failure that the different parts of the wind farm present. These faults are difficult to predict and, although there are models that evaluate these potential failures, during the operational life of the wind farm they arise unexpectedly. Another factor that may influence the maintenance costs increase is the number of repair trips to the site. That is the reason why offshore wind farms are increasingly incorporating remote control systems, sensors and monitoring devices that can help preventing failures which imply offshore shifting.

According to the information provided by *GdES*, Maintenance activities can be divided in three sub-activities: scheduled preventive maintenance, corrective maintenance and major corrective maintenance, which accounts for the higher costs. The chart below shows the activities that are comprised in each section.



Scheme 10.1.Preventive and Maintenance activities to be done in an offshore wind farm . Source: Author, with the information provided by GdES

According to reference **[12],** the equipment expenses represent the largest proportional cost of offshore wind O&M, and can fluctuate depending on failure rates of items, when overhauls take place and the interim maintenance works.

There is an important aspect to be mentioned in this chapter: the operation insurances. Insurance coverage plays a crucial role when evaluating the costs of the wind farm operation lifetime and requires expert knowledge.

Liability insurances cover the risks against damage claims by third parties (both persons and properties) which can be caused by the operation of the wind turbines. Insurances against machine breakage cover repairs in case of an unusual accumulation of claims for damages. In the case of wind turbines, this should be at the manufacturer company's expense. Finally, a loss-of–profit insurance can be taken out by private owners and covers the loss of revenue in times of a standstill which is caused by a technical defect not attributable to the operator.

Finally, a comparison on the O&M costs of different projects and sources has been conducted in order to choose the most suitable value for the designed wind farm.

The estimation of O&M costs at Middelgrunden (40 MW offshore wind farm) are between 13 and 20 €/MWh per year (Svenson, Larsen, 2008) **[16],** whereas according to the Douglas Westwood Institute, the O&M costs for a large offshore wind farm account for up to 86,275.70 €/MW that, in the designed offshore wind farms would mean approximately 40 €/MWh per year.

However, this report considers this average O&M costs for large wind farms which are more than 10 km far from the coastline, and this estimation is not close to the characteristics of the designed 59.4 MW or 64.8 MW offshore wind farm. This is the reason why this estimation has been already ruled out.

Finally, a value of 22 €/MWh per year O&M costs has been considered due to its proximity to the Middelgrunden characteristics for SIEMENS wind turbines and 21 €/MWh per year for VESTAS wind turbines.

On the other hand, this matches the information provided by GdES, which suggested that O&M offshore costs are more than thrice the onshore O&M costs (between 6 and 7 €/MWh per year).

The following table shows the calculation of annual O&M costs from the annual net production of each wind park (depending on the turbines used) and the rated mentioned below:

	Rate	Net annual energy production (MWh)	TOTAL (€/year)
SIEMENS	22 €/MWh	130,586.26	2,872,897.74
VESTAS	21 €/MWh	106,009.47	2,226,198.82

Table 10.12. Annual O&M costs for the designed offshore wind farms. Source: Author

Just as the administrative expenses, these costs have been annually actualized with the inflation rate when carrying out the financial analysis.

10.3. Costs summary

'Accuracy of cost estimation varies with the complexity of the project, market uncertainty, contractual procedures, the impact of uncontrollable factors (i.e., weather), and the maturity of the industry. Cost estimation for offshore wind projects will be impacted by all of these factors' ***[15].***

After a review on the investment costs (CapEx), the Operation and Maintenance costs (OpEX), these are summarized below and expressed in unitary terms for each type of wind turbine:

Table 10.13. Capital costs and O&M costs summary for the two designed offshore wind farms. Source: Author

CAPITAL COSTS	€/MW (64.8 MW)	SIEMENS (SWT-3.6 MW)	TOTAL (€) PER 18 TURBINES
Wind turbines costs (€)			60,134,400.00 €
Wind turbine (€/unit)	928,000.00 €/MW	3,340,800 €	
Foundations (Jacket) costs			5,184,000.00 €
Foundations (€/unit)	80,000.00 €/MW	288,000 €	
Electrical infrastructure costs (OPTION 1)		7,817,565.24 €	7,817,565.24 €
- Small array cable	28,047.23 €/MW	1,817,460.24 €	
- Array cables to shore and the onshore substation	92,594.21 €/MW	6,000,105.00 €	
~~Electrical infrastructure costs (OPTION 2)~~		22,720,351.39 €	22,720,351.39 €
- Small array cable	28,047.23 €/MW	1,817,460.24 €	
- (Substation)	264,855.7 €/MW	18,722,890.80 €	
- Power export cables	33,641.98 €/MW	2,180,000.35 €	
Transport and installation costs			18,378,593.10 €
Transport & Installation (wind turbines and foundations) (€)	226,106.38 €/MW	14,651,693.10 €	
Cables installation	57,513.89 €/MW	3,726,900 €	
Planning & Development costs			592,146.0 €
Planning	9,138.06 €/MW	592,146.0 €	
Development		-	-
Decommissioning			6,000,000 €
Decommissioning (to be incurred in 20 years)	92,592.59€/MW	6,000,000 €	6,000,000 €
TOTAL CAPITAL COSTS (€)		**1,421,399.76** €/MW	**92,106,704.34** €
OPERATION AND MAINTENANCE COSTS	TO BE ACTUALISED WITH THE INFLATION RATE*		
Management and administrative expenses	0.4% of the revenues each year		
O&M costs	22 €/MWh each year		

CAPITAL COSTS	€/MW (59.4 MW)	VESTAS VT105-3.3 MW	TOTAL (€) PER 18 TURBINES
Wind turbines costs (€)			55,123,200.00 €
Wind turbine (€/unit)	928,000.00 €/MW	3,062,400.00 €	
Foundations (Jacket) costs			4,752,000.00 €
Foundations (€/unit)	80,000.00 €/MW	264,000.00 €	
Electrical infrastructure costs (OPTION 1)		4,959,702.40 €	4,959,702.40 €
- Small array cable	18,407.28 €/MW	1,093,392.40 €	
- Array cables to shore and the onshore substation	65,089.39 €/MW	3,866,310.00 €	
~~Electrical infrastructure costs (OPTION 2)~~		~~20,436,042.72 €~~	~~20,436,042.72 €~~
- Small array cable	18,407.28 €/MW	1,093,392.4 €	
- (Substation)	315,200.18 €/MW	18,722,890.80 €	
- Power export cables	36,700.34 €/MW	2,180,000.35 €	
Transport and installation costs			16,362,855.90 €
Transport & Installation (wind turbines and foundations) (€)	212,726.53 €/MW	12,635,955.90 €	
Cables installation	62,742.42 €/MW	3,726,900 €	
Planning & Development costs			592,146.0 €
Planning	9,968.79 €/MW	592,146.0 €	
Development		-	-
Decommissioning			
Decommissioning (to be incurred in 20 years)	101,010.10 €/MW	6,000,000 €	
TOTAL CAPITAL COSTS (€)	1,376,934.42 €/MW		81,789,904.30 €
OPERATION AND MAINTENANCE COSTS	TO BE ACTUALISED WITH THE INFLATION RATE*		
Management and administrative expenses	0.4% of the revenues each year		
O&M costs	21 €/MWh each year		

As it can be calculated from the tables above, the wind turbines account for the major investment costs of the offshore wind farm (approximately a 67% share for the SIEMENS wind turbines and a 62.4% share for the VESTAS wind turbines). This percentage is relatively higher than the one presented at the opening of the chapter (45-50%). This can be justified by the absence of a marine (offshore) substation in the designed project, whereas in the report carried out by Douglas Westwood the erection of an offshore wind farm is considered.

As it has been seen, these structures constitute a high amount of investment and this is the reason why they have been avoided in this project.

From these two tables, a comparison on the amount of investment per megawatt and the total amount of investment can be made between the two types of offshore wind farms (64.8 MW offshore wind farm using 18 SIEMENS wind turbines or a 59.4 MW offshore wind farm using 18 VESTAS wind turbines).

	SIEMENS (64.8 MW offshore wind farm)	VESTAS (59.4 MW offshore wind farm)
€/MW installed	1,421,399.76 €/MW	1,376,934.42 €/MW
TOTAL (€)	92,106,704 €	81,789,904 €

Table 10.14. Total amount of investment for each offshore wind farm and total amount of investment per Megawatt. Source: Author

From the table above it can be concluded, as it was predictably, that the initial investment to be made in the case of installing the 64.8 MW offshore wind farm is considerably larger (more than 10 Million euros) than installing the smaller offshore wind farm (59.4 MW).

However, if one looks carefully at the capital costs per power unit, it appears that those are not very higher in the larger offshore wind farm (the one with SIEMENS wind turbines installed, of 64.8 MW). This fact confirms that economies of scale arise in this project, i.e. the average cost of installing a turbine decreases as the scale of the rated power increases.

The concept of economies of scale is used in long-term periods and refers to reductions in unit cost as the size of the installation increases.

11. Financial analysis of the offshore wind farm

The aim of this section is to determine whether the project is financially feasible. Assuming that the designed wind park is technically viable, that is to say, that it can produce the minimum required energy to operate, and with the annual energy production of the system (see section 8), the capital costs and the operation and maintenance costs, it is possible to determine the financial viability of the project.
According to reference **[9],** the components of wind energy systems have to be treated separately. On the one hand, one will find the costs, which have been studied in chapter 9. On the other hand, the market value of the wind energy produced by the system has to be studied. This is done in this chapter, considering that the annual net energy production is the calculated in section 8.3: 130,586.26 MWh for the wind farm using SIEMENS wind turbines, and 106,009.47 MWh for the wind farm using VESTAS wind turbines.

After a review on the financial parameters fixed in this project, the financial analysis is conducted in order to answer the main question of this project: Is it economically viable to erect a large offshore wind farm on the Catalan coastline?
In order to answer the previous question two indicators have been selected among others to study the feasibility of the project: the NPV (Net Present Value) and IRR (Internal Rate of Return).

11.1. Revenues

Once defined and analyzed the types of costs (Capital, O&M and variable costs) of the wind farm, the next step for carrying out the economic viability study should be the determination of the economic compensation for the sale of the energy produced or the revenues of the project.

Three possible scenarios have been considered in order to calculate the economic income from the sale of the electricity produced in the wind farm. These scenarios have been chosen among others with a special criteria: the changes in the energetic industry law in Spain since 2007 until today, which has had an impact on the investment of new wind energy projects in Spain. A comparison between the three scenarios will be conducted and if possible, it will be justified the concerns expressed by the AEE about the Energetic Reform in 2013.

The calculations for the three scenarios are shown in ANNEX VI. It must be noticed that all these calculations are actualised with an annual interest rate of 2.5% in order to homogenise and take the same criteria for all the calculations.

11.1.1. Background and review of the economic regulations for the *special regime*

A detailed regulatory framework of the wind industry is indispensable for the well-functioning of the industry in Spain and the motivation of the population for renewable energies use.

As said in section 4, Spain is a European and worldwide leader in the optimization of the wind resource, and that has been possible only with the existence of regulations that stimulate companies to invest in clean energies and, more specifically the wind energy.

The most important law in the electric industry is the *'Ley del Sector Eléctrico'*, which was developed in 1997. Among its implementing regulations, some specific Decrees determine the price at which the electricity has to be sold. It is the case of the RD 661/2007, which established, among others, the levels of remuneration of *the special regime* energies, in which the offshore wind energy was included.

The RD 1028/2007 standardized the bonus to be received by the producers of wind energy according to the RD 661/2007, which is subjected to changes in ministerial orders regulating rates. The following table shows the compensation methodology for offshore wind energy (announced as group b.2.2. in the Royal Decree). It has to be noticed that TMR is the acronym for Average Regulated Rate, which, in 2007 was of about 60.00 €/MWh. (**Scenario I**):

Type of energy	Power	Rate	Bonus	BONUS II
b.2.2. Offshore wind energy	Power < 5 MW	90% of the TMR during the firsts 15 years and 80% of the TMR the following years	0.4	0.1
	Power > 5 MW	90% of the TMR during the firsts 5 year, 85% of the TMR the following 10 years and 80% the rest.	0.4	0.1
	Price pool 2007	57 €/MWh		
	Power warranty	4.80 €/MWh		

Table 11.1. Compensation methodology in Scenario I (2007). Source: RDL 1028/2007

In Scenario I, the amount of energy produced is sold following the next formula:

$$Revenues = \{(Price\ pool + Power\ warranty) + (Bonus\ I + BONUS\ II) \cdot TMR\} \cdot Net\ energy\ prod.$$

The TMR should be actualized every trimester according to what the RD establishes. However, it has been considered that the TMR increases with an inflation rate of 2.5%.

Later on, this Royal Decree was amended by the RD 1614/2010 and RD 1565/2010, which changed and implemented modifications and actualizations for the bonus rates. In 2010, a bonus system or 'feed in tariff' was used, consisting of a grant on the generated electricity by the producing companies to the grid. They had two options when selling the electricity, as shown in the following table:

- OPTION 1: to sell the electricity produced at a fixed rate
- OPTION 2: to sum a bonus benchmark to the price of the market ('pool') and to establish a maximum (*cap*) and minimum (*floor*) limit for the sales.

Option 1	Fixed rate	79.08	€/MWh
Option 2	Bonus benchmark	20.142	€/MWh
	Cap	91.737	€/MWh
	Floor	76.975	€/MWh
	Average price pool (2011)	59.07	€/MWh

Table 11.2. Compensation methodology in Scenario II (2011). Source: RD 1614/2010 actualised to the first trimester, 2011

According to the Royal Decree, this prices had to be updated annually or in trimesters with the fluctuations of the IPC and the inflation among the project life.

In **Scenario II**, the revenues will be taken from option 2 (Bonus benchmark) at year 2011, so the results can be compared with the ones in Scenario I, in which a kind of bonus retribution is considered.

In Scenario II, the amount of energy produced is sold following the next formula:

$$Revenues = \{(Price\ pool + Bonus\ benchmark)\} \cdot Net\ energy\ prod.$$

Given that the sum of the price pool and the bonus benchmark does not exceed the cap and it is higher than the floor, the rate for the sale of the energy accounts for 79.21 €/MWh. This calculation would be valid only for the year 2011 and the calculation should be made every trimester in function of the fluctuation of the price pool, as well as in Scenario I with the TMR. However, an extrapolation with the inflation rate has been conducted in order to estimate the revenues at 20 years to the future.

11.1.1.1. <u>2013 Energy Reform (Scenario III)</u>

More recently, the new Royal Decree Law 9/2013, on July 13th lays down 'urgent measures to ensure financial stability of the electrical system'. This amends the previous system and eliminates premiums, grants and supplements for new wind energy projects, as well as for other renewables. The new law will only consider a minimum grant for investments.

Quoting verbatim from the RD 9/2013: '*the compensation for the sale of the energy generated will be valued at the market price, and facilities may receive remuneration consisting on a **term** specified by power unit installed, covering, where appropriate, the investment cost of a typical installation that cannot be recovered from the sale of energy and a **term** that covers the operation costs, if the difference between operating costs and revenues of the market share of this type installation is not competitive'*.

For the calculation of the specific remuneration shall be considered, for a typical installation, along its regulatory useful life and in reference to the activity carried out by an efficient and well-managed company:

a. The standard income from the sale of the energy generated valued at the market price of production.

b. Standard costs.

c. The standard value of the initial investment.

Despite all this, the new law does not specify the methodology to be followed by investors for receiving these grants and the text of the Royal Decree has not been approved in its definitive form at the time this study has been carried out.

In the opinion of the AEE (‘*Asociación Empresaria Eólica’,* or *Wind Corporate Association),* this new law can have a direct impact on the financial viability of wind energy projects, thus causing a disinterest from potential investors in wind energy. The AEE believes that the industry will not accomplish the goal of attracting new investments due to the high degree of legal uncertainty that has settled in Spain as a result of the retroactivity of the Energy Reform in 2013 **[17].**

In Scenario III, a calculation will be made on the revenues of our prototype wind farm using the ‘pool’.

11.1.1.2. Actual price of the electricity on the market (Price ‘pool’)

OMIE manages the wholesales (or ‘spot’) of the electricity market in Spain and Portugal. The electric market allows the purchase and sale of electricity between agents (producers, consumers, distributers, etc.) at a certain price or ‘pool’. This transactions consist on establishing different prices to the obtained energy from many resources so that the OMEL entity (*Operador del Mercado Ibérico de la Energía, Polo Español S. A*.) conducts an auction and the price of the overall energy is fixed depending on the energy produced with carbon, considering that this last one is the most expensive form of electricity obtaining.

The price of the wholesale market (Pool) varies every hour, depending on the existing result between the interchange of the market demand and the offer sales of the electricity producers.

In this market, the network operator REE makes an estimation of the electricity demand in Spain the next day (daily horizon). From that moment, the producers start submitting their offers at a fixed price, gauged at € MW/h per production unit.

Through a bidding system, they are awarded electricity packages to cover the total electricity demand of the day, following an upward price range, i.e. from the cheapest to the most expensive deal.

The final price of electricity, which is paid to all producers alike, is determined by the last bid to be accepted. This value will be billed the day after the market session and will fix the price for every hour the next day.

OMIE provides data of the price of electricity sold in every hour of the day, as well as estimations on monthly and annual average price of pool of the electricity. As it can be seen in Figure 11.1, the evolution of electricity prices is difficult to predict, as there are many factors influencing its fluctuation.

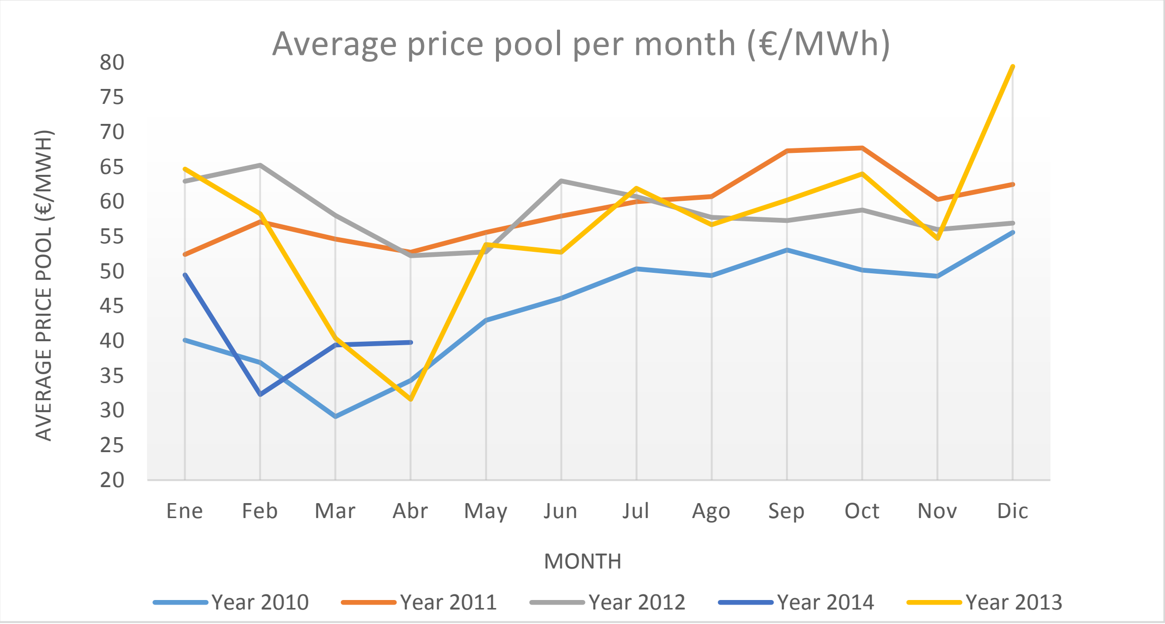


Figure 11.1. Fluctuation of the price 'pool' per months since 2010 until 2014 (April). Source: Author, with data extracted from OMIE

After considering this data, the average price pool per year has been extracted from the OMIE website and is shown in the following table.

Average price pool per year (€/MWh)	
2010	40.285 €/MWh
2011	59.066 €/MWh
2012	58.473 €/MWh
2013	**56.531 €/MWh**
2014 (Until April)	40.2325 €/MWh

Table 11.3. Average price pool per year (€/MWh). Source: Author

According to the RD 9/2013, the electricity coming from offshore wind farms with more than 50 MW installed, will be sold at the 'pool' price, without any grants or bonus.

As the fluctuation of the pool price can not be predicted at 20 years' time, the price of the year 2013 will be taken as a reference and updated with the annual 2.5% inflation rate chosen.

11.1.2. The income of the energy produced: analysis of the results

The calculation of the revenues for the sale of the electricity is shown in the following section for Scenario I as an example.

However, the mid-calculations and the annual results for the sale of the energy at each of the three scenarios and for the two type of wind farms (59.4 and 64.8 MW for VESTAS and SIEMENS wind turbines respectively) are shown in ANNEX VI and will be used to calculate the cash-flow of the project

The 64.8 MW offshore wind farm is the one which accounts with more revenues, as it was predictably. This is due to its major energy production (approximately 24.000 MWh per year). This difference is especially remarkable in Scenarios I (~58 M€) and II (~50 M€), whereas in Scenario III the difference reaches 36 M€, as shown in the table below, which summarizes the total amount of income after 20 years for each Scenario.

Offshore wind farm type (depending on the wind turbines)	SCENARIO I (2007)	SCENARIO II (2011)	SCENARIO III (2013)
64.8 MW (SIEMENS)	313,880,343 €	270,828,360 €	193,288,860 €
59.4 MW (VESTAS)	254,806,959 €	219,857,511 €	156,911,217 €

Table 11.4. Revenues for the sale of the energy for each scenario and type of offshore wind farm. Source: Author

However, to decide which the most economically feasible project is, not only the revenues can be considered, but also the expenses, interest rates, taxes need to be considered as this will be done in the following section.

However, the aim of this section was another: to compare the revenues for different Scenarios (different years and legislation at those years).

As it can be seen, the most economically favorable scenario is Scenario I, accounting for more than three hundred million euros of revenues at the end of the lifetime of the largest offshore wind farm, but which is clearly alarming is that investing in this project in 2007 would have meant obtaining almost twice the benefits of investing in the same project in 2013 as a consequence of the crop policies in the clean energies industry.

This results can confirm the fears expressed by the AEE: investing in the wind energy industry nowadays in Spain, with permanent changes in the laws governing the remuneration of the sale of the electricity could have devastating consequences for the sector.

Having seen this results and having calculated the costs of the total investment needed for the project, the following step will be to determine the cash-flow, the NPV and the IRR of the project. This parameters will help determining whether the project is economically feasible or not.

11.1.2.1. Example: Scenario I (Year of investment: 2007)

Type	Rate		Bonus I	BONUS II
B2.2	Power < 5 MW	During the first 15 years 90% TMR and 80% TMR for the following years	0.40	0.10
	Power > 5 MW	90% TMR for the first 5 years, 85% TMR for the following 10 years and 80% the rest years	0.40	0.10

Technical installation data	SIEMENS	VESTAS	Price	Units
Annual gross energy production	135,863.91	109,878.28		MWh/year
Annual net energy production	127,032.76	102,736.19		MWh/year
Value of the electricity				
TMR (*'Tarifa Media Regulable'*)			60.00	€/MWh
Average price pool 2007			57.00	€/MWh
Power warranty			4.80	€/MWh

Revenues for the electric market

YEAR	1	2	3	4	5	6	7	8	9	10
Total Revenues (SIEMENS)	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819
Total revenues + inflation (SIEMENS)	12,287,514	12,594,702	12,909,570	13,232,309	13,563,117	13,902,194	14,249,749	14,605,993	14,971,143	15,345,421
Total Revenues (VESTAS)	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669
Total revenues + inflation (VESTAS)	9,974,961	10,224,335	10,479,943	10,741,942	11,010,490	11,285,753	11,567,896	11,857,094	12,153,521	12,457,359

Revenues for the electric market

YEAR	10	11	12	13	14	15	16	17	18	19	20
Total Revenues (SIEMENS)	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819	11,987,819
Total revenues + inflation (SIEMENS)	15,729,057	16,122,283	16,525,341	16,938,474	17,361,936	17,795,984	18,240,884	18,696,906	19,164,329	19,643,437	15,729,057
Total Revenues (VESTAS)	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669	9,731,669
Total revenues + inflation (VESTAS)	12,768,793	13,088,013	13,415,213	13,750,594	14,094,359	14,446,717	14,807,885	15,178,083	15,557,535	15,946,473	12,768,793

11.2. Main parameters of the financial analysis

The main target of this section is to determine whether the project is financially viable or not, thus the main question that has led to the undertaking of this project (Is it economically feasible to install an offshore wind farm at the Catalan coastline?) will be answered.
To this end, the Net Present Value (NPV) and the Internal Rate of Return (IRR), the main indicators of the profitability of the investment, will be calculated for each of the Scenarios presented in the previous section (different years and regulation rates legislation) and for each of the designed offshore wind farm projects (59.4 and 64.8 MW).
At the end of this section a sensibility analysis will be conducted in order to determine if the parameters fixed in this section are the optimum or, otherwise they should be reviewed in order to obtain more benefits from the investment on the project.

The main parameters needed to conduct the first financial analysis have been extracted from a website whose aim is to support renewable energy [21]. These initial values are used for a first iteration and a sensitivity analysis will be carried out in order to determine which influence the results the most.

First and foremost, the project life has been fixed on 20 years. Although there is very few available data to support this decision due to very few projects having finished its lifetime, some articles show that common values for this kind of offshore large wind systems range between 20 and 25 years. As it would be expected, as the offshore wind technology is optimized, it is expected that this parameter will increase in the coming years.

Two main parameters are of huge importance in this analysis: the interest rate and the discount rate.
On the one hand, the interest rate is the price of money or pay stipulated above the stored value that an investor must receive per unit of time by the debtor as a result of having used their money during that time. The interest rate can vary from company to company, depending on the quality of collateral and credit risk involved in the transaction. On the other hand, the discount rate is the one used to calculate the present value of cash flows in the valuation of a project for a company. In other words, it is a financial measure that is applied to determine the present value of a future payment.The discount rate takes into account the risk involved when investing. An investment with higher risk have a higher interest rate compared with low-risk investments **[11].**
The interest rate is often 1-1.5% above the base rate at which the bank borrows their own funds (referred to as the interbank offer rate). Given that the value for a Bonus state at 15 years accounts for 3.5%, the interest rate has been set at 7%. The discount rates need to be set as a standard value for large investment projects with a certain degree of risk involved, thus it has been fixed 8%. The sensitivity analysis will confirm or reject these values as good or bad ones.

In reference to the initial capital investment, it has been decided to leave an 80% share of the initial investment for external investors, which would enter into the project as co-owners of the offshore wind farm. This external investors could be banks or big energetic companies with acquisitive capacity. The rest of the investment is considered to be paid by the owner of the project, or the operator of the wind farm, which, in this case, would have conducted the planning and development analysis of the project. The benefits of this co-ownership is that the operator company does not need to make a big outlay (or expenditure).
The debt repayment period for the capital rendered by external investors has been fixed at 12 years. These two parameters have been fixed following the indications of the contact that the author ha in the company GdES, a specialist operator of wind farms company.

Referring to the taxes to be paid in this Project, a taxable base of 21% has been fixed, according to the *Agencia Tributaria de España* and its regulatory framework for Taxes on the Value of the Electric Energy Production. This regulatory framework is stipulated by the title I of Law 15/2012, of 27th December, on fiscal sustainability for energy, which creates "the tax value of production of electrical energy" (IVPEE) as a direct tribute. The tax period, as established in the previously mentioned Law, is a full tax year.

Finally, the amortization period (or depreciation) has been fixed at 8 years. The amortization allocates a lump sum amount to different time periods, particularly for loans, including related interest or other finance charges.
Both depreciation and amortization, refer to wear or exhaustion suffered by an asset to the extent that their use contributes to the generation of income of the company.
There is very few difference between the concepts of amortization and depreciation, since the goal, methods and procedures of calculation are basically the same. The important difference to be noticed is the type of asset on which each concept is applied. While depreciation refers exclusively to fixed assets, amortization refers to intangible assets. Thus, the concept to be applied here should be the depreciation of the assets (external investment).

There is one concept left to be mentioned: the inflation rate, which actualises the money value for each year. The inflation rate has been applied to the calculation of the variable costs (O&M and administrative expenses) and also to the calculation of the revenues. The most correct concept to be applied here should be the fluctuation of the IPC (*Índice de Precios del Consumo*) in Spain, but this depends on many parameters that its prediction becomes out of the scope of the project.
Thus, what it has been done is to make a review on the inflation rates in Spain among the last 10 years and extrapolate the same inflation rate for the following 20 years.

The inflation analyses how much the IPC has risen in percentage terms over a given period relative to the IPC in an earlier period.
According to the '*Instituto Nacional de Estadística'* (INE) **[18]** and reference **[19],** the evolution of

the IPC in Spain in the period from December 2005 until December 2013 has seen an increase of a 22.8%. If the average annual inflation rate of the last 9 years were done, that would give an annual inflation rate of 2.5%.

It has to be taken into account, however, that the actual financial situation in Spain could have an impact on the inflation rate of the following years, diminishing this rate. It is the case of what has happened if a review on the past 25 instead of the past 10 years is done. In the period from January 1990 until January 2000, the IPC suffered an increase of a 47.7%, while from January 2000 until January 2010, the increase suffered was of 32.4% (a 4% annual average increase in the past 20 years, considerably higher that the inflation rate taken for the past 9 years). It is unlikely that the country suffers an annual growth rate so high. Thus, an extrapolation a constant inflation rate has been done for the following 20 years at 2.5%.

The following table summarizes the financial parameters of the project:

	Initial value (SIEMENS)	Initial value (VESTAS)	Units
General parameters			
Interest rate	7.00%	7.00%	%
Inflation	2.50%	2.50%	%
Taxes (IVA)	21%	21%	
Project parameters			
Discount rate	8.00%	8.00%	%
Project life	20	20	years
Investment			
Total investment	92,106,704.3 €	81,789,904.4 €	euros
Own investment (%)	20.00%	20.00%	%
	18,421,340.9 €	16,357,980.9 €	euros
External investment (%)	80.00%	80.00%	%
	73,685,363.5 €	65,431,923 €	euros
Debt repayment period	12	12	years
Amortization period	8	8	years

Table 11.5. Parameters of the financial analysis for the two types of offshore wind farms designed. Source: Author

11.3. Methodology followed for the financial analysis

This section aims to explain and detail some aspects of the methodology followed in order to obtain the NPV and IRR of the designed project. The concepts applied here have been extracted from reference **[11]** and **[21],** an economic textbook from the *Universitat Oberta de Catalunya*.

The income statement is a statement that collects the income for the year, broken down into each of its components. The cash-flow is a dynamic statement, i.e. it does not refer to a specific date, but a period of time. Unlike a normal balance, which represents a net stage at a given time, the income statement shows a flow associated with a period of time.

Some considerations to be taken into account when carrying out the cash-flow of the project are described in the following list:

- In an environment where there are taxes, as it is in the case studied, the net operating profit including the amortization, should be calculated first given that this represents a tax savings and then re-add the amortization (or depreciation).
- No grants have been considered in the accounting years of the project due to its inclusion when calculating the revenues.
- The annual nominal values for the revenues as well as the variable costs have been referred to the year 0 of the accounting years in order to take into account the inflation rate.
- It has been assumed that all the components of the cash-flow are affected in the same way by the inflation rate, thus the calculation of the NPV can be done in real terms.

11.4. Results of the financial analysis

The cash-flow for Scenario I for both projects (59.4 and 64.8 MW offshore wind farm) is shown in Table 11.6, whereas the cash-flow for Scenario II and Scenario III can be consulted in ANNEX VIII and IX. The results for the NPV and the IRR of each of the scenarios and for both projects are also discussed in this section.

AÑO	0	1	2	3	4	5	6	7	8	9
Revenues (SIEMENS)		12,287,514	12,594,702	12,909,570	13,232,309	13,563,117	13,902,194	14,249,749	14,605,993	14,971,143
Revenues (VESTAS)		9,974,961	10,224,335	10,479,943	10,741,942	11,010,490	11,285,753	11,567,896	11,857,094	12,153,521
Costs (Siemens)		2,993,870	3,068,717	3,145,435	3,224,071	3,304,673	3,387,289	3,471,972	3,558,771	3,647,740
Costs (VESTAS)		2,321,754	2,379,797	2,439,292	2,500,275	2,562,782	2,626,851	2,692,522	2,759,835	2,828,831
EBITDA SIEMENS		9,293,644	9,525,985	9,764,135	10,008,238	10,258,444	10,514,905	10,777,778	11,047,222	11,323,403
EBITDA VESTAS		7,653,207	7,844,537	8,040,651	8,241,667	8,447,709	8,658,901	8,875,374	9,097,258	9,324,690
Amortization SIEMENS	For 8 years	-11,513,338	-11,513,338	-11,513,338	-11,513,338	-11,513,338	-11,513,338	-11,513,338	-11,513,338	
Amortization VESTAS		-10,223,738	-10,223,738	-10,223,738	-10,223,738	-10,223,738	-10,223,738	-10,223,738	-10,223,738	
EBIT SIEMENS		-2,219,694	-1,987,353	-1,749,203	-1,505,100	-1,254,894	-998,433	-735,560	-466,116	11,323,403
EBIT VESTAS		-2,570,531	-2,379,201	-2,183,087	-1,982,071	-1,776,029	-1,564,837	-1,348,364	-1,126,480	9,324,690
Interests Siemens		5,157,975	4,728,144	4,298,313	3,868,482	3,438,650	3,008,819	2,578,988	2,149,156	1,719,325
Interests Vestas		4,580,235	4,198,548	3,816,862	3,435,176	3,053,490	2,671,804	2,290,117	1,908,431	1,526,745
BAT SIEMENS		-7,377,670	-6,715,497	-6,047,516	-5,373,582	-4,693,544	-4,007,252	-3,314,548	-2,615,272	9,604,078
BAT VESTAS		-7,150,765	-6,577,749	-5,999,949	-5,417,247	-4,829,519	-4,236,640	-3,638,481	-3,034,911	7,797,945
Taxes Siemens	21.00%	-1,549,311	-1,410,254	-1,269,978	-1,128,452	-985,644	-841,523	-696,055	-549,207	2,016,856
Taxes Vestas	21.00%	-1,501,661	-1,381,327	-1,259,989	-1,137,622	-1,014,199	-889,694	-764,081	-637,331	1,637,568
NET PROFIT Siemens		-5,828,359	-5,305,243	-4,777,538	-4,245,129	-3,707,900	-3,165,729	-2,618,493	-2,066,065	7,587,221
NET PROFIT Vestas		-5,649,105	-5,196,422	-4,739,960	-4,279,625	-3,815,320	-3,346,946	-2,874,400	-2,397,580	6,160,377
Amortization Siemens		11,513,338	11,513,338	11,513,338	11,513,338	11,513,338	11,513,338	11,513,338	11,513,338	
Amortization Vestas		10,223,738	10,223,738	10,223,738	10,223,738	10,223,738	10,223,738	10,223,738	10,223,738	
Expenditure Siemens	**18,421,341**	6,140,447	6,140,447	6,140,447	6,140,447	6,140,447	6,140,447	6,140,447	6,140,447	6,140,447
Expenditure Vestas	**16,357,981**	5,452,660	5,452,660	5,452,660	5,452,660	5,452,660	5,452,660	5,452,660	5,452,660	5,452,660
CASH-FLOW SIEMENS	-18,421,341	-455,468	67,648	595,353	1,127,762	1,664,991	2,207,162	2,754,398	3,306,826	1,446,774
CASH-FLOW VESTAS	-16,357,981	-878,027	-425,344	31,118	491,453	955,758	1,424,132	1,896,677	2,373,498	707,716

Table 11.6. Cash-Flow of the Project for the two types of offshore wind farms in Scenario I (2007)

YEAR	10	11	12	13	14	15	16	17	18	19	20
Revenues (SIEMENS)	15,345,421	15,729,057	16,122,283	16,525,341	16,938,474	17,361,936	17,795,984	18,240,884	18,696,906	19,164,329	19,643,437
Revenues (VESTAS)	12,457,359	12,768,793	13,088,013	13,415,213	13,750,594	14,094,359	14,446,717	14,807,885	15,178,083	15,557,535	15,946,473
Costs (Siemens)	3,738,934	3,832,407	3,928,217	4,026,423	4,127,083	4,230,260	4,336,017	4,444,417	4,555,528	4,669,416	10,786,151
Costs (VESTAS)	2,899,552	2,972,041	3,046,342	3,122,501	3,200,563	3,280,577	3,362,592	3,446,656	3,532,823	3,621,143	9,711,672
EBITDA SIEMENS	11,606,488	11,896,650	12,194,066	12,498,918	12,811,391	13,131,676	13,459,968	13,796,467	14,141,378	14,494,913	8,857,286
EBITDA VESTAS	9,557,807	9,796,752	10,041,671	10,292,713	10,550,031	10,813,781	11,084,126	11,361,229	11,645,260	11,936,391	6,234,801
Amortization SIEMENS											
Amortization VESTAS											
Grants	0	0	0	0	0	0	0	0	0	0	0
EBIT SIEMENS	11,606,488	11,896,650	12,194,066	12,498,918	12,811,391	13,131,676	13,459,968	13,796,467	14,141,378	14,494,913	8,857,286
EBIT VESTAS	9,557,807	9,796,752	10,041,671	10,292,713	10,550,031	10,813,781	11,084,126	11,361,229	11,645,260	11,936,391	6,234,801
Intereses Siemens	1,289,494	859,663	429,831								
Intereses Vestas	1,145,059	763,372	381,686								
BAT SIEMENS	10,316,994	11,036,987	11,764,235	12,498,918	12,811,391	13,131,676	13,459,968	13,796,467	14,141,378	14,494,913	8,857,286
BAT VESTAS	8,412,748	9,033,380	9,659,985	10,292,713	10,550,031	10,813,781	11,084,126	11,361,229	11,645,260	11,936,391	6,234,801
Taxes Siemens	2,166,569	2,317,767	2,470,489	2,624,773	2,690,392	2,757,652	2,826,593	2,897,258	2,969,689	3,043,932	1,860,030
Taxes Vestas	1,766,677	1,897,010	2,028,597	2,161,470	2,215,506	2,270,894	2,327,666	2,385,858	2,445,505	2,506,642	1,309,308
NET PROFIT Siemens	8,150,425	8,719,220	9,293,746	9,874,145	10,120,999	10,374,024	10,633,374	10,899,209	11,171,689	11,450,981	6,997,256
NET PROFIT Vestas	6,646,071	7,136,370	7,631,388	8,131,243	8,334,524	8,542,887	8,756,460	8,975,371	9,199,755	9,429,749	4,925,493
Amortization Siemens											
Amortization Vestas											
Expenditure Siemens	6,140,447	6,140,447	6,140,447								
Expenditure Vestas	5,452,660	5,452,660	5,452,660								
CASH-FLOW SIEMENS	2,009,978	2,578,773	3,153,299	9,874,145	10,120,999	10,374,024	10,633,374	10,899,209	11,171,689	11,450,981	6,997,256
CASH-FLOW VESTAS	1,193,411	1,683,710	2,178,728	8,131,243	8,334,524	8,542,887	8,756,460	8,975,371	9,199,755	9,429,749	4,925,493

11.4.1. Discussion of the results

The aim of this section is to determine which of the three scenarios presented in section *11.1* generates a higher profitability if investment on the project is made, taking into account the two offshore wind farm projects designed (depending on the type of turbine to be installed).

To this end, two dynamic indicators based on the discount of the cash-flows have been studied: the NPV and the IRR.

The criteria that has been taken for a theoretical acceptance of investing in the project is the IRR to be higher than the discount rate. Therefore, a scenario for each project will be accepted when the NPV is positive and when the IRR is higher than 8%.

The NPV criterion chosen to determine whether an investment is acceptable or not has been accepting only NPV's higher than zero. The NPV will be positive (higher than 0) provided that the IRR is greater than the discount rate.

Specifically, the criterion of NPV and IRR are closely linked in project evaluations, and the decision of acceptance or rejection derived from one method or another will always be the same as long as the discount rate is used as a reference thereof.

Table 11.7 shows the two indicators described above for each scenario and type of wind turbines:

		Scenario I	Scenario II	Scenario III
SIEMENS (64.8 MW)	NPV	16,337,915 €	296,235 €	-11,791,147 €
	IRR	13%	8%	- 2%
VESTAS (59.4 MW)	NPV	8,594,305 €	-20,446,413 €	-32,125,286 €
	IRR	11%	6%	-3%

Table 11.7. Values for the main indicators of the financial analysis: the NPV and the IRR for each scenario and type of offshore wind farm. Source: Author

Having seen the results, several conclusions can be driven. These conclusions have been separated in three scenarios:

- On the one hand, it can be seen that the scenario that presents the most favorable results is Scenario I, as it could be expected, given that the rate at which the electricity is sold is the highest of the three scenarios. Both Siemens and Vestas offshore wind farms present an IRR higher than the 8% and in both offshore wind farms the NPV's are positive. Therefore, one may state that installing a 59.4 MW or a 64.8 MW offshore wind farm at the Tarragona coastline is absolutely viable. While in the SIEMENS offshore wind farm the benefits are almost twice the benefits in the VESTAS offshore wind farm, the difference between the IRR accounts for only two points.
- On the other hand, in Scenario II only the offshore wind farm using SIEMENS wind turbines presents acceptable results which can determine that investing in the Project

would be profitable. In the case of the VESTAS wind turbines in Scenario II, the IRR is lower than the interest rate. Thus, it is not surprising that the NPV is negative and this case should be dismissed when considering possible investment. The difference between the two types of wind farms may be due to the difference in the energy production of each type of offshore wind farm. Athough the wind farm using SIEMENS wind turbines requires a higher initial investment, the annual energy production performance is significantly higher; making profits or revenues from the sale of energy up the difference to make investment in a project or another. For the wind farm using VESTAS wind turbines the annual energy production is lower (because the rated power of the turbine is lower) and therefore, profits from the sale of energy are lower.

- Finally, the worst scenario performance is Scenario III. In this scenario none of the two possible offshore wind farms appears to be economically viable given that both projects present a negative IRR, which in economic terms makes no sense.

Once the three scenarios have been compared separately, noting only the difference between the two possible offshore wind farms (SIEMENS and VESTAS wind turbines), now a focus on comparing the three different scenarios will be driven.

It should be taken into account here that the different scenarios refers to three methods of payment for the sale of energy, in line with changes in the law '*Ley del Sector Eléctrico'* since 2007. Therefore, one can see how due to cuts in the bonus system have directly affected the profitability of wind energy projects, making them increasingly less attractive to investors. While in 2007 (Scenario I) the sale of the energy could account for 91.8 €/MWh if the supply of the power could be guaranteed, in 2011 (Scenario II) the price for the sale of the energy would be established at 79.212 €/MWh with the bonus benchmark, almost a 10 € difference. However, it has to be noticed that if the price pool had gone down while exploding a project hosted in the law of 2011, a 'floor' price of 76.975 €/MWh would be guaranteed by the state. Finally, in 2013 (Scenario III) the Energetic Reform established that no grants or bonus would be given to wind energy producers, being the price of the sale of the energy the 'pool', which in 2013 accounted for 56.531 €/MWh, which is considerable lower than the previous prices.

The results for third scenario are very pessimistic and harbor little hope for investors in offshore wind energy, confirming the concerns of the AEE. In addition to the financial results, special attention to the changes which have taken place the law '*Ley del Sector Eléctrico'* from 2007 until now should be paid. Instability and lack of common approach could create uncertainty among investors, and this could have devastating consequences for the renewables sector.

Finally, after a review on the results, the wind turbine model to be installed in the offshore wind farm can be chosen. Although SIEMENS wind turbines require further investment than the VESTAS wind turbines, the energy performance is clearly better, making the revenues increase when selling the electricity produced. Thus, the offshore wind farm using SIEMENS 3.6 MW wind turbines is the best investment option.

From these conclusion, another point can be outlined: economies of scale greatly influence the profitability of the project: although the investment for the project using SIEMENS turbines is higher than the project using VESTAS model, this difference does not make up for the higher revenues provided by the sale of the energy produced by the first one. Economies of scale indicate that, the higher the nominal power of the turbines installed (if justified by the wind resource), the more profitable the initial investment will have been.

12. Sensitivity analyisis

Once the financial analysis of the investment required for the construction of the two type of offshore wind farms has been done, in this section a sensitivity analysis on three financial parameters will be performed and the variation of the Net Present Value (NPV) and the Internal Rate of Return (IRR) will be observed. The sensitivity analysis will determine if the parameters initially chosen in the previous section are valid for each of the three scenarios studied (Scenario I, II and III).

In a sensitivity study, a number of system variables are chosen while some reference vales are fixed and taken successively as long as the sensitivity analysis lasts.

The variables to be studied here are: the amount of own/external investment to be made in the Project, the interest rate and the discount rate.

On the other hand, the fixed parameters are the lifetime of the project (20 years), the inflation rate (2.5%), the debt repayment period (12 years) and the amortization period (8 years).

The calculations and data needed to elaborate the graphs of the sensitivity analysis can be seen in ANNEX X.

12.1. Sensitivity of the NPV and the IRR with the percentage of own/external investments

The following tables show the evolution of the NPV and the IRR with the percentage of own/external investment for each Scenario assuming that the rest of the parameters that have been used to conduct the financial analysis remain unchanged, with the same values as in section 11.2.:

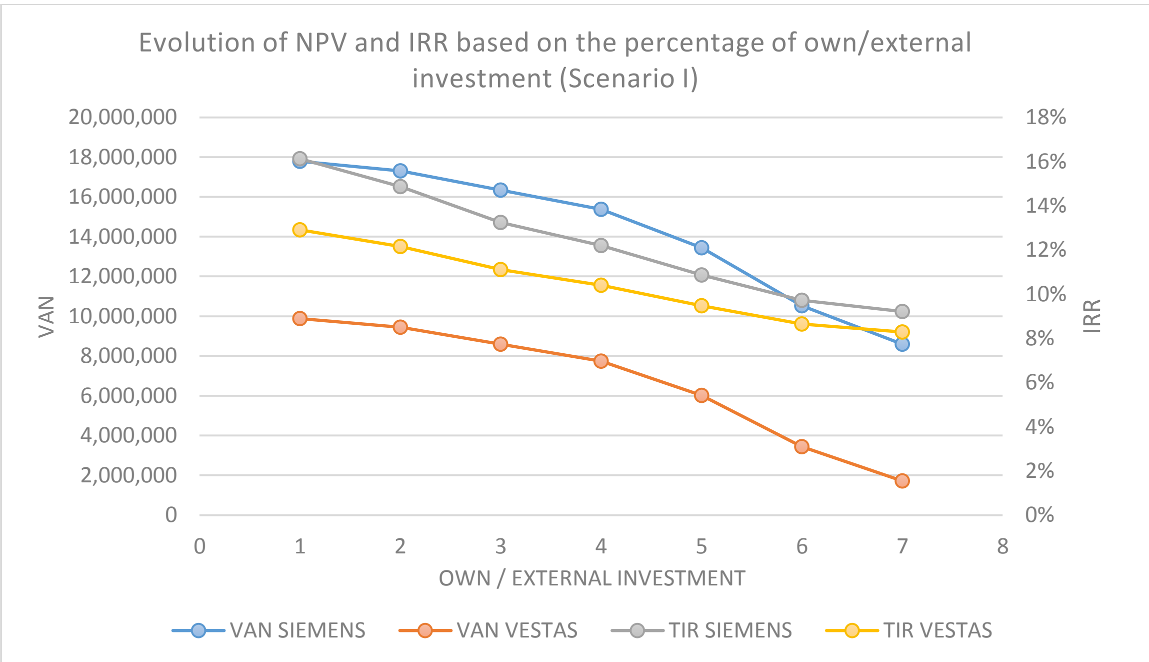


Figure 12.1. Evolution of the NPV and IRR with the percentage of own/external investment in Scenario I. Source: Author

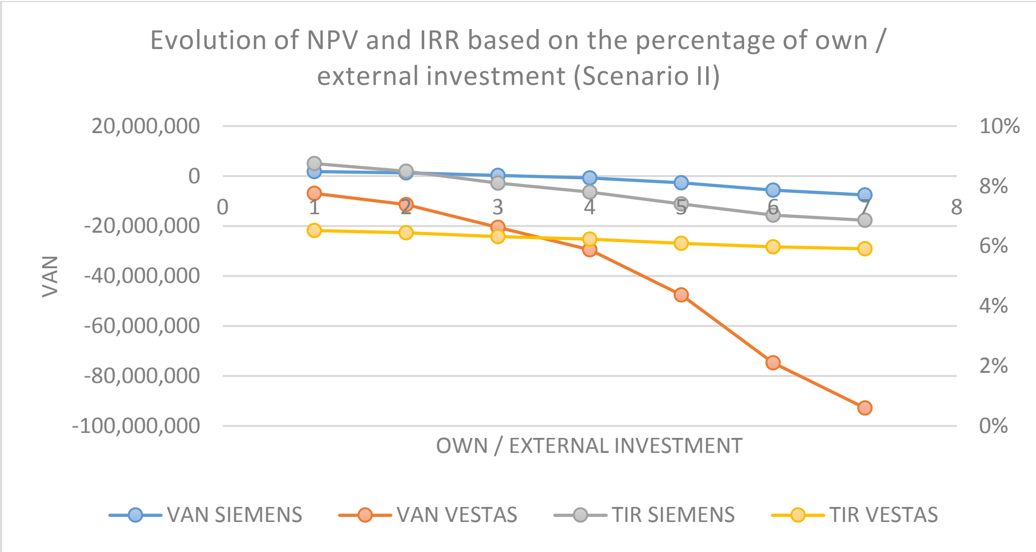


Figure 12.2. Evolution of the NPV and IRR with the percentage of own/external investment in Scenario II. Source: Author

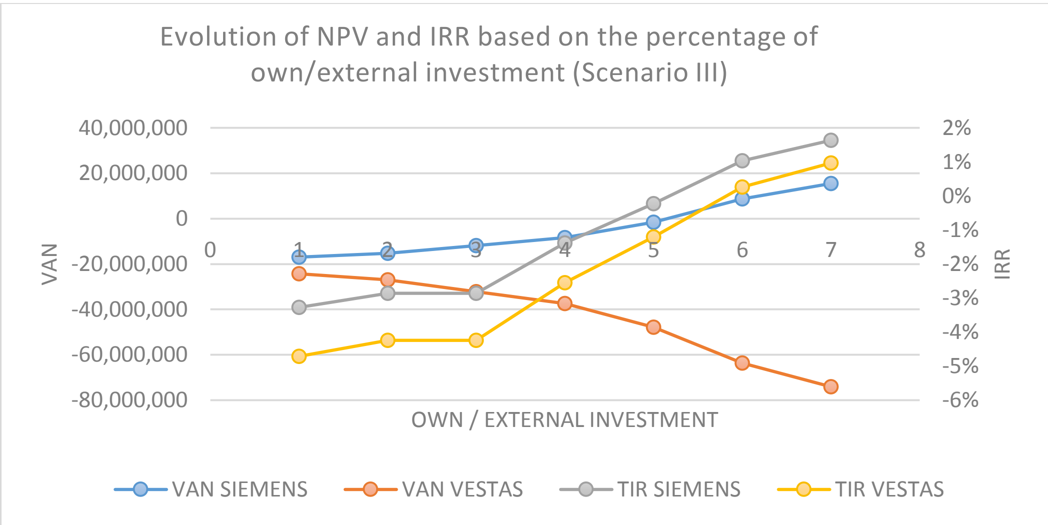


Figure 12.3. Evolution of the NPV and IRR with the percentage of own/external investment in Scenario III. Source: Author

In Scenario I, a decrease on the NPV and the IRR parameters can be observed with the increase of the own investment. That is to say, if the operator company or the owner of the offshore wind farms only invests a 5% of the total initial capital investments, the IRR and the VAN will be higher than if a 20% is invested.

Looking at the graph in Scenario I, it can be seen that both projects (the 64.8 MW and the 59.4 MW offshore wind farms) are economically viable in terms of profitability of the investment given that the NPV is higher than 0 and the IRR is higher than the discount rate (8%) for both SIEMENS and VESTAS wind turbines. It can also be observed from Graph 12.1 (Scenario I) that the two curves for the NPV's follow the same tendency, being almost parallel one from the other but displaced near 10 M€.

The same tendency could be expected to continue in Scenario II and III. However, this does not occur, as it can be seen in Graphs 12.2 and 12.3 (Scenario II and III).

It can be seen looking at the Graph 12.2, for Scenario II, that the curves that show the evolution of the NPV also decrease with the increase of the own investment. However, this tendency is more noticeable in the VESTAS offshore wind farm Project.
In Scenario III it can be seen that the two curves belonging to the IRR are almost parallel between both Projects (SIEMENS and VESTAS), while the curves representing the evolution of the NPV start at a similar value and moving away as the percentage of own investment increases and the external investment decreases.

Despite the growing tendency of the evolution of the IRR curves, the profitability for the Project if the third scenario is considered for the VESTAS wind turbines is very bad, while in the Project performed by the SIEMENS wind turbines, this profitability increases with the percentage of own investment. The difference is mainly due to that being the third Scenario such a pessimistic scenario, external investors would require a higher profitability for the project; being the interests to be paid so high that it would be better the operator or owner company of the large offshore wind farm to invest itself a large percentage of the total capital investment.

Having seen the results, it is obvious that it would be better to establish an own investment of 5% and leave the rest for the external investors. However, according to the information provided by GdES, this is not a usual procedure for a simple reason: the external investors would expect the operator company to extract the maximum benefit of the Project with the available economic resources of the company. Such a small investment from the operator company would make the external investors suspect about the risk on investing in the Project. Thus, a common standard value for the investment of 20 %own/80% external has been fixed in the main financial analysis.

12.2. Sensitivity of the NPV and the IRR with the interest rate

The following tables show the evolution of the NPV and the IRR with the interest rate for each Scenario assuming that the rest of the parameters that have been used to conduct the financial analysis remain stable, with the initial values chosen in section 11.2.:

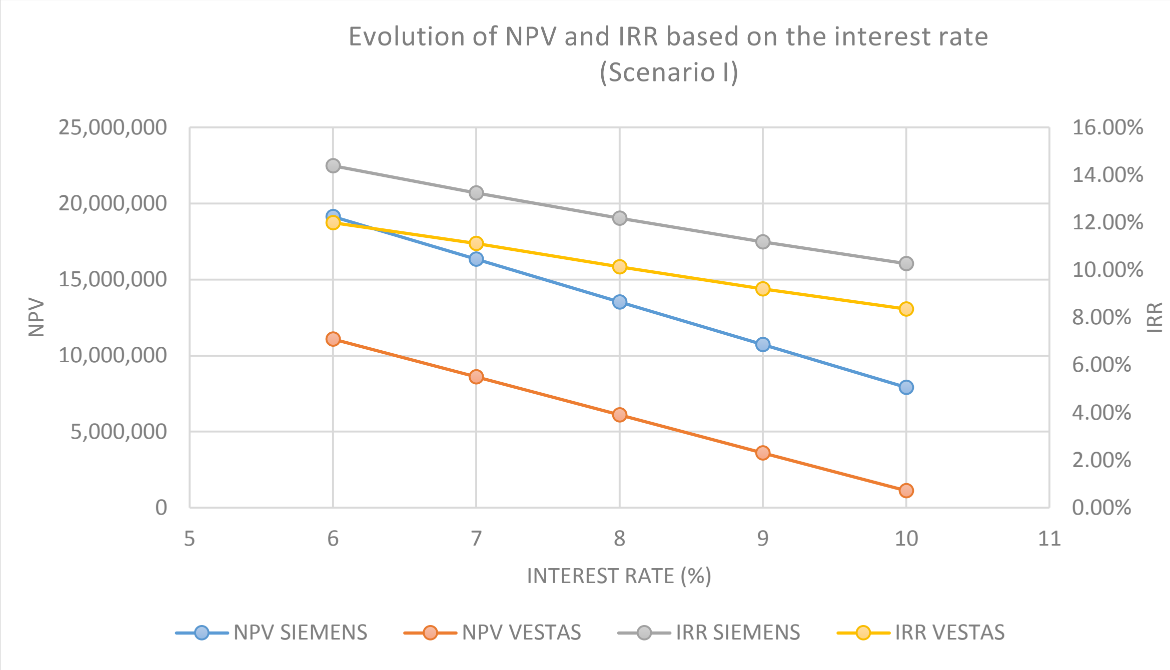


Figure 12.4. Evolution of the NPV and the IRR with the interest rate in Scenario I. Source: Author

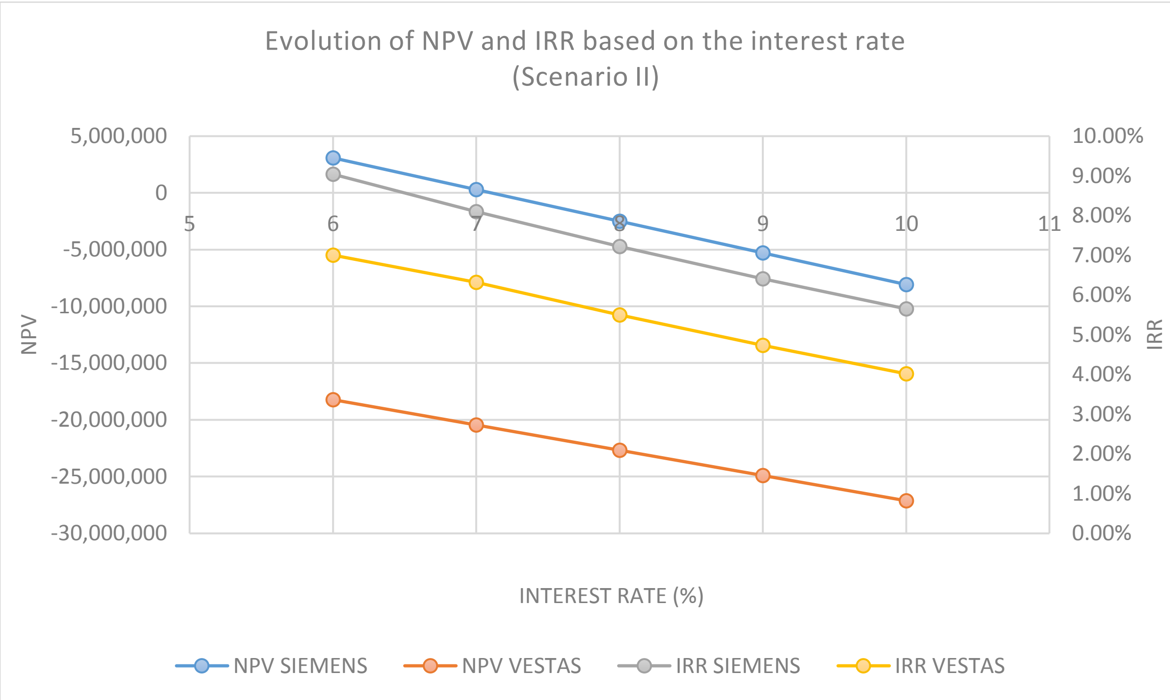


Figure 12.5. Evolution of the NPV and the IRR with the interest rate in Scenario II. Source: Author

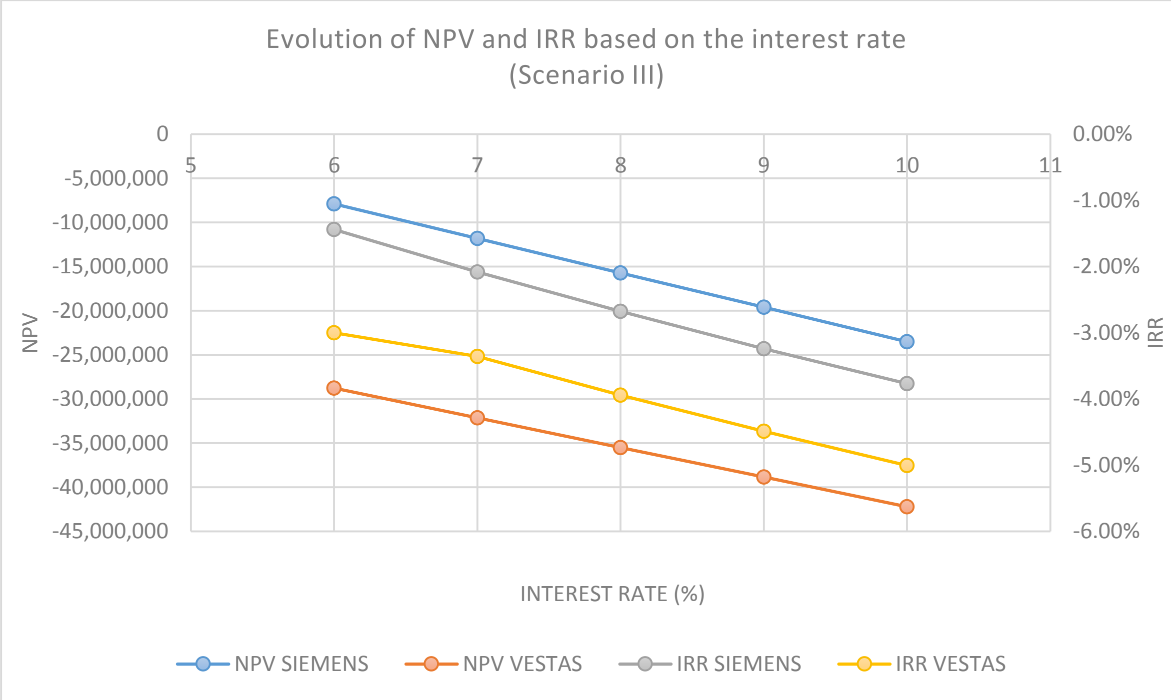


Figure 12.6. Evolution of the NPV and the IRR with the interest rate in Scenario III. Source: Author

In this analysis it can be seen how the curves representing the evolution of the NPV and the IRR for both projects (using SIEMENS and VESTAS wind turbines) decrease with the increase of the interest rate. The curves for the three Scenarios evolve following the same trend or tendency. This behavior can be explained by the higher interest rate is, the higher will be the amount to be refunded to external investors; and this is reflected in a decrease of the revenues to be perceived by the owner or the operator company themselves.

Apart from the tendency on the NPV and IRR curves, it can be observed that the unique Scenario which shows positive results referring to the viability of the Project is Scenario I, in which the NPV's are higher than zero for both SIEMENS and VESTAS wind turbines for each interest rate. The IRR's for both projects are also greater than the discount rate (8%).

In Scenario II only the interest rate of 6% establishes economically feasible Projects (both) and the interest rate of 7% makes only the SIEMEN offshore wind farm economically feasible.

In Scenario III, none of the Projects (nor SIEMENS neither VESTAS) are economically feasible if one looks at the NPV and IRR evolution curves.

12.3. Sensitivity of the NPV and the IRR with the discount rate

The following tables show the evolution of the NPV and the IRR with the discount rate for each Scenario assuming that the rest of the parameters that have been used to conduct the financial analysis remain stable, with the initial values chosen in section 11.2.:

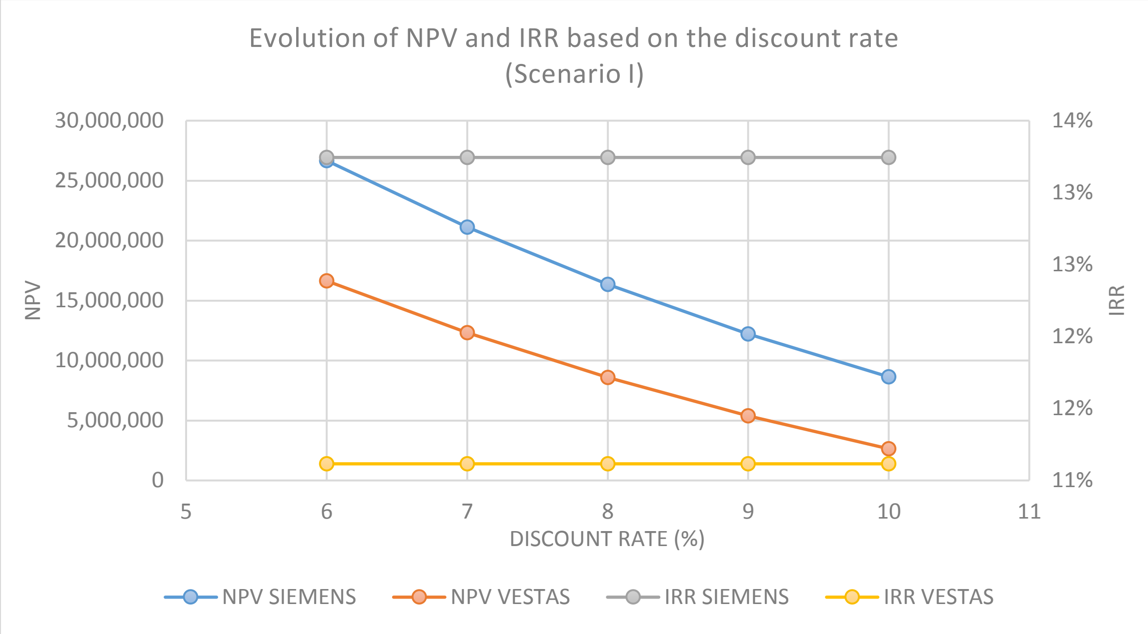


Figure 12.7. Evolution of the NPV and the IRR with the discount rate in Scenario I. Source: Author

From the graph representing the NPV parameters and IRR for Scenario I, it can be deduced that the IRR does not depend on the discount rate, since the curve representing the variation of the IRR based on the discount rate is an horizontal line for the two types of offshore wind farm (using SIEMENS and VESTAS wind turbines respectively). For the 64.8 MW wind farm, the internal rate of return has a constant value of 13%, while in the 59.4 MW wind farm, the IRR accounts for 11%.

On the other hand, it can be observed that the curves showing the variation of the NPV decrease with the increase of the discount rate, which could be expected, since it is part of the theory of investments. There is a discount rate for which the NPV is 0 (the IRR). In Scenario I, the discount rate for which the NPV is zero is a discount rate greater than 10%.

Given that the discount rate involves the risk assumed when investing in a project, a higher discount rate would mean that the risks considered are greater.

It can also be observed that the NPV for both SIEMENS and VESTAS wind turbines Projects decreases approximately at the same rate, being the NPV for SIEMENS wind turbines higher.

Apart from the tendency on the NPV and IRR curves, it can be observed that the unique Scenario which shows positive results referring to the viability of the Project is Scenario I.

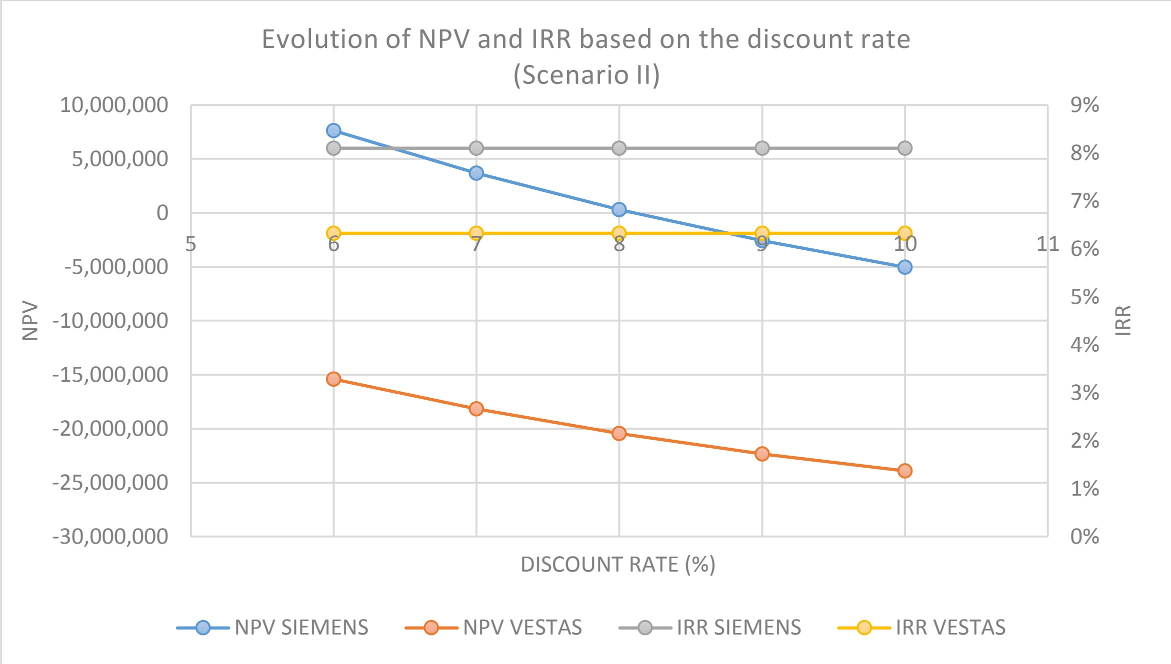


Figure 12.8. Evolution of the NPV and the IRR with the discount rate in Scenario II. Source: Author

As it could be expected, in Scenario II the curves representing the variation for the IRR and the NPV with the discount rate show the same tendency as in Scenario I.

The difference here is that the IRR are lower than in Scenario I (8 and 6% for SIEMENS and VESTAS wind turbines respectively), while the NPV shows positive results only for discount rates under 8% for SIEMENS wind turbines and negative results for each discount rate when VESTAS wind turbines are considered.

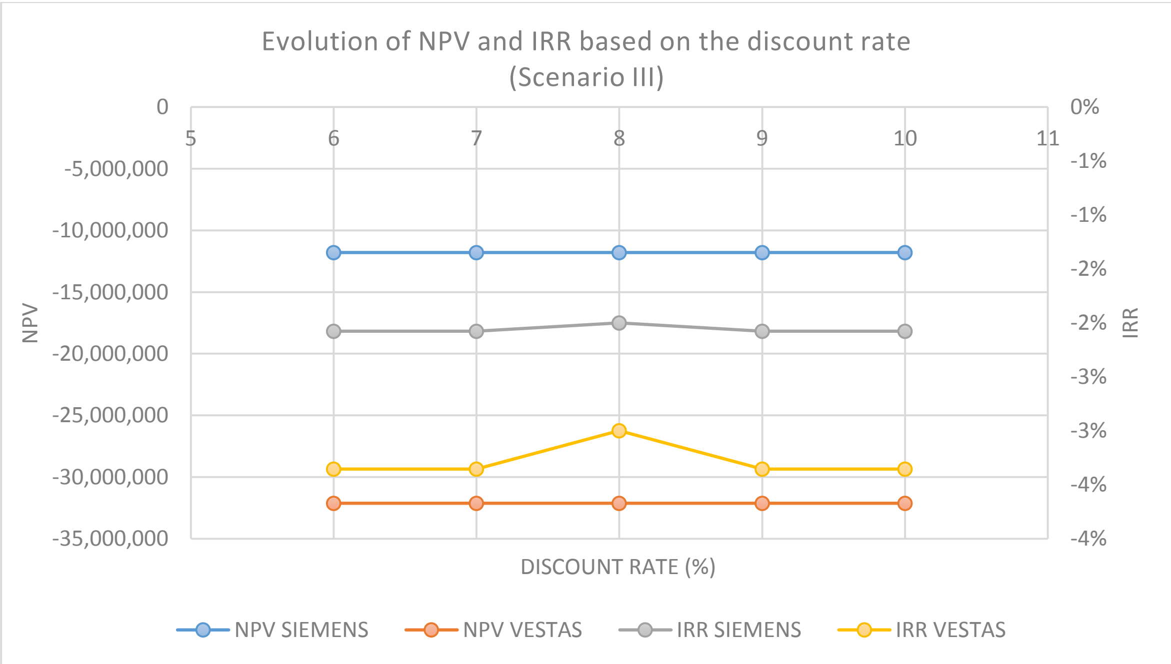


Figure 12.9. Evolution of the NPV and the IRR with the discount rate in Scenario III. Source: Author

Finally, in Scenario III the results are very pessimistic, as it could be expected from the previous analysis. The curve representing the variation of the IRR is nearly constant but negative (which economically makes no sense). Additionally, the curve representing the NPV are constant, which means that the NPV for both Projects does not depend on the discount rate.

After a review on the third sensitivity analysis two important conclusions can be deduced:

- The criterion of NPV and IRR are closely linked and in project appraisal decision of acceptance or rejection, which is derived from the use of one method or another, the decision will be the same whenever the discount rate used as a reference is the same **[11]**. That is why the results for the NPV and IRR in this sensitivity analysis have such unusual values as a constant TIR with the discount rate.
- It should be noticed here that the NPV is a decreasing function of the discount rate. There is a discount rate for which the NPV value is zero (the IRR).

Finally, after the financial analysis is carried out, a decision has been taken in order to reduce the interest rate from 7% to 6% in order to enlarge the profitability of the project.
Thus, the final values for the two indicators used in the financial analysis are:

		Scenario I	**Scenario II**	**Scenario III**
SIEMENS (64.8 MW)	NPV	19,147,489 €	3,085,340 €	-7,885,822 €
	IRR	14.4 %	9%	- 1.44%
VESTAS (59.4 MW)	NPV	11,089,181 €	-18,220,857 €	-28,765,356.5 €
	IRR	12%	7%	-3%

Table 12.1. Values for the main indicators of the financial analysis: the NPV and the IRR for each scenario and type of offshore wind farm (with a discount rate of 6%). Source: Author

However, the conclusions reached by analysing the results are the same that could be extracted from the previous financial analysis (with an interest rate of 7%), with the particularity that the profitability of the investment is higher.
Thus, the best scenario performance is Scenario I for both offshore wind farms.

13. Environmental impact

Any feasibility study should present an environmental impact study to be considered as such since discussing the characteristics of energy sources without simultaneously considering the impact they have on the environment is not possible in the present days.
According to reference **[15],** even the operation of wind turbines is not without its effects on the environment although the utilisation of wind energy deserves the attribute 'environmentally friendly'.

This section aims to summarize the main impacts on the environment that the installation of an offshore wind farm at the Catalan coastline would have in the immediate surroundings of the installation.
According to reference **[8],** the main effects to be considered on the environment emanating from wind turbines are the noise emission, the shadow effects, the possible interferences with radio or television signals, the visual impact the turbines cause on the coastline, the destruction of marine fauna and habitats caused by the installation of the foundations and the impact on the birds life.
Another important factor to be considered when performing an environmental impact analysis is the CO_2 savings that would imply the use of the offshore wind energy instead of the same production with the Spanish energetic mix.
Thus, two main impacts will be considered here: the CO_2 savings and the visual impact.

In this analysis it has also been considered important to calculate how many homes could take benefit from the energy production of the designed offshore wind farms.
On the one hand, the energy production for the designed offshore wind farm Projects are 130,586.26 MWh for the SIEMENS offshore wind farm and 106,009.47 MWh for the VESTAS offshore wind farm.
On the other hand, the IDAE [30], has estimated the annual energy consumption of electricity per home: 3,487 kWh per home.
With all this information, it can be estimated how many homes could fed from the offshore wind farm:

$$130{,}586.26\ MWh \cdot \frac{1000\ KWh}{1\ MWh} \cdot \frac{1\ building}{3{,}487\ KWh} = 37{,}449\ buildings$$

$$106{,}009.47\ MWh \cdot \frac{1000\ KWh}{1\ MWh} \cdot \frac{1\ building}{3{,}487\ KWh} = 30{,}401\ buildings$$

13.1. Tones of CO_2 saved with the offshore wind energy produced

Although not being exempted from other environmental impacts, the energy production of an offshore wind farm is free of CO_2 emissions.

In order to calculate the emissions associated with the offshore wind energy production, a CO_2 emission factor attributable to the electric supply – known as Energetic mix - needs to be applied. This factor, calculated in g CO_2/kWh represents the emissions associated to the electricity generation connected to the national grid to cover the CO_2 consumption.
According to a report elaborated by the '*Oficina Catalana del Canvi Climàtic'* ***[20]***, the CO_2 emission factor in 2010 accounted for 181 g CO_2 per KWh of electricity generated in Spain.

Having seen the annual energy production for both offshore wind farm Projects the CO_2 savings can be calculated as shown below:

$$130{,}586.26\ MWh \cdot \frac{1000\ KWh}{1\ MWh} \cdot \frac{181\ g\ CO2}{1\ KWh} \cdot \frac{1\ t\ CO2}{10^6\ g\ CO2} = 26{,}636.11\ tones\ of\ CO_2 saved$$

$$106{,}009.47\ MWh \cdot \frac{1000\ KWh}{1\ MWh} \cdot \frac{181\ g\ CO2}{1\ KWh} \cdot \frac{1\ t\ CO2}{10^6\ g\ CO2} = 19{,}187.71\ tones\ of\ CO_2 saved$$

Thus, the construction of the offshore wind farm would allow to save 26,636.11 tCO_2 per year if the SIEMENS offshore wind farm is considered while 19,187.71 tCO_2 can be saved if the VESTAS offshore wind farm is considered.

13.2. Visual impact on the landscape

One of the environmental effects of the erection of an offshore wind farm which has caused controversial discussions among the past years is the visual impact of erecting an offshore wind farm of such characteristics in front of the coastline.

The popular acceptance of the installation of a park of these characteristics will be crucial for local authorities to approve the project at the time of its submission. However, in recent years a change in the general attitude of the population towards these kind of projects has been seen, as public awareness about the environment preservation is growing significantly and the individuals become placing higher value on the contribution of wind farms to the global protection of the environment rather than the preservation of the local landscape.

14. Analysis on the organisational and economic viability of the project

14.1. Organizational viability

The feasibility study carried out in this project could be part of the Planning and Development tasks, as it has already seen in section 9. In real projects, however, this work is usually developed by a team specialized in renewable of a consulting firm subcontracted by the operator company or the owner of the offshore wind farm project.

The role associated of each consultancy profile is described in the following figure:

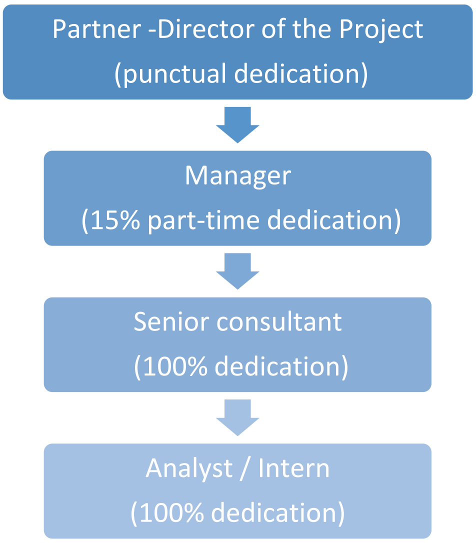


Figure 14.1. Estructure of a Projct team in a consulting firm. Source: Author, with data extracted from PwC

As part of human resources, the feasibility study in this project has been carried out by a team of three people: two junior consultants (the students carrying out the analysis from the UPC) and a Manager, the professor who has led the Project. No senior consultants have participated in the project but instead, an external assessor has been subcontracted in order to externalize some of the studies carried out.

The Manager is the responsible for the management and development of the project. One of its main tasks consists on allocating resources and to ensure compliance with targets. He or she has significant experience in developing similar projects.

The functions of the analyst is to structure the information, perform the necessary analysis and consulting to provide the necessary documentation for the development of the project. These have been the main tasks of the students who have develop this project. The junior consultant has analytical skills acquired during its training and developed in various projects in the industrial sector. In this project the fellows have had the role of an analyst.

14.2. Human resources costs

It has been seen in section *9.1. Capital costs*, that the wind farm erection requires a high initial investment. Specially, the research, planning and development phase of the project accounts for a big part of this investment, much higher than in other projects due to the difficulty to obtain reliable and constant wind resource data at the candidate offshore site.

Thus, it has been decided to separate the planning and development costs from the costs of the salaries to be perceived by the professionals working on the feasibility analysis (which has been done in this project).

It has to be taken into account that the infrastructural expenses (electricity, telecommunications, and office material) have been not considered in this budget given that it has been considered that these are carried out by the construction or the operator company.

Taking into consideration only the human resources costs (the engineers' team, dedication and duration of the project outlined in the previous sections), the budget of these works is presented below:

Professional profile	Number of resources	Fees per day (taxes included)	Dedication to the project (days)	Total PROJECT
Manager	1	250 €	10	2,500.00 €
External assessor	1	150 €	40	6,000.00 €
Junior consultant	1	75.0 €	137	10,275.00 €
				18,775.00 €

Table 14.1. Necessary investment on human resources for the Technical and economic feasibility analysis of a large-scale offshore wind farm. Source: Author.

As it can be seen in the table above, it has been considered that the junior consultant has dedicated 670 hours entirely to this project (approximately 5 hours per 137 working days).

The external assessor has been also considered as part of the human resources costs.

Finally, the total amount for the human resources costs for the planning and development phase of the Project ascends to 18,775.00 € and would be included into the personnel costs in the phase Market Study, which accounts for a total budget of 294,280.0 €. Thus, the analysis realized in this project would meant approximately a 6% share on the Planning and Development costs.

14.3. Duration of the project

In order to establish the order and the approximate time commitment dedicated to each analysis (technical and economic) a Gantt chart has been conducted. The total time estimated to develop the project is approximately of 130 working days.

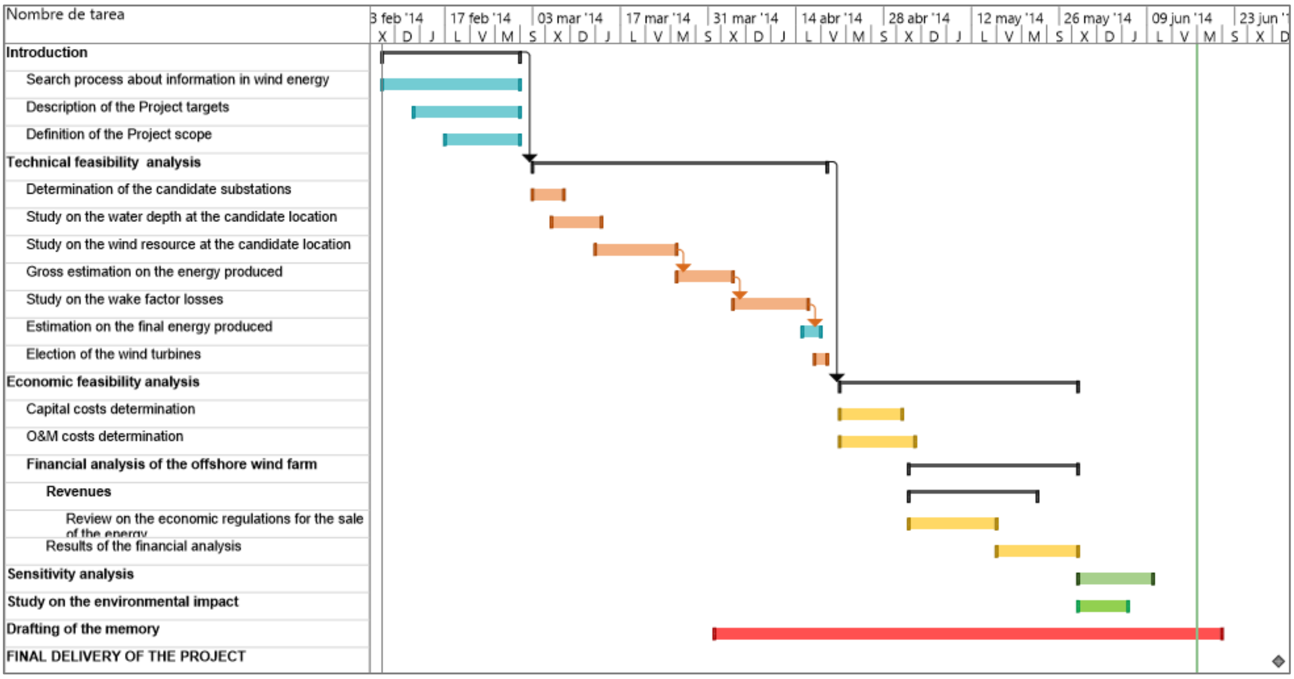


Figure 14.2. Gantt chart of the Project planning. Source: Author

CONCLUSIONS

Once the two types of analysis this project has been divided into have been done, several conclusions can be drawn in order to answer the question posed by this essay: Is it technically and economically feasible to install an offshore wind farm on the Catalan coastline?

The two results should be treated separately:

On the one hand, the technical feasibility analysis has confirmed that the designed power plant is capable of producing enough annual energy to consider its installation.
The park, of a rated nominal power of 64.8 MW with the SIEMENS turbines, produces an annual average of 130,586.26 MWh, corresponding to 2015.22 hours of use.
With the Vestas model, these figures would be translated into 59.4 MW of nominal power, producing 106,009.47 MWh a year in 1784.67 hours.

The decision to install a park of 18 turbines with the mentioned power instead of a larger offshore wind farm, like the ones in the UK, comes from the proposal of a similar plant to *Middelgrunden*. With 40 MW nominal power, it has amply proven its technical and economic efficiency.
Furthermore, the fact that the location is so close to the coast of Tarragona prevents the installation of a larger park, as it would face dissatisfaction from the public opinion due to its visual impact and would possibly interfere with some sea routes.

The revision of the rules and regulations when considering possible locations has helped to ensure that the candidate site is within the permitted areas comprehended by the *Ministry of Industry, Tourism and Trade (Ministerio de industria, Turismo y comercio)*.

On the other hand, the economic study has included both investment costs and variable cots (O & M and administrative expenses) involved in the implementation and execution of the project. The total investment to be made accounts for € 92,106,704.34 if the installed base is SIEMENS and € 81,789,904.37 if the project is finally carried out using the Vestas turbines model.
The financial analysis has suggested three possible scenarios of profitability for the various changes in the law of retribution of seaward wind energy since 2007.

Particular attention should be paid to the results obtained regarding the cost-benefit of the two proposals. It has been observed that the role of the state has been fundamental in the development of this technology and how the decrease in the bonus system can significantly compromise future offshore wind projects. A system that does not ensure that the capital invested will be recuperated, and fails to guarantee a safe recovery with gainings is not attractive to investors.
This argument is very important if Spain wants to maintain its leadership in the development of wind power thus far.

From these results it can be concluded that only with escalating oil prices, together with an optimization of the necessary technology, we could truly speak of Wind Energy as a profitable energy source without state aid.
It is important to note that the only scenario that can be considered economically viable is the first one, using the primed remuneration of 2007. Scenario II would also be feasible in case the SIEMENS turbine is used. That is why this model was ultimately chosen, obtaining an NPV of € 19,147,489 and an IRR of 14.40% in Scenario I, which is the optimum one.

Another conclusion drawn from this analysis is that economies of scale greatly influence the profitability of the project: although the investment for the project using SIEMENS turbines is higher than the project using Vestas model, this difference does not make up for the higher revenues provided by the sale of the energy produced by the first one. Economies of scale indicate that, the higher the nominal power of the turbines installed (if justified by the wind resource), the more profitable the initial investment will have been.

Finally, the sensitivity analysis has revealed that one of the most influential factors in profitability is the rate of interest. A slight variation in a point of interest rate can increase the profitability of the project (using IRR), in more than two points.

Thus, it can be said that the profitability of installing an offshore wind farm depends largely on the actions taken by the Government regarding bonus remuneration of offshore wind energy production. These actions will determine the future of the offshore wind energy in the country.

AGRAÏMENTS

Aquest projecte no hagués sigut possible sense la implicació de vàries persones, a les quals vull agraïr la seva aportació:

A l'Oriol Gomis agraïr la seva paciència amb els dubtes sobre temes elèctrics.

Agraïr a Manuel Chavarria les seves aportaciones en matèria econòmica i de finançament de parcs eòlics. La informació proporcionada ha estat de molta utilitat.

Gràcies Ariadna pel teu positivisme. Sense les aportacions de 'l*'external assessor'* aquest treball hauria estat incomplert.

Finalment, m'agradaria reconèixer el suport al llarg de tota la carrera dels meus pares i tu, Albert, i els ànims que m'heu donat en els moments més difícils. Sense vosaltres no sé si ho hauria aconseguit.

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