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Development status of global marine wind energy and contribution to the future development in Spain

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Abstract

Everybody agrees that fossil fuel energies are not sustainable and renewable energies should be introduced (eolic, solar, biomass, etc) in the electricity mix; however, there is sometimes reticence to have these installations in the own territory. To reach future sustainable growth goals like Europe to be climate neutral in 2050 the energy provided by the forces that take place in the sea called "blue energy" will be a key technology. Offshore wind energy is one of these energies, the ongoing increasing size of wind turbines decreases its costs of production and maintenance taking advantage of the scale economy. Marine wind turbines solve this space problem and have the advantage that the absence of obstacles in the sea provide more favorable conditions. This energy is rapidly growing and maturing in some parts of the world starting to play an important role in the energy system of some countries like the UK, China, Germany or Denmark. Even is expected that offshore wind power could reach onshore wind power in the next few years in terms of new aerogenerators installed. Although Europe currently has the largest floating wind energy capacity in the world, in some countries the deployment of this type of renewable energy has not started yet. Spain has great wind potential to produce clean energy that is not currently being exploited due to some economic and technological limitations. These limitations are beginning to be overcome with the evolution of technology, so the exploitation of the wind resource in the sea begins to be a viable option.

In this context, the aim of this work is to conduct a study of the global development of offshore wind energy, review the state of the art of marine wind turbines and analyze the case of development in Spain, its limitations and future steps to follow. Based on the analyzed information, conclusions have been drawn that contribute to the expansion of this energy in Spain.

Keywords: Sustainable growth, wind aerogenerators, offshore wind energy, global development.

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1. Objectives of the work.

The main objectives to develop in this work are:

1. Analyze the state of art of the offshore wind energy market actually and its perspectives for the future.
2. Analyze the evolution of offshore wind energy turbines and foundations.
3. Review the most common marine aerogenerators currently in use around the world.
4. Classify existing marine aerogenerators most used according their characteristics.
5. Analyze the state of development of marine wind power in Spain: current state, impediments to its development and conditions for future development.

2. The offshore wind energy market worldwide: state of the art, trends and analysis.

2.1. The need for renewable energies.

The main need for wind energy, as it is for the other renewable energies in the actual energy systems, is to replace fossil fuels based energy generation, to combat climate change in a global scale. But also it has the goal to mitigate environmental concerns in a regional and local scale, associated to fossil fuel-fired power plants emission of particles, nitrogen oxides and sulfur oxides. Global energy-related CO2 emissions reached a historic high in 2018, due to an increase in coal use in the power sector. Despite an impressive gain for renewables recently, fossil fuels still account for nearly two-thirds of electricity generation, the same share as 20 years ago (Gielen, et.al, 2019)

Wind energy is also increasing the security of energy supply of our energy system because it is a domestic fuel that doesn't need to be imported from other regions of the globe. Furthermore, it provides local employment and regional economic development and it can be installed very fast compared to conventional power plants.

2.2. The implication of wind energy in the European energy transition.

Offshore energy is an actual growing resource for electricity generation, especially in Europe. This type of renewable energy is based in transforming the wind's kinetic energy into electricity using large wind turbines installed in coastal waters supported by either rigid or floating structures that are anchored to the seabed. This resource will continue to grow because of ongoing technological advancements, chasing the goal of producing clean renewable energy to deal with actual environmental issues (AGI, 2016). This would contribute to limiting global warming to less than 1.5°C by the end of the century in line with the guidelines that the Paris Climate Agreement sets. Since the current energy model has very high economic, social, environmental and health costs for the people, it has been stablished an objective of an energy model 100% based on renewable energy desirable by 2050. To achieve this foremost long-term ambitious goal, Europe has applied some legislation to contribute to the decarbonization of the economy. These policies are based on fulfilling the objectives of the new EU "Clean Energy for All Europeans" package and to deliver on the EU's Paris Agreement (EC, 2015), (ICAEN, 2016):

1. 27% of the final "gross" energy consumption and 50% of the electric mix must be renewable.

2. Target of 32% for renewable energy sources in the EU's energy mix by 2030.

3. 40% reduction in GHG emissions from the energy sector compared to 1990.

To reach these objectives set at European level, the recast Renewable Energy Directive (2018/2001 / EU) entered into force in December 2018, which include a normalization rule in the Annex II explicitly for accounting the energy generated from offshore wind power.

Figure 1. Potential of offshore wind in Europe until 2050 (Wind Europe)

More and more ambitious objectives are proposed by the European institutions to accelerate as much as possible this transition to go carbon-neutral. According to the

IEA Europe could become the number one source of power generation considering that is settled on one of the world's best offshore wind resources. The European Commission says Europe needs between 230 and 450GW of offshore wind by 2050, that would do of this energy a crucial pillar in the energy mix together with onshore wind. Compared to the just 20 GW installed at that moment, this growth in installations could supply Europe with a 30% of its electricity demand in 2050, which would have grown 50% compared to 2015 due to electrification. This 450GW potential would be distributed in 212GW corresponding to the North See, 85GW in the Baltic, 83GW in the Atlantic (including the Irish Sea) and 70GW in the Mediterranean and other southern European waters. This 70GW would correspond to 17GW for France, 13GW for Spain, 9 GW for Portugal and the rest distributed throughout the rest of the Mediterranean. An important investment should be done by Europe in offshore networks that would require going from 2 billion in 2020 to 8 billion per year by 2030. Europe should increase investments in terrestrial networks to between 10 billion and 50 billion annually by 2030 (Wind Europe, 2019).

The role of offshore wind energy is key in future sustainable development as it has a lot of growth potential. This is because the sea areas where it could be implemented are huge, and currently the areas where it is implemented are small compared to the potential for expansion it has.

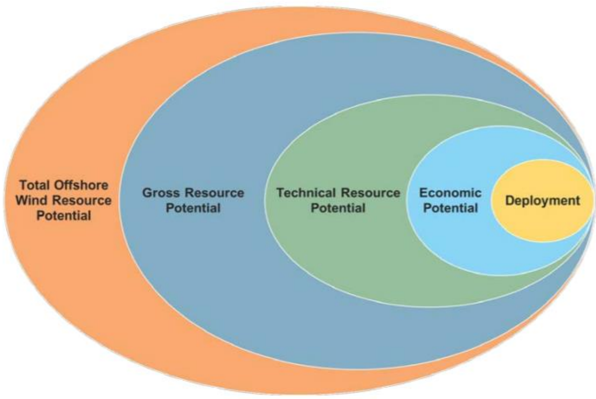

Figure 2. Offshore wind energy resource classification (National Renewable Energy Laboratory)

Figure 2 shows the idea that only a small part of the wind potential in the sea is actually used. Total offshore wind resource potential represents the entire set of offshore wind resources (recoverable and unrecoverable), regardless of whether the resource can be developed under present available technological, land-use or commercial conditions. An example of unrecoverable offshore wind resource is the wind in the Alaska EEZ (exclusive economic zone), where most of the vast energetic resource is remote from load centers. In this categorization of the resource competing use and environmental exclusions are not considered (National Renewable Energy Laboratory, 2016).

2.3. Offshore and inland wind farms: comparison and evolution.

Even though this type of energy is currently being widely studied due to its potential, it is true that it is less developed than its predecessor: onshore wind farms. Part of the potential of offshore wind exploitation is the benefits that has in front of conventional inland wind energy exploitation, that are resumed in the forthcoming points:

1. Offshore wind turbines are tend to be more efficient than onshore because wind speed and direction in the sea are more consistent. Therefore, less turbines are needed to provide the same amount of electricity.
2. Inland visual impact and noise pollution disappears due to the placement of the wind farm.
3. Absence of obstacles such as mountains, buildings and trees. As a result there are no design restrictions as distance from houses or inland grid connection, as well as local acceptability of people living there.
4. Problems related to the use of land are not a threat, although the EEZ's must be studied to see to which country corresponds the competition to exploit the marine resources of each sea.
5. Offshore wind farms can improve the marine environment around and protect the marine life of that area by supporting the growth of new artificial reefs and by protecting sea life with no-fishing areas. Recently the idea of integration in mixed marine complexes, involving for example fishing structures, is being studied.
6. Recent offshore wind projects are cheaper than new nuclear power capacity and gas-fired power plants. Offshore wind has lower variability and high capacity factors.
7. Job creation is greater than in terrestrial projects since in the construction, assembly and maintenance phases, due to the greater complexity during installation and operation.

The main point that makes it hard to justify offshore over onshore is that the technology necessary to transmit energy from turbines in a body of water is expensive. This could change as the industry matures but transporting energy through too long a wiring system can involve significant energy losses, so alternatives are being studied to reduce these losses. This is the case for hydrogen storage facilities. Its main advantage is that it allows to take advantage of the energy that, with other storage systems, would be thrown away in situations where production exceeds demand. Globally this would make the technology cheaper and more efficient (AleaSoft Energy Forecasting, 2020).

Furthermore, offshore turbines endure more wear and tear from wind and waves than onshore. This brings up operation and maintenance costs, making the price of offshore wind farms higher. Moreover, because offshore turbines are harder to get to, it could take longer to fix problems and restore them to function properly, which increase once more maintenance. As technologies improve, offshore wind developments in areas with stronger and more stable winds are likely to become more common when it becomes cheaper to build and maintain them, owing to the fact that economic factors are its main limitation (The University of North Carolina at Chapel Hill, 2016).

In addition, the sitting of wind turbines offshore is restricted by the distance to land and to harbor which is very important, as it will determine how far the wind turbines must be transport in the construction phase, but also in the operation phase. The water depth and seabed properties are very important when designing the foundations of the installation. The deeper the water, the more expensive the foundations.

To avoid conflicts between the location of the wind farm and the ship routes it's important to map the navigation routes. The grid connection is also evaluating, is done by means of a subsea cable and it's important to make sure that the sea bottom is appropriate for the connection and prevent any conflict with fisheries for instance. Generally, the wind resource offshore has a great potential, but it's not constant and it has to be evaluated before the construction of the wind farm. Finally, there is a lot of environmental concerns that must be aware of offshore, as the impact on marine mammals or migratory species.

Offshore wind energy development shows a quite unsteady progress since the beginning of its appearance as figure 3 shows but is expected to expand significantly in the years to come. Offshore wind power started to experience a record growth in 2010 leading to an average growth rate which is by far higher than the one related to the onshore wind energy sector. As for 2030, the wind industry has also set the ambitious target of 400 GW of wind power installations in Europe, out of which 150GW to be located offshore (Kaldellis and Kapsali, 2013).

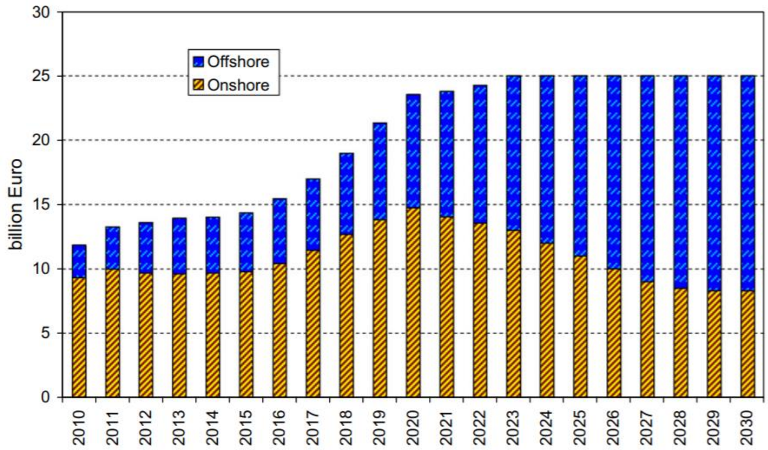

Figure 3. Projected annual wind energy investments up to 2030 (EWEA).

2.4. Evolution of offshore wind turbines and future trend.

Offshore wind technology has made impressive advances since the first turbines were installed near the shore in Denmark in 1991. Since then the objective of equipment suppliers have focused in research and development tasks to develop bigger and better performing offshore wind turbines. Actually, the legal limitation of size of the wind turbines in terms of height and rotor diameter are not that restricted in offshore wind farms as it is in inland wind farms due to visual impacts. As it can be appreciated in figure 4 wind turbine capacity has been continuously increasing since this industry started in the 90s. In the beginnings all offshore wind turbine models rated power was below 1MW, while in 2003 the first wind turbines above 2MW started to be installed all around. Since then the manufacturing trends of wind turbines capacity operating in maritime environments as well as wind farms' total capacity has increased year by year. The technology has grown dramatically in physical size and rated power output. The tip height of commercially available turbines increased from just over 100 m in 2010 (3MW turbine) to more than 200 m in 2016 (8MW turbine) while the swept area, which allows more wind to be captured by the turbine, increased by 230% (blue circumferences in the figure 4). A 12MW turbine is actually under development and is expected to reach 80% of the height of the Eiffel Tower, and the industry is even targeting larger 15-20MW turbines for 2030. Technology advances enabled offshore wind turbines to become bigger in just a few years.

Nevertheless, the vast majority of the existing large-scale projects still use shallow-water technology located at less than 30m water depth, so the goal to gradually move deeper where the wind speed is higher is one of the main points of the projects being actually developed.

Similarly to water depth, the average distance from shore was below 5km in the first projects developed, while today is close to 30km. That ensures that offshore wind turbines are installed increasingly away from the shores (IEA, 2019).

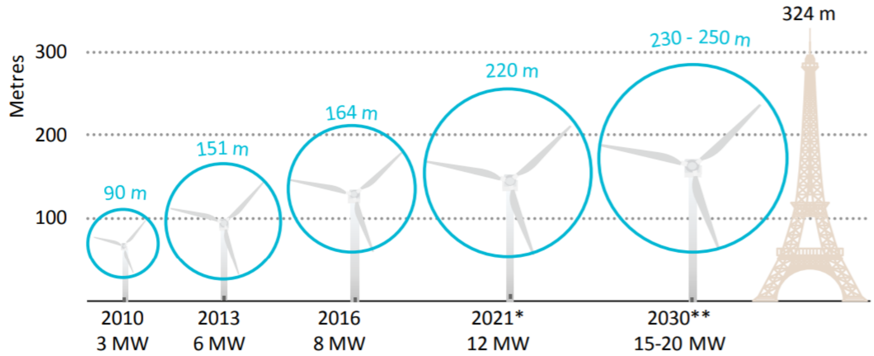

Figure 4. Size evolution of largest commercially available existing wind turbines (IEA).

2.5. Actual global offshore wind energy market and its perspectives.

Actually, lots of studies are being developed to make the most of this renewable resource. The main development will be led by the United Kingdom, Germany and Denmark. The United Kingdom and Germany currently have the largest offshore wind capacity in operation, while Denmark produced 15% of its electricity from offshore wind in 2018. In New Zealand a Geospatial multi-criteria analysis has been developed to study the best site selection to place wave and wind energy projects as it is surrounded by ocean within the Southern Hemisphere Westerly Wind belt (Soukissian et. al, 2017).

In November of 2019 the industry Siemens Gamesa provided the complex that will be implemented in Dutch waters with the largest offshore turbines in the world. The equipment will be able to reach a unit capacity of 11MW. The project plans the disposition of 140 turbines, and it will be able to generate 1,540MW which will cover the energy consumption of three million homes in the Netherlands. These new models, with shovels that will reach a length of 94 meters, will allow the use of fewer turbines and therefore less investment, to generate the same amount of energy (Siemens Gamesa, 2019).

The global offshore wind market grew close to 30% per year between 2010 and 2018, benefitting from rapid technology improvements. Yet today's offshore wind market doesn't even come close to tapping the full potential, this green energy has the potential to generate more than 420,000TWh per year worldwide, which is more than 18 times global electricity demand today. This data is showed in figure 5, developed by the IEA (IEA, 2019).

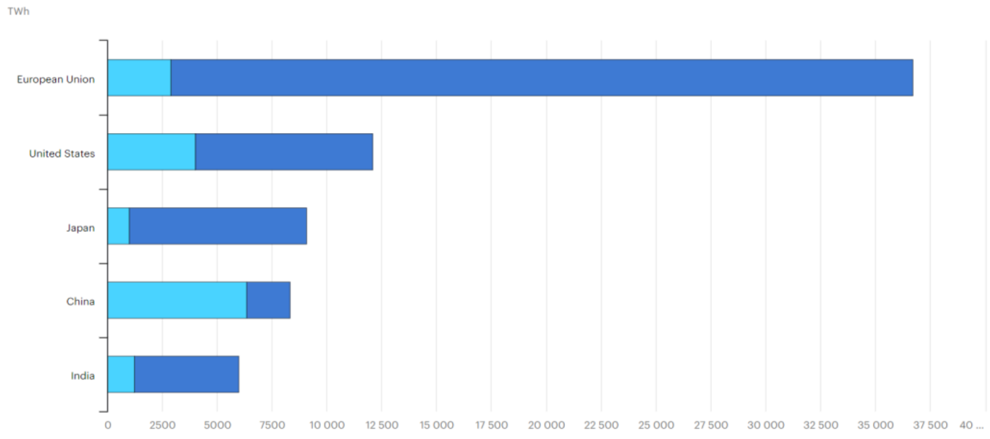

Figure 5. Offshore wind technical potential and electricity demand, 2018 (IEA).

Compared with the record 32% growth in 2017, offshore wind electricity generation increased only 20% in 2018. Given its relatively small base and high potential to expand and grow, the offshore wind industry should accelerate even further to reach the generation levels demonstrated in the Sustainable Development Scenario (SDS). This scenario is contemplated as a path to meeting global climate, air quality and universal energy access goals. Cost reductions, technology improvements and rapid deployment achieved in Europe need to be extended to other regions.

The most recent data from the IEA says that grid-connected offshore wind capacity additions reached 4.6 GW in 2018, 13% higher than the additions corresponding to 2017. While EU additions declined by 17%, in China they more than tripled to 1.6GW in 2018. This data shows that for the first time China installed more offshore capacity than any other European country, followed by the United Kingdom (1.3GW) and Germany (1.0 GW). Nevertheless, offshore wind annual capacity additions need to more than quadruple by 2030. To reach the SDS not only positive technology developments and cost reductions are needed, but also growth must accelerate.

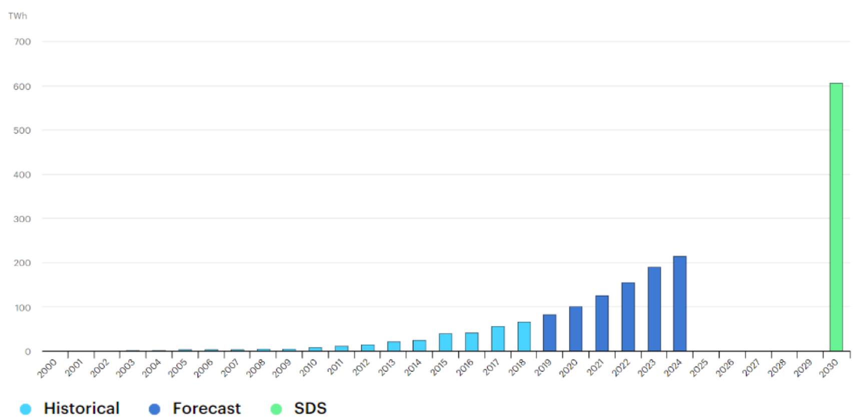

Figure 6. Offshore wind power generation in the Sustainable Development Scenario, 2000-2030 (IEA).

That is the way that a decarbonizing energy which potential is near limitless and today supplies just 0.3% of global power generation expands more and more to reach global objectives.

The next important point to consider is the dynamics of the costs related with its installations. The technology costs are falling making it more affordable and cost of electricity produced by offshore wind is projected to decline by nearly 60% by 2040. The average upfront cost to build a 1GW offshore wind project, including transmission, was over 4$ billion in 2018. This global cost is set to drop by more than 40% over the next decade, driven by a 60% reduction in the costs of turbines, foundations and their installation. Transmission actually implies around one-quarter of total offshore wind costs today, but it's expected to increase to about one-half of the total costs in the new projects to come. Innovation in transmission will be essential to support new projects without raising their overall costs as well as government policies to enhance these innovations will continue to play a critical role in the future of offshore wind and the clean energy transitions around the world.

3. Analysis of turbines and structures for offshore wind energy.

3.1. Classification of marine aerogenerators currently in use around the world.

Offshore wind turbines are structurally as same as the onshore wind turbines except for some adjustments in their designs, to put up with the harsh sea conditions. Structurally a wind turbine consists of six main parts which are: tower, nacelle, hub, and three blades. A figure that shows the location of each part of the turbine and explanation of it's working principle can be found in the annexes. The main providers of this technology in Europe are GE Renewable Energy, MHI Vestas Offshore Wind, Senvion and Siemens Gamesa Renewable Energy. Table 1 resumes the most powerful models that are actually in development as prototypes and its characteristics:

Table 1: Most powerful offshore turbine prototype models (Own elaboration).

Model name	Producer	Power capacity (MW)	Rotor diameter (m)	Nominal speed (m/s)
Haliade-X 12 MW	GE Renewable Energy	12	220	-
V164-10.0 MW	Vestas	10	164	10
SG 11.0-200 DD	Siemens Gamesa	11	200	-

We can appreciate that the Haliade-X 12 MW will be the most powerful offshore wind turbine in the world, with 220-meter rotor and 107-meter blade. Because these models are in development, commercially available models are shown in Table 2 below. To choose the most suitable turbine model to install in the chosen location some calculations will have to be developed to find out what is the behavior of the wind in the area, treated in later sections. The next table shows the basic information of the wind turbines extracted from the websites of the companies that manufacture them.

Table 2: Most powerful commercial wind turbines (Own elaboration).

Model name	Producer	Nationality	IEC wind class	Power capacity (MW)	Rotor diameter (m)	Hub height (m)	Cut-in speed (m/s)	Rated output wind speed (m/s)	Cut-out speed (m/s)
V164-9.5	MHI-Vestas	Denmark	S	9.5	164	105 – 140 m	3.5	10	25
SG 8.0-167 DD	Siemens Gamesa	Spain	I b	8	167	According to location	3	12	25
E-126 7.580	Enercon	Germany	I a	7.5	127	135	3	16,5	34

A brief explanation about power curves in wind turbines can be found in the annexes.

Wind turbines are designed for specific conditions. Wind classes determine which turbine is suitable for the normal wind conditions of a particular site. This classification of the wind class resource for the wind turbine can be consulted in the annexes.

3.2. Evolution and classification of structures for offshore wind energy.

From 2000 until 2010, the turbines used had a power ranged from 2 to 3.6MW mainly supplied from Siemens and Vestas, so offshore wind projects had an average production size ranging from 25 to 209MW. Then the projects of that time can be considered as near shore, with an average distance to shore of 12.5km and an average water depth of 11m, which implied that the monopiles, steel cylinders that are buried tens of meters underground, and GBS (gravity-based structures) concepts, used in waters where it is not possible to drill the earth, were the most common substructure type in near-shore projects. But this type of structures are not technical feasible in deep water conditions exceeding 30m of water depth. That is why spaced frame like the tripods, tri-piles or jacket type concepts have been developed and are increasingly used and installed for water depth between 30-50m, these welded structures are used in deeper waters. Related with the grid connection, the near shore location of these projects made it possible to either directly connect into onshore substations or alternatively use offshore transformer stations (Manzano et. al, 2020).

However, most near shore and shallow sites have been developed by now so actually there is a clear trend towards far-offshore projects. Consequently, increasing water depth up to more than 100m requires floating wind turbines which need to compensate the increased capital expenditure (CAPEX) for foundations and the grid connection (Slengesol, 2017).

Hywind was the first large scale floating wind structure ever developed. The producer of this spar type substructure was Statoil and it's first installation was in 2009 equipped with a standard 2.3MW Siemens offshore turbine. Principal Powers WindFloat was the second large scale floating system build, installed in 2011 at the Portuguese coast. The WindFloat is an equipment composed of a semi-submersible type floater equipped with a 2MW Vestas wind turbine.
As is mentioned is previous chapters, as the industry matures offshore wind power plants increase the large of the turbines size and the wind farms are moving further away from shore. Because of actual technology development, this progress is currently limited by the availability of locations exceeding 50m water depth, but in relatively close proximity to the shoreline. The new floating solutions that are being developed actually have the potential to unlock vast areas no further than 100km from shore but exceeding water depth of 50m. This advance allows the use of new areas previously inaccessible, which in Europe include the Atlantic and Mediterranean Sea and is most interesting for countries like Norway, Portugal, Spain and the UK. For some countries like Spain, with a narrow continental shelf, floating foundations allow the opportunity to develop large-scale offshore wind deployment. In addition, for placements that don't exceed mid-depth conditions, from 30 to 50 meters of depth, they normally offer a lower-cost alternative to fixed-bottom foundations. They also have a less impact on the marine environment as they apply less harm to the seabed during installation and development processes. (European wind energy association, 2013).

A fundamental difference between fixed and floating wind turbine support structures is the additional motions that the offshore environmental forces apply to the floating platform. The three main floating support structure classifications used in the industry are the semisubmersible, which use distributed buoyancy; spar buoys that make use of gravity and tension leg platforms (TLP), as figure 7 shows. This technologies stem from the oil and gas industry. (Cruz, 2016)

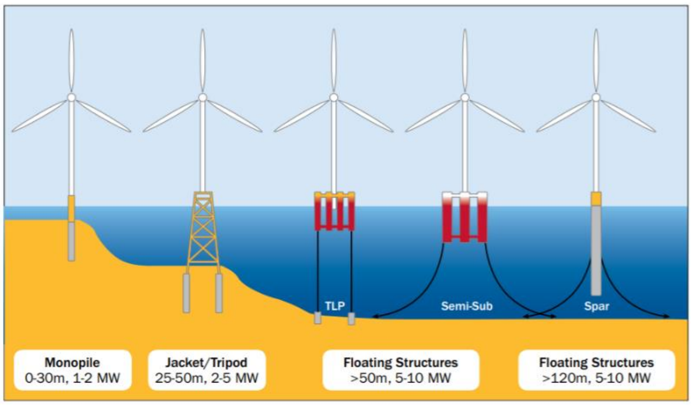

Figure 7. Offshore wind foundations (Principle Power)

Getting more in depth with the floating technologies commercially available, a brief comparison between them will be developed continuously. These structures allow access to big markets with the greatest wind resources in deep sea, breaking the 50 m depth limit of the fixed structures. This comparations are based in the information provided by European Wind Energy Association. A more detailed image can be found in the annexes (European Wind Energy Association, 2013) (IRENA, 2016).

The first option is the Spar Buoys:

- Technology name: Spar Buoys.
- Model: Hywind.
- Companies: Statoil.
- Manufacturer: Siemens.
- Description: Constituted of cylinder structures, ballasted to keep the center of gravity below the center of buoyancy. The foundation is kept in position by catenary or taut spread mooring lines anchored to the seabed.
- Pros:
    - Tendency for lower critical wave-induced motions because they have a lower center of gravity.
    - Simple design.
    - Lower installed mooring cost.
- Cons:
    - Offshore operations require heavy-lift vessels and currently can be done only in relatively sheltered, deep water.

- Needs deeper water than other concepts (>100 metres).

- Turbine capacity available: The capacity available to put in the Hywind concept were 2.3MW for the first prototypes but actually the commercial models can assume 3 to 7MW turbines.
- Placements previously installed: The first company to deploy this technology was Statoil with Hywind in Norway in year 2009 with a power installed of 2.3MW. Later in 2013 2 more MW were installed in Japan.

The second option includes TLP:

- Technology name: Tension leg Platform.
- Model: Blue H TLP.
- Companies: Blue H.
- Description: Highly buoyant, with central column and arms connected to tensioned tendons which secure the foundation to the anchors.
- Pros
    - Tendency for lower critical wave-induced motions, because their low mass.
    - Can be assembled onshore or in a dry dock.
    - Can be used in water depths to 50-60m, depending on metocean conditions.
- Cons
    - Harder to keep stable during transport and installation.
    - Depending on the design, a special purpose vessel may be required.
    - Some uncertainty about impact of possible high-frequency dynamic effects on turbine.
    - Higher installed mooring cost.
- Companies: Principle Power, EDP and Repsol.
- Manufacturer: Vestas.
- Turbine capacity available: The commercial models can support between 5 and 7 MW.
- Placements previously installed: In 2007, Blue H technologies installed the first test floating wind turbine in Italy. A manufacturing demonstration was done in 2015 allowing the new model to offer a more stable floating foundation for commercially available 5-7MW wind turbines.

The third and last option is named Semi-submersible.

- Technology name: Semi-submersible or “spar-submersible”.

- Model: Wind Float.
- Companies: Principle Power, EDP and Repsol.
- Manufacturer: Vestas.
- Description: A structure that remains semi submerged and stabilized making use of catenary or taut spread mooring lines and drag anchors, anchored to the seabed.
- Pros:
    - Constructed onshore or in a dry dock.
    - Fully equipped platforms (including turbines) can float with drafts below 10m during transport.
    - Can be used in water depths to about 40m.
    - Lower mooring and installation costs because it's high stability.
- Cons:
    - Tendency for higher critical wave-induced motions.
    - Makes use of more material and larger structures in comparison to other concepts, necessary to provide enough stability.
    - Complex fabrication compared with other concepts.
- Turbine capacity available: The capacity available to put in the WindFloat concept were 2MW for the first prototypes but the actual commercial models can assume 5 to 7MW turbines.
- Placements previously installed: In 2012 WindFloat started producing energy off the Portuguese coast equipped with a 2MW Vestas wind turbine. More powerful projects are planned also for Portugal and Oregon waters in the Pacific Ocean.

4. Regulations applicable to the offshore sector.

4.1. International.

The IEC 61400 Regulation (International Electrotechnical Commission) is a set of technical requirements that are established to guarantee the safety and proper functioning of offshore wind turbines and their components. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime of the project. More specifically, the sections IEC 61400-3-1: 2019 details design requirements for fixed offshore wind turbines and section 61400-3-2: 2019 details the design requirements for floating offshore wind turbines.

Another interesting section regarding environmental impacts is IEC 61400-11: 2012 + AMD1: 2018 CSV that presents measurement procedures that enable noise emissions of a wind turbine to be characterized (IEC, 2019).

There are several ISO international laws that apply to this sector, which are:

- ISO 19902, regulates fixed steel offshore structures (UNE, 2013).
- ISO 19903, regulates fixed concrete offshore structures (UNE, 2019).
- ISO 19904-1, regulates floating offshore structures: mono-hulls, semisubmersibles and spars (UNE, 2019).
- ISO 19904-2, regulates floating offshore structures - tension-leg platforms (UNE, 2019).

Also applies to the sector API RP 2A-WSD, Recommended practice for planning, designing and constructing fixed offshore steel platforms - working stress design.

4.2. European.

Europe has an important role in the development of OWF since it has developed ambitious policies and investments in the industry. Actually, is the manufacturing and producing leader in the sector. Some key facts are that EU companies have experience because they were the pioneers who built the first offshore wind farm installed in1991 in Vindeby (Denmark). Also, the EU contains three out of five of the top turbine manufacturers on the global offshore market, and the European companies represent a 90% of the total offshore global market.

The main directives that apply in the development of OWF in European seas are:

- Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. This Directive includes provisions that simplify permitting processes for developing renewable energy projects.

- Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency.
- Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources.
- Communication from the EC (2014 / C 200/01) referring to state aid in the field of environmental protection and energy 2014-2020.

It is also relevant the new European growth strategy in accordance with sustainable development released in 2020. The European Green Deal strategy provides a roadmap to face three main objectives which are: achieving a zero net emissions of greenhouse gases by 2050, arrive to an economic growth that is decoupled from resource (circular economy objective) use and no letting behind any European country with his mission. Some actions needed by the all sectors of our economy are (European Comision, 2020):

1. Investing in environmentally friendly technologies.
2. Support the industry partners to innovate.
3. Make the energy sector go carbon neutral.
4. Working internationally to improve global environmental standards.

4.3. National.

In a National level, the most relevant legislation that apply to the sector are:

- *Real Decreto 1028/2007*, of July 20, which establishes the administrative procedure for processing applications for authorization of electricity generation facilities in the territorial sea.
- *Ley 21/2013*, of December 9, 2013, Environmental Assessment.
- *Ley 24/2013*, of December 26, 2013, from the Electricity Sector.
- *Real Decreto 413/2014*, regulating the activity of producing electrical energy from renewable energy sources, cogeneration and waste.
- *Real Decreto 1074/2015*, of November 27, which eliminates the limit of 50 MW of minimum power for offshore wind projects. Before this modification, the minimum was 50 MW, except for experimental installations, which could be 10 MW. Installations of up to 50 MW will be regulated by Royal Decree 1955/2000, of December 1.
- *Real Decreto 1955/2000*, of December 1, which regulates the activities of transportation, distribution, marketing, supply and authorization procedures for electrical energy installations.
- *Real Decreto 79/2019*, of February 22, which regulates the compatibility report and establishes the compatibility criteria with marine strategies.
- *Plan Nacional Integrado de Energía y Clima (PNIEC)* 2021-2030 that defines the objectives of reducing greenhouse gas emissions, penetration of renewable energy and energy efficiency.
- *Plan de Energías Renovables (PER)*, of November 11 of 2011, has the objective of achieving in 2020 at least 20% of the gross final consumption of energy from the use of renewable sources.
- *Real Decreto-ley 15/2018,* of October 5, on urgent measures for the energy transition and consumer protection.

5. The offshore wind energy in Spain.

5.1. State of the art of offshore wind energy development.

Eleven European countries already have in their territorial waters one hundred offshore wind farms totaling 18.500 megawatts (MW) of power in the year 2019. The United Kingdom (8,185MW) and Germany (6,400MW) lead this sector at a great distance from the rest. Spain occupies one of the last places in this classification, with only 2 wind turbines and 10 MW of power. And it is not the case that the wind energy is stagnant in the country since a lot of power on land has been developed this year.

Although there are more that 6000km of coast, in Spain there is a physical limitation for the development of offshore wind with fixed technologies. This fact is related with the sparse continental shelf that descends very quickly, reaching very high depths at few kilometers of the coast that contrasts with the shallow waters of northern Europe. For reasons of technical and economic feasibility, the use of fixed solutions is limited to the range of shallow water, generally up to 30 or 50m, from which much more expensive floating systems must be used. Even so the use of floating turbines is becoming more frequent because they allow the implementation of wind farms in areas of great depth (more than 60m) overcoming the limitation of the depth of the marine environment. Floating wind turbines multiply the energy potential of this form of energy several times, since it takes more advantage of the wind resource deeper in the sea and can obtain much higher capacity factors (electrical energy output over a given period of time compared to the maximum possible electrical energy output over that period). The extra cost of floating offshore wind compared to other technologies is being progressively reduced more and more with the advance of technology, and year by year it is becoming a very competitive alternative. Some economic studies of the IEA suggest that in the year 2050 floating structures will be the ones that reduce the most its LCOE, reaching a 50% less cost compared with their actual cost. The Levelized Cost of Energy calculates present value of the total cost of building and operating a power plant over an assumed lifetime, obtaining a result cost in terms of lifetime costs divided by energy production.

It is important to note that the Spanish industry has high potential in the sector since of the thirty companies around the world that are developing different types of flotation platforms, seven are Spanish. So, this constantly evolving technology seems to be the solution to the stranding of offshore wind energy in Spain.

In terms of projects built in the Spanish seas, offshore wind has had little development so far, limited only to specific research projects in Gran Canaria. With the actual fast development of floating solutions, the need to exploit the great potential of wind production that exists in Spain in deep waters is evident. The goal for Europe is to reach 450,000MW (450GW) of offshore wind by 2050, which means multiplying current power by almost 25. The Spanish government is developing incentives to promote this energy, such as exclusive auctions for the implementation of new projects, interrelate the existing regulations in the field of coasts with the measurement of the resource potential in the high seas and facilitate the procedures and permits for the projects. These administrative facilities would help to assume the growth in terms of installed power, which has to evolve to 17,000MW until 2050 compared to only 10MW currently installed in the Spanish waters (Tomás Romagosa, 2018).

5.2. Experimental projects and first wind farms being developed.

The installation in Gran Canaria of the first offshore wind turbine in Spain was done in June from 2019. It was the first with a fixed foundation in the south of Europe and one of the pioneering developments in the world using automated technology. The placement was done in the port of Arinaga, where the prototype has been located, installed in the test bench for renewable energy of the Oceanic Platform of the Canary Islands (Plocan). The structure is made entirely of concrete, a material that gives durability to the structure in the aggressive conditions of the marine environment. The rotor is 132 meters in diameter and has a generating capacity of 5MW (Virgilio, 2018).

In Spain two more experimental projects are about to be developed by initiatives such as the European Financing Program for innovative projects in renewable energies called NER300. The two projects are going to be built in the Basque Country and the Canary Islands and have the mission to experiment on the best possible technological solutions in floating wind to allow consolidating competitive commercial solutions. The name of the experimental platform will be FloCan5 and will include five 5MW wind turbines, with a total capacity of 25MW. The other Spanish wind platform, which will be located on the high seas off the Bay of Biscay, on the Armintza coast, it will consist of two 5MW wind turbines and another two 8MW wind turbines (El Economista, 2019).

Consulting the European Atlas of the Seas it can be appreciated that some other spanish projects are in a state of planning, which mean that they are passing through the process to quantify the time and resources that a project will cost. Table 4 shows the projects and their state of development in Spanish waters, the location of the projects can be seen in images 8 and 9.

Table 3: Marine wind projects developed in Spanish waters (European Atlas of the Seas, 2019)

Name of the Project	Autonomous community	Number of turbines	Power (MW)	Status
Flocan 5	Canary Islands	5	25	Planned
Elican	Canary Islands	1	5	Production
Esdras Canarias	Canary Islands	-	10	Planned
Juan Grande	Canary Islands	-	200	Planned
Hexicon-WunderEnergy	Canary Islands	-	300	Planned
Nautilus	País Vasco	-	8	Planned

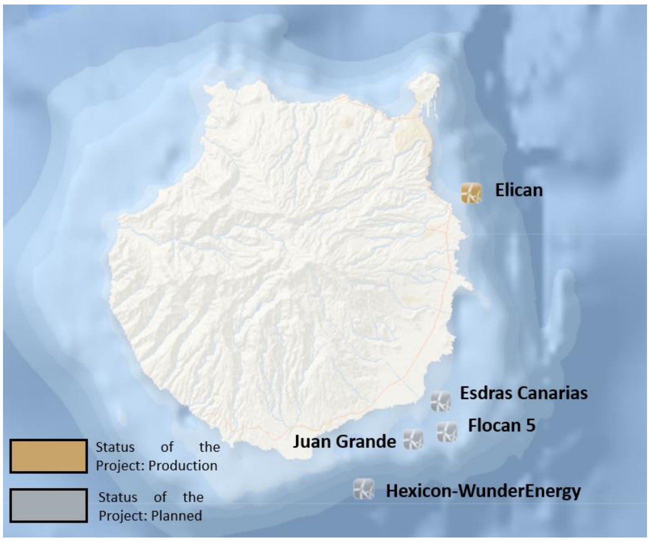

Figure 8 and 9. OWF projects and their state of development (Adapted from European Atlas of the Seas).

Currently the first non-experimental offshore wind energy projects in Spain are about to be developed, located also in the Canary Islands. More detail about these plants are explained below:

- The first project named Juan Grande, is led by Equinor, a norwegian oil company that has been authorized to settle in the Canary Islands Special Zone (ZEC) and will invest 860 million in the installation of 200MW of power. The OWF is expected to be operative by 2024. The project would reduce the high cost of energy on the islands, still produced mostly by conventional sources consisting of thermal energy and oil.
- The second case is the Greenalia company that will promote its first floating offshore wind installation in Gran Canaria, for which it has already begun its

administrative procedure. The wind farm is called GOFIO, located in the Southeast of the Island of Gran Canaria. This installation foresees the implantation of 4 marine wind turbines of 12.5MW of unit power arranged in floating foundations, generating 50MW of energy. This park, located in one of the most resource-intensive marine areas in all of Europe, will be connected to the Transport Network for evacuation using submarine cables.

- The third project is the one developed by Wunder Hexicon group. The project is under a planning phase of deploying 300MW in 35km^2 of the South-East part of Gran Canaria. The power will be deployed in the way of multi turbine floating wind platforms. The technology has been successfully tested as a demo unit in the North-East part of Canary Islands, funded by the Spanish and Canary Goverments. The project is presented as a way of conveying cost reduction through serial production and investing in local supply chain developments. The company is actually investigating several additional opportunities around the Iberian Peninsula (Wundersight group, 2018)

For this reason, the Canary Islands Government indicates as a priority to delimit as soon as possible the offshore wind areas in which the exploitation and use of the wind resource must be centralized, without impeding the development of other activities such as fishing. It is also relevant to mention that the Canary Islands has one of the strongest tax incentives available in a developed country optimal for OWF foreign project investments. That is why it has presented a preliminary study that includes the delimitation of three areas in the southeast of Gran Canaria, in Tenerife and west of Fuerteventura. These areas meet the conditions of wind, depth, topography and proximity for the development of offshore wind energy (Schellenberg and García, 2018).

5.3. Most suitable zones for marine wind energy development.

The regulatory framework in Spain for the development of marine wind farms dates from 2007 and is RD 1028/2007, which establishes the procedure to be carried out for the processing of wind farms (a brief explanation of the RD can be found in the annexes). Closely linked to the publication of this decree, the Strategic environmental study of the Spanish coast for the installation of offshore wind farms was carried out in 2009 (EEALE), seeking to facilitate the characterization of the area and guide developers.

This study was realized by the Ministry of Industry, Tourism and Trade; the Ministry of the Environment and the Ministry of Agriculture, Fisheries and Food, within the scope of their respective powers and after consulting the affected public administrations. This document is the most recent in the field of offshore energy development in Spain and divided the Spanish sea within a total of 9 eolic marine areas. The objective of this study is the determination of this areas of the maritime public domain that, for environmental reasons, meet favorable conditions for the installation of offshore wind facilities. For this purpose, exclusion zones and suitable zones have been delimited, establishing a gradation based on environmental conditions for the last ones. These zones are delimited within the scope of *Real Decreto* 1028/2007. The study suggests that the best areas to place OWF are in the waters of Galicia, Asturias, the Strait of Gibraltar, the mouth of the Ebro, Castellón and the Canary Islands.

Analyze the potential of Spanish seas for the implementation of the technology is a multicriterial process which is not simple. To evaluate the useful surface available for the installation of OWF, it is necessary to take into account a variety of <u>environmental effects</u> of which the main one is the zoning of the marine space. Other factors to take into account are the <u>technical ones</u> according to their geological and bathymetric characteristics, according to the moment in which the evolution of the technology is quantified. The <u>economic considerations</u> imply the study of the availability of enough wind resources so that OWF can be implemented, considering the higher investment and associated operating costs compared to onshore wind farms.

The first step is an environmental filtering consisting of the zoning of the "Strategic Environmental Study of the Spanish Coast" (EEAL) approved in April 2009. The tool used in this case is strategic environmental planning, an instrument to implement long-term planning of environmental and sustainable objectives in the territory, considering both private and government initiatives. This filtering concludes in a marine zoning according to the degree of affection of the potential offshore wind farms (only the potential parks greater than 50 MW are considered) in each area of the coast, with a color code:

- <u>Red color</u>: “exclusion zones”, in which an incompatibility between the existence of offshore wind farms (greater than 50 MW) and the established uses or activities was detected, or because potential environmental effects have been identified as incompatible.

- <u>Yellow color</u>: “suitable areas with conditioning factors”, where the development of offshore wind farms is conditioned, in the absence of more detailed information. The possibility of certain negative environmental effects from the installation of wind farms has been detailed, in which the environmental impact assessment of the corresponding projects must be deepened.

- Green color: "suitable areas", in which no incompatible environmental affection at the planning scale was detected in terms of strategic planning at the time of the Study was developed.

In all the situations the final environmental suitability of offshore wind implantation in the green and yellow areas will be determined for each specific project, after the necessary detailed studies.

The environmental characteristics of the places that may be affected are highly varied due to the environmental diversity shown by the selected field of study. With regard to the environmental assessment of the possible location of offshore wind farms, the following thematic groups have been considered:

- Fishing resources and activities
- Maritime-terrestrial public domain
- Biodiversity and protected areas
- Cultural heritage
- Environmental security
- Landscape

Each of the thematic groups has a wide variety of subgroups to consider for the preparation of the final diagnosis, the clues can be seen in the original strategic plan. For each group, the effects that the installation of a park would have during the construction, exploitation and dismantling phases are analyzed.

The result of the aforementioned study, following the two main objectives of developing the offshore wind energy alternative and protecting the natural values and resources of the marine environment, is shown in figure 10. A total of 72 offshore wind areas have been defined as the surface area between two parallels and two meridians affected by the study area of approximately 23.7 million hectares. The coordinate system used is WGS 84 on Spindle 30.

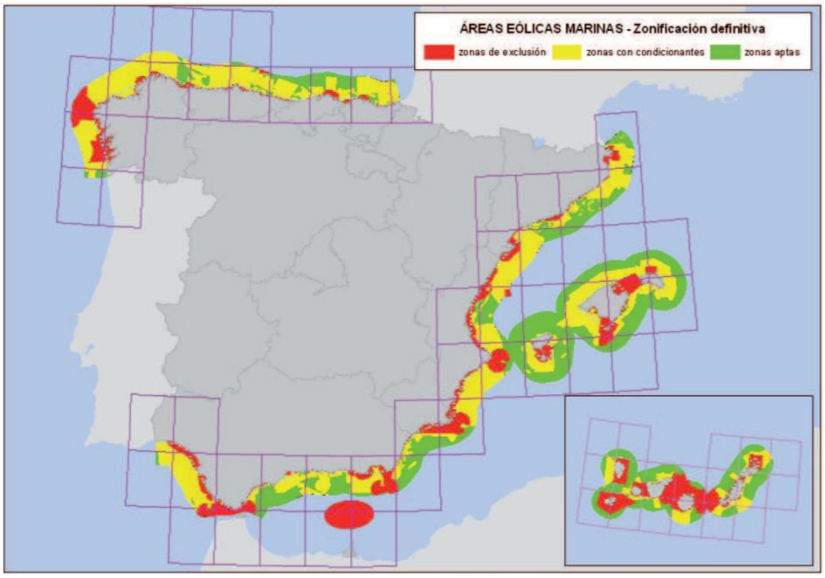

Figure 10. Zoning result of the strategic environmental study (Strategic environmental study of the Spanish coast for the installation of offshore wind farms, 2009).

The results of the study showed positive results: 36,7% of the costal territory (84.666 km2) was listed as suitable areas, 39% (89.759 km2) as suitable areas with conditioning factors and 24,3% (55.889 km2) as exclusion zones. More detailed maps of the 5 marine demarcations can be found in the annexes.

These results allow to conclude that 75% of the Spanish coast would be available, a priori, for the implementation of offshore wind farms as a result of the zoning of the EEAL. Even so, detailed studies would be necessary to determine the final environmental viability.

The second filtering that was carried out was related to technical limitations, that means according to bathymetry. At the time of the study, floating techniques were still under development and the need to implement an offshore wind farm at shallow depths below 50 m was considered. This technical restriction greatly reduced the useful area up to 8.15% of the initial extension. Floating modules are currently widely developed and can be implemented without problems, which eliminates this limitation in the present time.

Finally, a filtering by availability of wind resources was related. Offshore sites with an average annual wind speed of less than 7.5m/s at 80m, the estimated hub height for an offshore wind turbine, were considered to be technically and economically unfeasible for an offshore wind project in that area. This would result in a reduction in the useful area of less than 1.6% of the initial extension. Today, the modern turbines that are being produced have the capacity to adapt their production to the wind speed that occurs in the area in a more flexible way, which would improve this drastic drop in production capacity. Moreover, currently the costs of this technology have been greatly reduced in recent years (as mentioned in previous sections), which makes it economically viable (D. Rodríguez et.al, 2016).

According to the data provided by the study and adapting the last two limitations to the current reality, which differs technologically and economically from the year 2009 when it was published, a calculation of the offshore wind potential on the Spanish coast has been made.

The average offshore wind utilization ratio per unit area is in the order of 6 MW / km2 (IDAE, 2011). Considering that currently the advance in floating technologies is over 50 m deep (so the bathymetric limitation does not apply) and considering the surface of suitable and suitable areas with constraints, there is a usable area of 174425 km2. Overall losses of between 15 and 20% have been considered (IDAE, 2011). The result in usable potential that is obtained is 890 kW in the most favorable case (15% of losses) and 837 kW in the least favorable case (20% of losses).

The offshore areas that the study concludes have been detected as most suitable in terms of bathymetry and wind resources available for the implementation of large-scale offshore wind farms in Spain, are the following:

- Cantabrian Coast: coasts of the province of La Coruña, under the influence of the Atlantic fronts.
- South Atlantic coast: western coasts of the province of Cádiz.
- Mediterranean coast: eastern coasts of the province of Cádiz; coasts of the province of Almería, coasts of the Ebro Delta in the province of Tarragona; coasts of the province of Gerona (Cap de Creus and Medes Islands); and north-eastern coasts of the Island of Menorca.
- Coast of the Canary archipelago: south-eastern and north-western coasts of the Islands of Fuerteventura, Gran Canaria, Tenerife, La Gomera, and specific areas in Lanzarote and La Palma.

These results are in concordance with the wind map of Spain publicated by the IDAE.

Figure 11. Wind map of Spain, annual mean speed at 80 m high (IDAE, 2011).

5.4. Impediments to the development of offshore wind power.

Although Spain is a European leader in wind energy production is not the same with the development of offshore wind facilities. Data from 2019 showed that the wind power installed capacity was 25.742MW, of which offshore just 5MW. Also the electricity production that year was a total of 54.212MW, of which offshore is considered negligible. (Eurobserver, 2020).

According to the PER, the objectives where to deploy 22MW at 2015 and 750MW at 2020, results that have not been achieved since there has not been enough investment or political effort, added to the legal limitations that exist in the sector, to deploy this type of energy. The plan also estimates the emissions that would be avoided according to each renewable energy park in the period from 2011 to 2020. A savings of 1.554.616 tCO_2 was estimated, which evidently has not been achieved by not developing the technology (IDAE, 2011).

This situation must change in the years to come with new global policies and objectives to combat climate change. From the analysis of the bibliography that has been carried out, two main limitations have been considered for the development of offshore energy in Spain, which are mentioned below:

- <u>Technical and economical limitations</u>: Marine wind energy has had a significant deployment in Europe that has resulted in lower costs. In the case of fixed foundation technologies, they have decreased thanks to the increase in the size of wind turbines and economies of scale (in which the average cost of each unit decreases as quantity of production increases). The award prices of projects by sub-level have been decreasing greatly: in 2014 the price was 156€/MWh and in 2019 it was 44€/MWh. (Wind Europe, 2019).

As the floating structures are actually in development and some of its components still are in an early stage of demonstration, there is the need that this technology become less costly and, in turn, to be widely deployed. This limitation is being overwhelmed with the advance of the market, which reduces costs and makes it possible to install OWF more than 60 meters deep. This is reflected in previous sections, where it is seen that the first installations of this type have already been made and are currently operating producing clean energy. It's the case of Hywind Tampen, an 88MW floating wind power project that will be the world's largest floating offshore wind farm (Equinor, 2019). The costs of commercial projects that go from 80 to 100€/MWh are already viable in geographical areas such as the Canary Islands. It involves a conservative business sector and affects a broad range of stakeholders.

- Legal limitations: At the time that the strategic zoning study was published, 28 projects were submitted for processing with a power of 7,300MW in the areas with the most wind resources. Despite the regulatory framework of the RD 1028/2007, no progress was made with the processing of any of the projects for different reasons. Some of them are that the requirements for characterization of wind areas had to be very exhaustive, or that in some areas such as the Strait of Gibraltar there was conflict with other economic activities or social rejection.

  In Spain, it is necessary to update the regulation regarding offshore wind to adapt to current times. Various circumstances indicate that the development of offshore projects will take place in the coming years, as indicated by the projects mentioned above. If a correct update of the regulation, setting of concrete objectives and an adequate administrative procedure in coordination between the different agents was done, the growth of offshore wind power in the following decades could be notable in Spain.

Currently the Spanish industry is very well positioned for the manufacture and export of offshore wind components, such as fixed anchorage structures, floating platforms or mooring systems mainly to the northern seas. This information is supported by the following table that shows that, of the 27 float solutions that have been patented worldwide, 7 of them are Spanish.

FFS	Manufacturer	Concept Name	Country	Material
Semi-submersible	Principle Power	WindFloat	US	Steel
	Naval Energies	Semi-submersible	France	Hybrid
	Mitsubishi Heavy Industries	MHI 3 column V-shape	Japan	Steel
	Mitsui Eng. & Shipbuilding	Compact semi-sub	Japan	Steel
	GustoMSC	Tri-Floater	Netherlands	Steel
	Aqua Ventus Maine	VolturnUS	US	Concrete
	SAIPEM	HexaFloat	Italy	Steel
	Nautilus	Nautilus	Spain	Hybrid
	Cobra	Cobra Semi-spar	Spain	Concrete
	UoU, Mastek, Unison & SEHO	UOU 12-MW FOWT	South Korea	Steel
	EOLINK	EOLINK	France	Hybrid
Barge	IDEOL	Damping Pool	France	Hybrid
	SATH	SAITEC	Spain	Concrete
Spar-Buoy	Equinor	Hywind	Norway	Hybrid
	TODA Corporation	TODA Hybrid spar	Japan	Hybrid
	JMU	Advanced Spar	Japan	Steel
	Stiesdal	TetraSpar	Denmark	Steel
	SeaTwirl Engineering	SeaTwirl	Sweden	Hybrid
	ESTEYCO	TELWIND	Spain	Concrete
TLP	SBM & IFP Energies Nouvelles	Inclined-leg TLP	France	Steel
	FloatMast	FloatMast	Greece	Hybrid
	GICON GmbH	GICON-SOF	Germany	Steel
	Iberdrola	TLPWIND	Spain	Steel
	X1WIND	X1WIND	Spain	Hybrid
Multi-platform	Hexicon	Hexicon	Sweden	Steel
	Pelagic & EnerOcean	W2Power	Spain	Steel
	FLOW Ocean	FLOW	Sweden	Steel

Figure 12. Spanish floating technologies marked in red, of all the floating technologies worldwide (Windeurope, 2019).

Taking into account the main producers of wind energy, Spain is a leader in the sector. According to the Wind energy barometer, the Spanish company Iberdrola is the one with the most MW that has put into operation and maintained its existing parks in 2019 at the European level, with 17,854MW operating. In the ranking we find another Spanish company in position number 5, Acciona Energy, with 7,929MW (Eurobserver, 2020).

5.5. Solutions and future steps to take for the development of offshore wind power.

The conditions of the Spanish coast hinder the development of this technology, due to the real scarcity of suitable marine locations near the coast and of low depth. This situation is changing with the development of new floating technologies as it has been mentioned. The main objectives of the industry for the period between 2011 and 2020, according to the PER (Renewable Energy Plan) are (IDAE, 2011):

1. Development of wind turbines with unit power in the range up to 10 MW, adapted to the highest technical requirements for offshore implementation and with high technical reliability. This objective has been achieved globally since many technological advances have been achieved, not only by the Spanish industry but also internationally. Checking table number 2 it is verified that the Spanish industry itself has developed new highly profitable technologies to meet this objective, such as the SG 8.0-167 DD 8MW model from Siemens Gamesa.
2. Development of national experimental marine platforms for the R&D of foundation substructures for medium depths, floating designs for deep waters, and offshore wind turbines. This objective is beginning to be addressed, since there are some

experimental platforms in the Canary Islands that will allow the development of more extensive OWFs, as in the case of the Wunder Hexicon company. Even so, there is still a long way to go, and the number of experimental parks as of 2020 (final year to achieve the objectives) remains almost anecdotal.

3. Reduction of investment ratios and operating costs to achieve maximum international competitiveness. This is also an objective that is assumed globally due to competition between international companies, which makes flotation technologies economically compatible and can be installed.

The solutions to the legal and planification issues that prevent the development of marine wind power in Spain are:

1. Because sea energy can be positioned as non-priority due to higher generation costs compared to conventional renewable energy, it is necessary to design a remuneration framework for the implementation of floating offshore parks based on the cost avoided of each project. These subsidy-free bids have already been applied in the electricity markets of Germany and Netherlands (IRENA, 2020).
2. Include in the National Integrated Energy and Climate Plan (PNIEC) specific objectives for offshore wind power by 2030, in accordance with the current potential of the technology. This proposes that in 2030 renewables contribute 42% of final energy in Spain and 74% of electricity. This is a high figure, since the main objective is to drastically reduce the CO2 emissions that cause climate change, in addition to promoting and making our economy more competitive. In the longer term, the objective is to make Spain a carbon neutral country by 2050, considering that renewables by then provide no less than 100% of electricity. Another specific objective is the one proposed by the AAE, that suggests an objective of 2000-3000MW to be achieved (AAE, 2019)
3. Combine economic activities at sea that involve mutual aid between sectors, such as the fishing industry, the extraction of oil and gas extraction in deep waters or other renewable energies from the sea such as tidal power. The development of offshore wind is also an important vector of economic development promoting national industrial sectors such as the shipbuilding industry or civil engineering.
4. Modify and adapt the existing administrative procedures (RD 1028/2007) to present time, making possible to expedite the processing of wind farms. The adequacy of the regulatory framework would allow developers to start their projects, so, develop an agile processing that favors all interested parties is essential. To cope with this situation and identify the priorities to be developed,

the IDAE has launched a public consultation under the name *"Hoja de ruta de la eólica marina y las energías del mar en España".*

5. Include the current technological advancements of offshore wind development in the process of preparing the Marine Spatial Planning Plans (POEM), which will increase the viability of projects at a greater distance from the coast and the number of locations available. The POEM will substitute the actual EEAL which is outdated in some of its aspects.
6. Continue reducing technical and economical limitations to make the wind resource available more accessible. This point is being resolved year by year as many new models of floating turbines are appearing and the market competition causes prices to drop, making these technologies more affordable.
7. More studies have to be developed to acquire more knowledge on the potential impacts of the turbines on the environment and health. Other future challenges for which studies will be necessary are to increase the circularity of wind energy technology, minimizing as much as possible impact to the environment; taking into account the end of life of turbines.
8. Promote the use of floating technologies in Spain, the floating technology that seems most suitable to apply in Spain would be the TLP for areas where the depth does not exceed 60m, and Spar buoys for areas where the waters are deeper. The Siemens Gamesa SG 8.0-167 DD 8MW turbines would allow for large electrical production, and a national company product would be used to favor the economy.
9. Due to the absence of previous experiences on the environmental impact of these facilities on the Spanish coast, environmental impact studies should contain detailed information on the pre-operational status of the area: fauna and flora, benthic habitats, coastal dynamics, fishing activity and perception of the landscape. Together with the results of the environmental monitoring plans, it will be possible to know the real impact of offshore wind farms on these elements, by applying a BACI (Before-After Control-Impact) methodology, so that the experience can be used in future offshore wind farm evaluations and projects.

6. Conclusions

An overview of the offshore wind energy development globally has been developed, as well as an analysis of the evolution and description of the most common turbines and foundations. Regarding the advancement of the technology in Spain, the main conclusion is that in the actual context is the key time to start developing this technology in Spain. The reason is because there are technological, economic and environmental reasons that allow it. Technological because floating technology that is becoming increasingly important in the market, multiplies viable sites reaching depths greater than 50 meters adapting to the morphology of the Spanish continental shelf where the power that can be extracted from the wind is greater (high capacity factors). The economic reasons imply that generation costs have decreased and will continue to do so in the future. Also at a national level there are national strategic sectors positioned in international markets. At the environmental level, floating techniques reduce potential impacts on the marine environment. Also, fixed foundation techniques have advanced, reducing their impact on marine biodiversity as a result of the experience gained by the deployment of more than 22GW in the North Sea by countries such as Germany, Denmark and the United Kingdom.

For the marine wind power to have a real contribution to the energy mix it is essential to start deploying OWF in the marine demarcations with more suitable areas. According to the 2009 coastal zoning study those would be the canarian demarcation, being the marine demarcation that has the most suitable areas and the pioneer in the development of the marine wind power, since it is the only place on the Spanish coast where there are prototypes in operation. The *estrecho y alborán* and *levantino-balear* demarcations would follow the Canary Islands in order of priority, since they have suitable and suitable areas with conditions both in similar proportions. In order to start the installation of projects, before an important economic investment effort and the involvement of the administrations to make the legislative changes is necessary.

The deployment of this technology would have favorable effects on environmental health since it would contribute to fulfilling national commitments to combat climate change. A decarbonized power system is essential to reach the Paris Agreement targets, considering the fact that from the more than 1 billion tons of equivalent CO_2 carbon footprint that the European power sector had in 2017, 97% of these emissions came from combusting fossil fuels.

Wind energy is presented as a part of the solution since according to the Intergovernmental Panel on Climate Change (IPCC), it is the energy with the lowest existing carbon footprint. It emits just 11.1 gCO_2 / kWh produced throughout its lifetime, considering its life cycle and operational phase producing energy. Comparing it with the other renewable source with more growth in recent times, it emits 4 times less than solar energy (48g / kWh). Compared to burning solid fossil fuels (820-1075g / kWh), reducing the carbon footprint by up to 100 times indicates that installing turbines is the most effective way to cut CO_2 emissions.

List of abbreviations

AAE: Wind Business Association (*Asociación empresarial eólica*).

BACI: Before-After Control-Impact.

EEAL: Strategic Environmental Study of the Spanish Coast.

EEALE: Strategic environmental study of the Spanish coast for the installation of offshore wind farms.

EEZ: Exclusive economic zone.

EU: European union.

GW: Gigawatt (1 watt x 10^9).

IEA: International Energy Agency.

IPCC: Intergovernmental Panel on Climate Change.

LCOE: Levelized Cost of Energy.

MW: Megawatt (1 watt x 10^6).

OWF: Offshore Wind Farm.

PNIEC: National Integrated Energy and Climate Plan.

POEM: Marine Spatial Planning Plans.

R&D: Research and development.

SDS: Sustainable development Scenario.

TLP: Tension leg platforms.

W: Watt (1 joule per second).

gCO2 / kWh: Grams of carbon dioxide per kilowatt-hour.

kW: Kilowatt (1 watt x 10^3).

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Annex

Parts of a wind turbine and principle

The next figure shows a specific a location of the main parts of an offshore wind turbine.

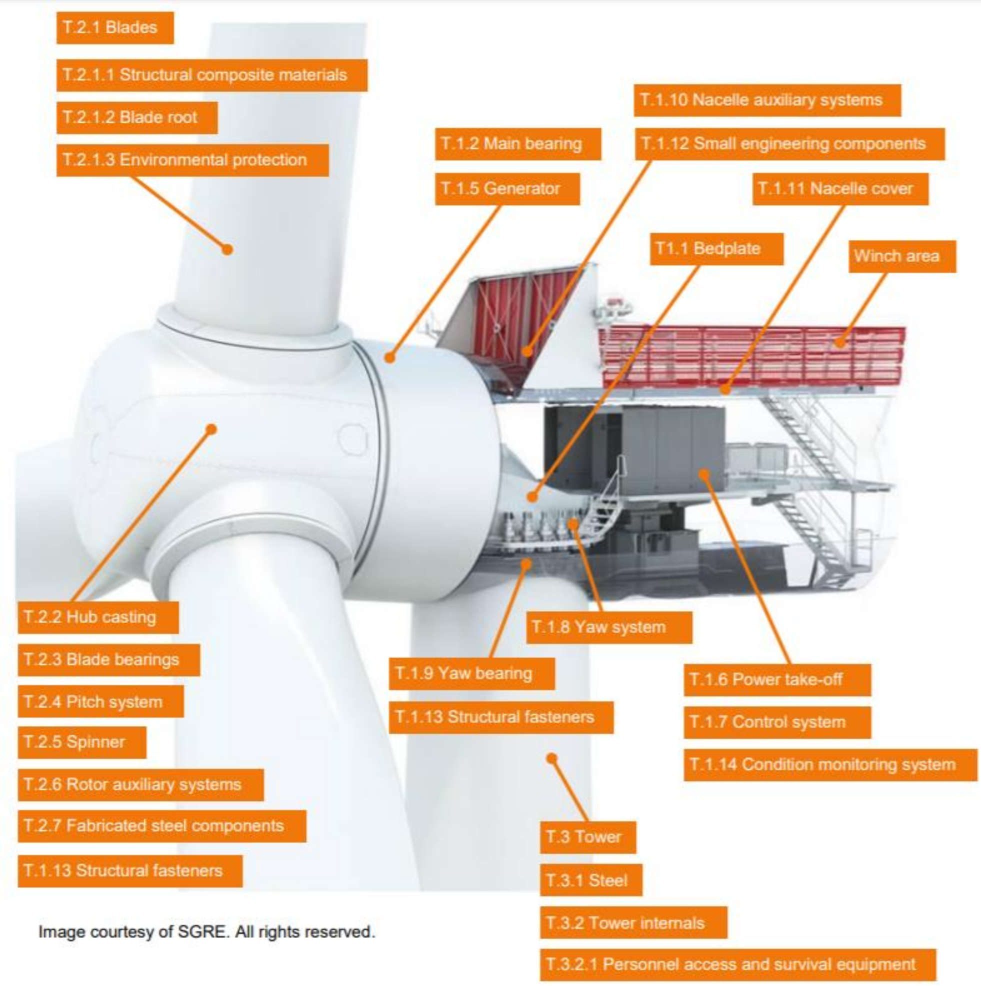

Figure 9. Parts of a wind turbine (BVG, 2019)

The process starts when the wind makes the blades of the turbine to rotate, approximately at a speed of seven to twelve turns every minute, which are connected with the turbines through a hub. A gearbox has the function of increasing this speed to over 100 times and also transforming the speed into a high-speed shaft. With a speed of over 1500 revolutions every minute, the speed is transferred to a generator. This speed gets into the generator and is when the energy transformation is done, the generator works to convert the mechanical power from the shaft into electrical power. Since the power is in a direct current form, a converter then transforms it into alternating current. From this point, a transformer increases the voltage to between 20 and 66 kV, which makes it possible to transmit this current through the onshore wind farm. The next step is to transport the electricity through medium voltage cables and take it to a substation.

After reaching the substation, the energy is again transformed into a high-voltage current of +132 kV. The final process implies an evacuation line that transports the electricity to the distribution network, finally reaching the consumption points.

Power curve of a wind turbine

The power curve is how wind turbines models are categorized and classified. This graphical representation shows how a turbine work, the electrical output of the turbine, depending on the wind speed. At low wind speeds there is not torque enough by the wind to make the turbine blades rotate. Then as the wind speed increases, the blades will begin to rotate and generate power, this speed is called “cut-in speed” and and its values generally move around 3 and 4 m/s.

As the wind speed increases above the cut-in speed, the electrical output rises a limit for which the generator is designed usually at 12-17 m/s, which is called the “rated output wind speed”. To prevent the blades and rotor of the turbine from being harmed by too high-speed wind, a braking system is employed to bring the rotor to a standstill, usually around 25 m/s. These values can be appreciated in table 2 where the cut-out speeds are from 25, 25 and 34 m/s.

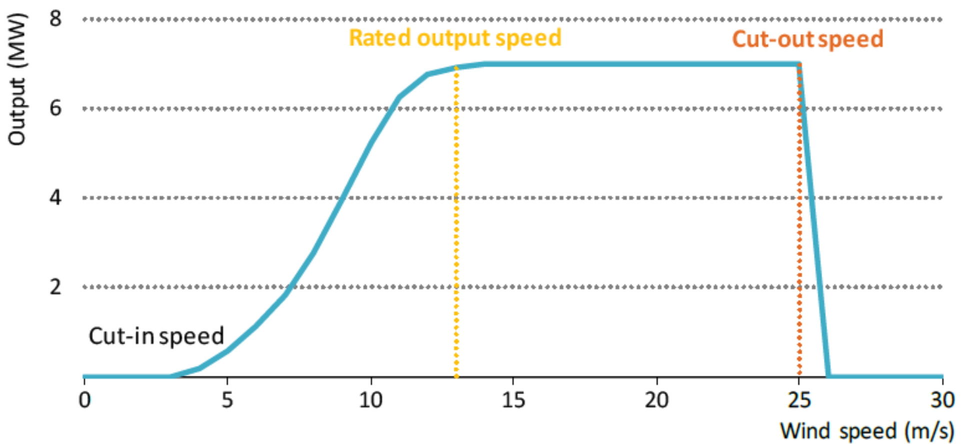

Figure 10. Typical power curve of a wind turbine (IEA, 2019)

The electrical output that a turbine can generate is determined by equation number 2.

$$P = \frac{1}{2}\rho A v^3 C_p \quad \textit{(eq. 1)}$$

Where:

- P = power output,
- ρ = air density (kg/m3),

- A = swept area (m2),
- v = wind speed (m/s)
- Cp = power coefficient, which has a maximum value of 0,59, meaning that no wind turbine can convert more that 59% of the kinetic energy of the wind in mechanical energy turning the rotor (Albert Betz, 1919).

Wind class for election of the most suitable wind turbine

During the construction and design phase a key point is the study of the environment to define the conditions of the energetic resource that the turbines will be exposed to. The critical points to analyze in the wind to choose the best turbine are:

(i) How turbulent is the wind at the site.
(ii) the average annual wind speed in the location.
(iii) The extreme gusts that could occur within a 50-year period.

These three dimensions define the wind class of a wind turbine. The International Electrotechnical Commission (IEC) sets international standards for the wind speeds each wind class must withstand, as seen in table number 3. The roman number refers to a wind speed category and the index letter refers to a turbulence category.

Table 4: IEC Aerogenerator class classification

Aerogenerator class		I	II	III	S
Vref	(m/s)	50	42.5	37.5	Values specified by the designer
Vave	(m/s)	10	8.5	7.5	
a	Iref	0.16			
b	Iref	0.14			
c	Iref	0.16			

Being:

- Vref: maximum extreme average wind speed over 10 minutes with a return period of 50 years. It can be calculated as (IEC, 2019):

$$Vave = Vref * 0.2 \quad (eq.\ 2)$$

- Vave: Yearly average wind speed.
- a: upper turbulence zone.
- b: medium turbulence zone.

- c: lower turbulence zone.
- Iref: reference turbulence intensity, predicted value of the turbulence intensity at 15 m/s.

The turbulence is one of the main parameters for obtaining energy from the wind, because the wind turbines are designed to rotate when the wind blows in a direction perpendicular to the rotor plane. The key is that this turbulence of wind has random variations, which causes loads on the wind turbines, or in other words the energy production varies depending on the stresses on the blade root. This fatigue loads of several major components in a wind turbine are mainly caused by turbulence, that's why the knowledge of how turbulent a site is of crucial importance.

The different turbine classes are defined by wind speed and the turbulence, therefore this classification being dependent on the location of the wind turbine. The parameters mentioned in the table are applied at the hub height.

Floating structures for offshore wind energy production

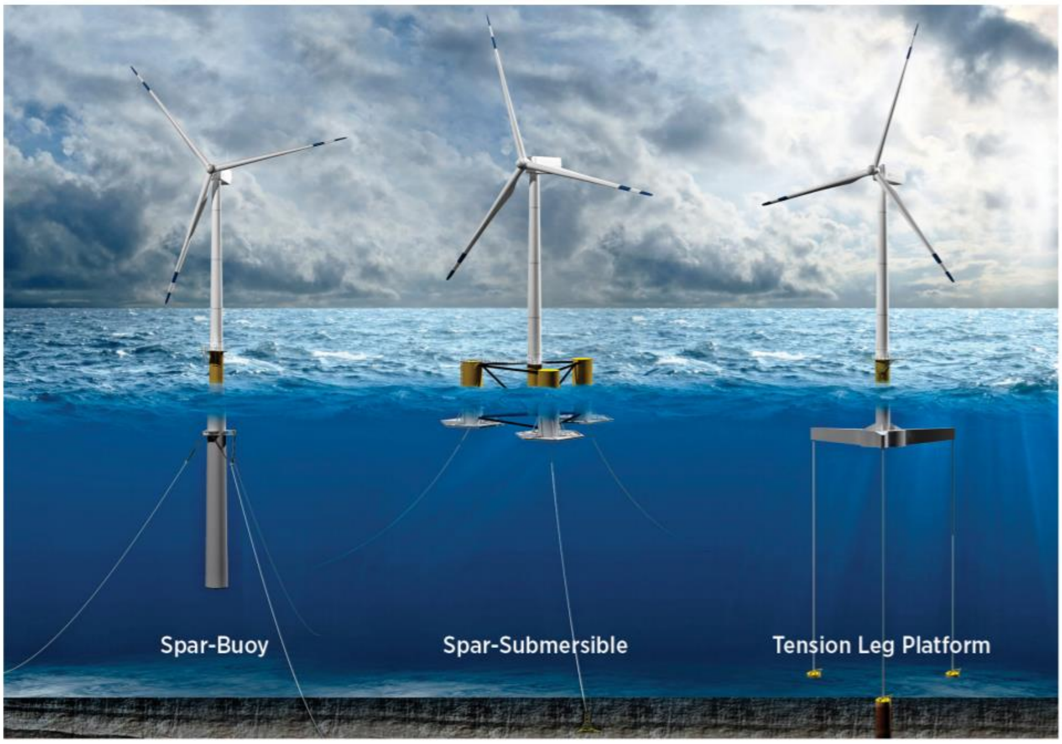

Figure 11. Offshore wind floating foundation concepts (US Energy Department, 2019)

Procedure to follow according to RD 1028/2007

RD 1028/2007 establishes the processing of applications for authorization of electricity generation facilities in the territorial sea. It includes two different procedures, one for installations of more than 50 MW of production, the ordinary procedure, and another for installations of less than 50 MW, the simplified procedure. The experimental stations that are in Canary waters currently applied the simplified procedure to be able to be developed. The current ordinary process can be summarized in 4 phases:

1) <u>Application and “Characterization of the Marine Wind Area”</u>

The first step by the interested developer is to reserve the marine area where he wants to develop the project. You can only book areas that are listed as "Eligible" or "Eligible with conditions" in the EEALE 2009. The promoter must prepare:

- A compilation of the affections of your project

- Report of access capacity, meaning the ease of transportation to the area where the installation will be carried out and the capacity to be connected to the current electricity grid, or the necessary facilities to build to make it so.

- Report on "Characterization of the offshore wind area", which would be published in the BOE and would be valid for 5 years.

2) <u>"Zone Reserve Concurrency" and Valuation</u>

All developers interested in the marine wind area must make a guarantee of 1% of the project budget, respect all their entire useful life. The different applications will be evaluated by an evaluation committee made up of the ministries and the autonomous communities with competences in the requested area or areas. In a period of 3 months, the BOE will communicate the resolution of the requests and the granting of the reservation. The "*Dirección General de Biodiversidad y Calidad Ambiental*" and the "*Dirección General de la Costa y del Mar*" will prepare the corresponding environmental assessment procedures for the area.

3) <u>Investigation of the area</u>

The right to the transport network is granted for the assigned power above 50 MW. This is the moment when the winner of the project has 2 years (extendable for 1 more year) to carry out the investigation of the wind resource in the area, carrying out the tests that it considers.

4) Administrative authorization

The promoter must carry out a series of administrative procedures before the construction of the wind farm can begin.

Detailed maps of the suitability of the 5 marine demarcations for the development of offshore wind energy

In the *"Borrador del Plan de Ordenación del Espacio maritimo*" detailed maps for the suitable areas for developing marine wind energy in the 5 marine demarcations of Spain can be found:

1) Northatlantic demarcation

Regarding the zoning of the coastline, the 2009 strategic study determined a zoning of the marine waters that include a wide surface of suitable areas with conditions for the installation of future wind farms.

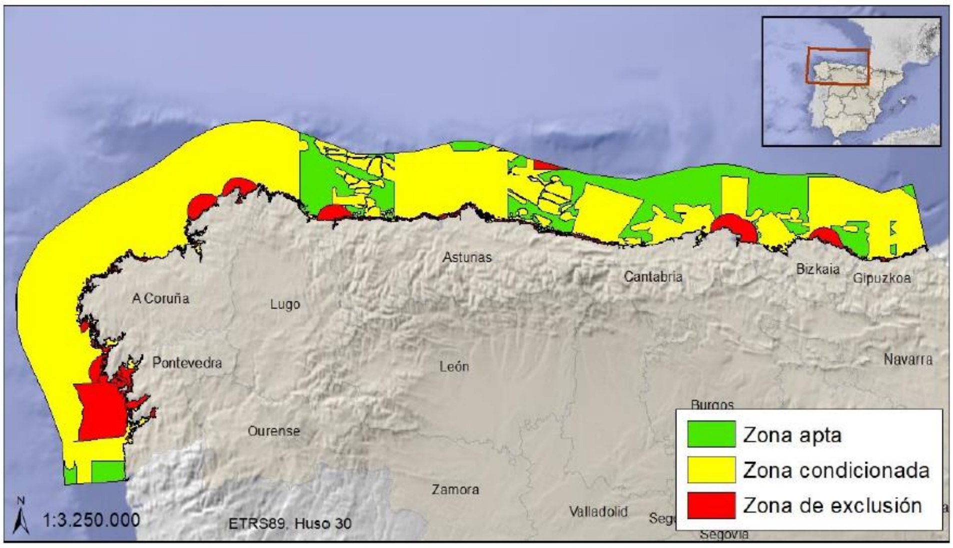

Figure 12. Zoning result of the strategic environmental study in the northatlantic demarcation (Strategic environmental study of the Spanish coast for the installation of offshore wind farms, 2009).

2) Levantine-Balearic demarcation

In the Levantine-Balearic Marine Demarcation there is currently no activity to study emerging technologies or generation of renewable energy. The zoning studied in 2009 defined certain suitable areas, areas with conditioning factors and areas not suitable for the installation of future wind farms

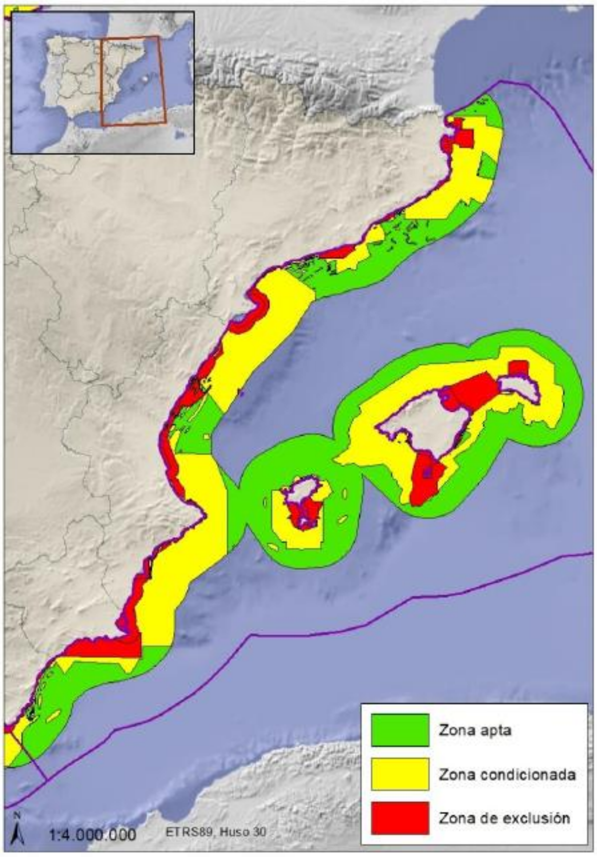

Figure 13. Zoning result of the strategic environmental study in the levantino-balear demarcation (Strategic environmental study of the Spanish coast for the installation of offshore wind farms, 2009).

3) Estrecho y alborán demarcation

Wide suitable and suitable areas with conditions were defined throughout the entire demarcation, although no project has been started in this demarcation.

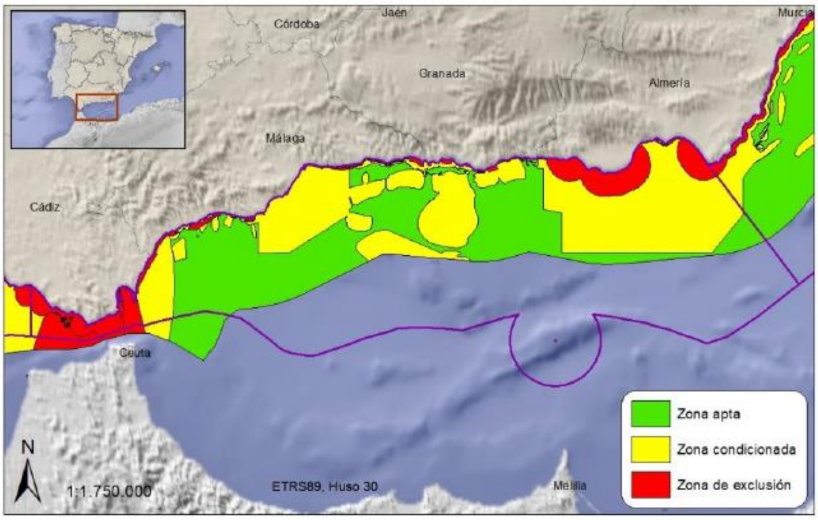

Figure 14. Zoning result of the strategic environmental study in the estrecho y alborán demarcation (Strategic environmental study of the Spanish coast for the installation of offshore wind farms, 2009).

4) South Atlantic demarcation

The technology has not been developed in this area either, but the 2009 coastal zoning study defined a wide strip that could be suitable with conditions for the installation of wind turbines to produce offshore wind energy, as well as a small suitable band without conditions.

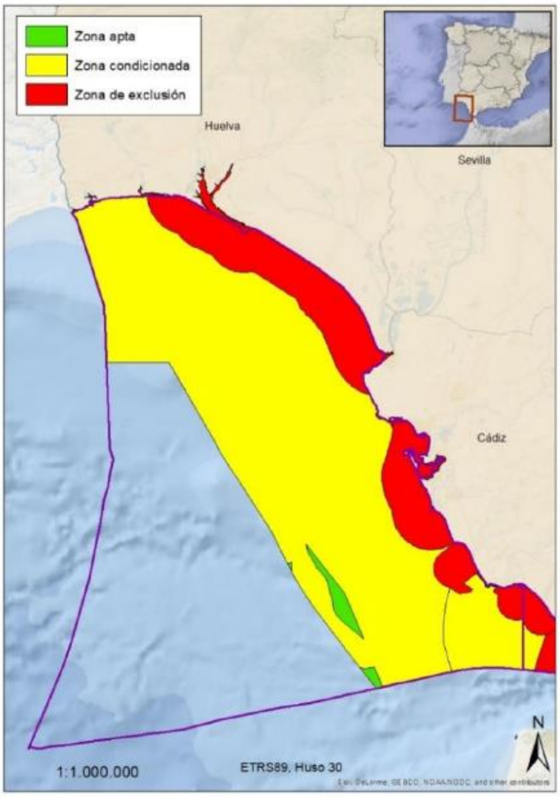

Figure 15. Zoning result of the strategic environmental study in the south atlantic demarcation (Strategic environmental study of the Spanish coast for the installation of offshore wind farms, 2009).

5) Canary Demarcation

This is the only demarcation in which marine wind energy has taken its first steps. In 2018, the first prototype of an offshore wind turbine was installed in the Canary Islands Marine Demarcation in the testing area of the Oceanic Platform of the Canary Islands (PLOCAN) by the Steyco company. It is a wind turbine that is anchored at a depth of 30 m, with a power of 5MW and whose blades reach a maximum height of 160 m.

In this demarcation the suitable areas abound, followed by the areas with conditions for the installation of future wind farms that were defined in the 2009 strategic study. It is the pioneering area where to start developing technology in Spain.

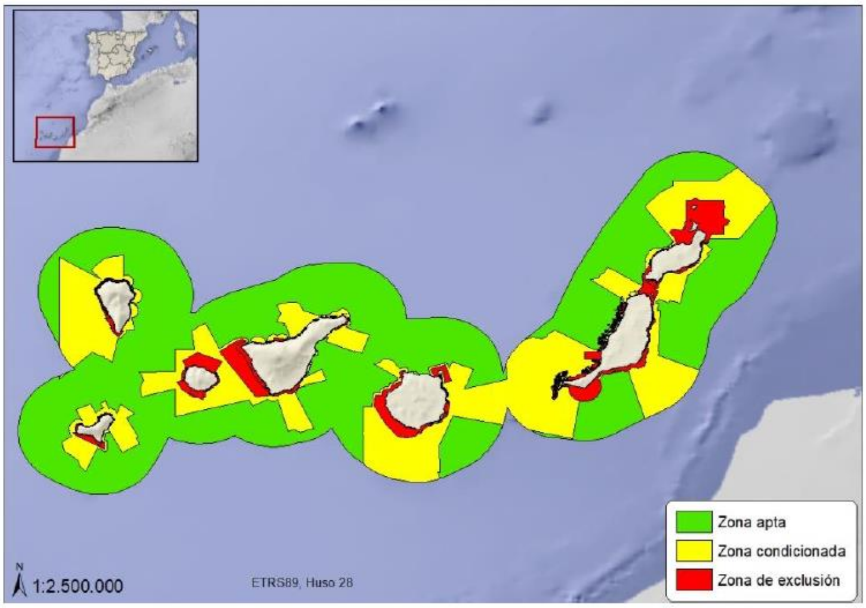

Figure 16. Zoning result of the strategic environmental study in the canary demarcation (Strategic environmental study of the Spanish coast for the installation of offshore wind farms, 2009).