Why offshore wind energy?

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A B S T R A C T

At the beginning of 2010, only 2000 wind megawatts had been installed offshore. Although the first offshore wind farm experiment took place in 1990, most of the facilities built up to now have been pilot projects. Then, offshore wind power can be considered as an incipient market. However, just at this moment, the growth of this technology finally seems to be happening, being several countries at the top of its development (the United Kingdom, Denmark, Holland, Sweden and Germany). This current situation, the raw materials problems and the general commitments to reduce the emissions of greenhouse gases are leading to predict a promising future for this technology. This paper deals with a brief revision of the state of the art of offshore wind power, followed by a critical discussion about the causes of the recently growth that is currently happening. The discussion is based on the comparison of offshore wind energy with other renewable energies (like onshore wind, marine hydrodynamics, hydraulic, solar, etc.) and even with conventional power.

1. Introduction

Several factors have been the key ones to push renewable energies, being the most important ones the attribution of the global warming to the carbon dioxide (CO_2) emission from the combustion of fossil fuels, the concern about the reduction of these emissions by means of the introduction of greenhouse gases emissions limits (Kyoto Protocol) and the search for energy security, together with the aversion to the traditional fission nuclear power and the lack of progression in the application of the fusion nuclear power. Moreover, the increase of energy demand for the last years and its recovery increase expected when the economical crisis will finish (see Fig. 1), lead to a higher renewable energy push.

Wind energy has been the renewable power most used up to now, mainly by means of onshore installations. This selective progress can be explained due to both the high wind resource availability and the high technology maturity of wind energy in comparison with the rest of renewable energies. These two reasons are likely the causes because the wind energy is considered essential to achieve the commitments acquired in the Kyoto Protocol. Anyway, the commitments success will require carrying out several measures simultaneously [2], being one of them the push of the construction of offshore wind farms.

Although the origin of offshore wind energy dates from the nineties of the last century, the growth of this technology is just beginning to happen in different ways depending on the country, and according to several decisive factors: the limited space in land for the development of onshore wind farms because of the competing site usage, the less general environmental impact caused by offshore wind energy, etc.

There are in fact reasons to expect the optimistic development of offshore wind. This paper tries to explain the main reasons, based on a summary and revision of the state of the art, and on the discussion about the different technologies to produce electricity and their relative efficiency and opportunities, differentiating between conventional and renewable sources, and even among the different renewable sources.

2. State of the art relating to offshore wind energy

Wind energy has been recognized as one of the key renewable energy sources, and its main development has been through the construction of onshore wind farms, having installed only 2000 offshore wind megawatts (MW) at the end of the year 2009.

Specifically, the first wind turbine in the sea was set up in Sweden in 1990. This facility was formed by a single 220 kW (kilowatts) wind turbine, located 350 m from the coast, and supported on a tripod structure anchored to the seabed about 6 m deep.

Between 1991 and 1998, experimental low rating projects were carried out whose different models of wind turbines and different

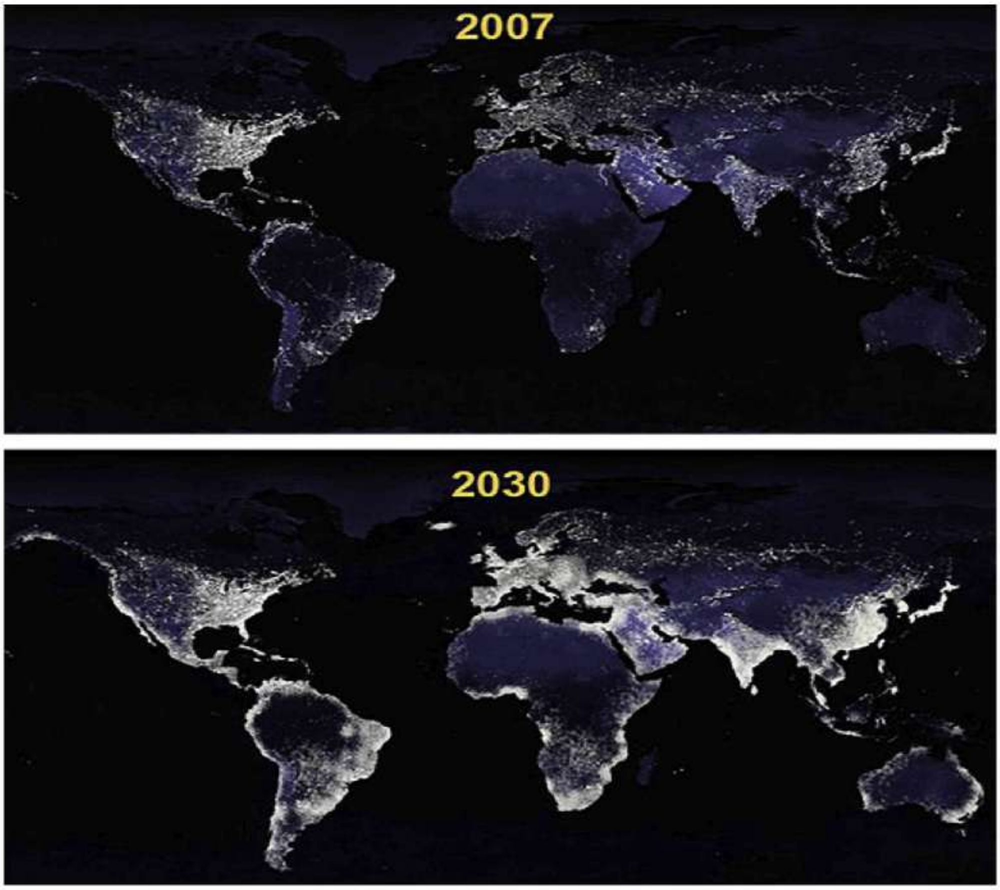


Fig. 1. (a) Energy demand around the world in the year 2007. (b) Energy demand forecasting in the year 2030 [1].

types of foundations were tested. Wind turbines of 450–600 kW units rating were used for these projects, and distances of up to 4 km from the coast and depths of up to 6 m were reached. Although certain doubts were initially raised, these facilities showed good profitability and reliability indices.

Multimegawatt wind turbines were brought in later, in a second experimental phase, having been the Utgrunden project, built in Sweden in 2000, the first project with those characteristics. Several of these facilities marked the commencement of the first commercial wind farms: Blyth, Middelgrunden and Yttre Stengrund. Later, the Horns Rev and Nysted facilities, both on Danish coasts, were the confirmation of this type of facility's adaptation to the marine environment.

As from then, facilities of this type have continued being built. And in fact, it is essential to push the use of offshore wind energy (see Fig. 2) to achieve the commitments acquired in the Kyoto Protocol.

As it has been exposed before, the growth of offshore wind power is currently happening in different ways depending on the country. This can be explained because of several decisive factors: the different environment of the different countries – as the lack of land space in some countries for the development of onshore wind farms, sometimes due to the competing site usage, the expected minor general environmental impact with offshore wind farms in comparison with onshore wind farms, the government support, etc. [3]. For example, while Holland has not practically free space in land for this kind of installations, in the United Kingdom and Denmark there are a public opposition to onshore wind farms and, as a consequence of this, there is an important push for offshore wind energy [4].

As a result of this, offshore wind farms are beginning to take part of the sea and coastal landscape in some countries, being located in dynamic and changing surroundings. An integral management model therefore needs to be applied enabling not only the technical and financial feasibility of the offshore wind farm project to be achieved, but also respect for the environment.

As an essential part of this state of the art exposition, the evolution of offshore wind power since 1990 up to 2007 is exposed in the Fig. 3, and the distribution of this power among the different countries is shown in the Fig. 4.

In the next future, it is expected a huge increase of the offshore wind power installed, not only in the already experimented countries, but also in another countries like France, Spain [4]. While

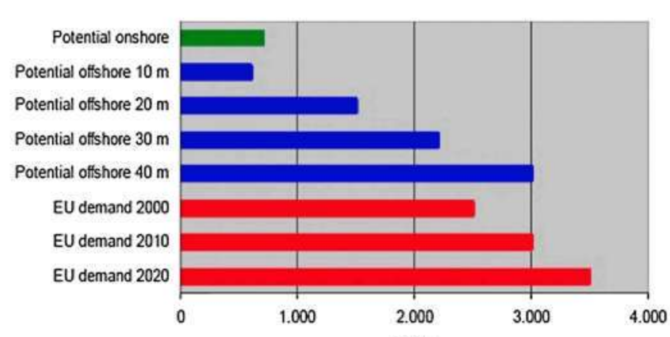


Fig. 2. Comparison between the potential of onshore and offshore wind energy in different depths, and the energy demand in Europe. This graphic shows the need to push offshore wind energy [5].

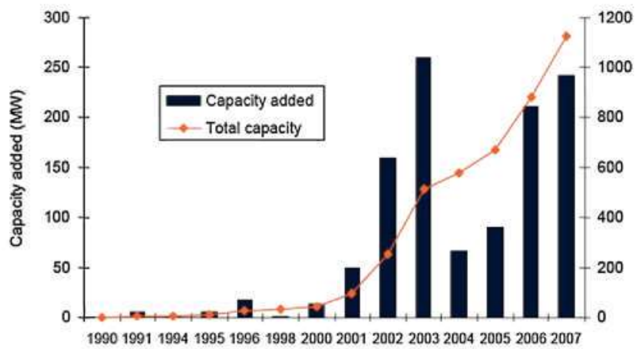


Fig. 3. Growth of the offshore wind energy capacity since 1990 to 2007 [6].

some of these countries have suitable coastal characteristics for offshore wind farm installations, not all of them; for example, the Spanish coastal platform is very slope, and the seabed is very depth close to the coast in comparison with other countries like Germany. In fact, there are several theories – all of them with optimist perspectives – about the evolution of the offshore wind power installed (see Fig. 5).

3. Discussion

This discussion goes from the most general to the most detailed issues, and it is organized in three sub-sections: 1) comparison between renewable and conventional energies, 2) comparison between wind energy and other types of renewable energies, and 3) comparison between offshore and onshore wind energy.

3.1. Renewable vs. conventional energy

Nowadays, the electricity market is based on the use of conventional or traditional energy technologies, being important also the participation of hydropower. Nevertheless, some of these technologies came into crisis lately. Firstly, fossil fuel-based ones came into crisis (oil crisis in the years 1973 and 1979); secondly, fission nuclear energy came also into crisis although not in such a general way as the fossil fuel-based technology. In fact, the opposition to the use of fossils was established depending on the countries and policy factors; thirdly, hydropower also fell into crisis, which was justified by an environmental attitude that appeared due to the lack of conservative criteria for the use of hydrological resources. The classic large hydropower projects were stopped, but also the development of small-scale hydropower.

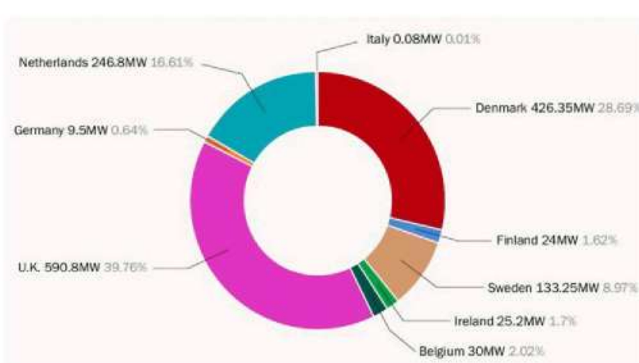


Fig. 4. Distribution of the offshore wind megawatts in operation in the different countries at the beginning of the year 2009 [7].

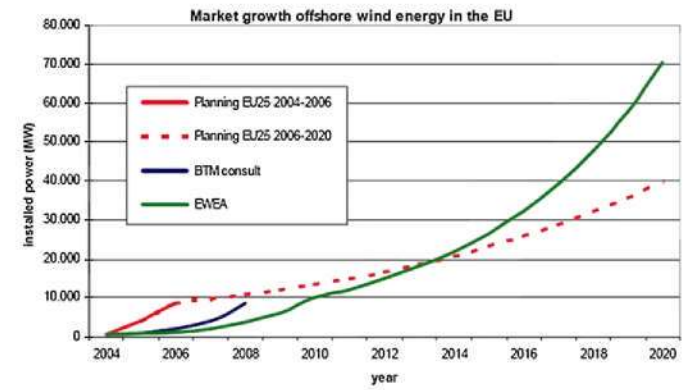


Fig. 5. Different theories about the expected development of offshore wind power in Europe [4].

In those years, a general interest about the adjustment of fusion nuclear power existed. The passage of time has made evident the error about the fusion power expectative, and renewed the demand for the fission power. And, on the other hand, the objections about hydropower and maritime installations were reduced.

All that leads to the push of renewable energy (including hydropower), which can already be considered as part of the current electricity market, although not in a general way. As has been exposed before, several are being the key reasons to push renewable energies, being one of them the reduction of the carbon dioxide emissions to the atmosphere.

This implies that renewable energies let to achieve additional energy security because of the use of the own resources of a region, being able these ones to answer in a relative way to the increase of the cost energy of the raw materials that are not controlled at all by this region. Besides, another advantage of renewable energies is the no contribution in a significant way to the emissions of carbon dioxide (see Fig. 6), leaving the Earth almost intact for next generations.

In the decision-making about investments, energy industry is supported on the use of economical models to calculate and compare the energy cost of the different technologies. The most used ones are related with the "levelized cost of power", which depends on capital cost, operating costs and fuel costs. In the Figs. 7 and 8, the comparison between the levelized cost of different technologies and the forecast for different years is exposed, and it can be observed the scarce difference between the relative to onshore wind and the conventional technologies. Also, it is important to take into account that some of these technologies, mainly the renewable ones, are capital intensive but have low operational costs, while fossil fuel-based technologies may be cheaper to construct but much more expensive to operate [8].

	Carbon Dioxide Emissions (t/GWh)
Coal	964
Oil	726
Gas	484
Nuclear	8
Wind	7
Photovoltaic	5
Large Hydro	4

Fig. 6. Lifetime emissions of carbon dioxide for various power generation technologies [8].

	Levelized cost ($/MWh)
Ultra supercritical PC	46.9
Ultra supercritical with capture	73.4
IGCC	51.3
IGCC with capture	65.2
Nuclear	30-74
Large hydropower	40-80*
Small hydropower	80-180*
Onshore wind	60-90
Offshore wind	120
Biomass	70-170
Solar photovoltaic	180-230
Solar thermal	150-170
Tidal power	80-230
Wave power	100-180

*Once loans are repaid, the generation costs can fall to $0.01/kWh, or less

Fig. 7. Comparative levelized costs of different generating technologies [9].

The levelized cost can be understood as the first analysis for the discussion about the economic issues of the different technologies to generate electricity. However, it is important to take into account the risk related with the difficulty to estimate the fluctuation of the cost of the raw materials for the operation of some of these technologies, mainly the fossil fuel ones. On the other hand, there are several factors than can distort the energy cost, which are the subsidies (related to the economic incentives fixed by the governments to push a specific power generation technology, modifying the offer and demand market. Subsidies are related to the economic incentives fixed by the governments to push a specific power generation technology, modifying the offer and demand market. Nowadays, renewable energies need from economic incentives to push the companies to invest in those kinds of technologies, but not in the same range depending on the technology), the externalities (related to the cost for the society because the use of a specific technology, and often are ignored. These include the cost to take into account factors such as the environmental degradation, the deteriorating human health, which some technologies incur, the security of fuel supply, etc. – see Fig. 9) and the structural costs (related to the costs of adapting conventionally structured electricity transmission and distribution delivery networks to accommodate intermittent sources of electricity) [10].

($2006/MWh)	2010	2020	2030
Onshore wind (Class 3)	86	76	70
Onshore wind (Class 4)	77	68	64
Onshore wind (Class 6)	67	60	57
Offshore wind (Class 4)	118	101	91
Offshore wind (Class 6)	104	90	82
Open cycle gas turbine	196	204	223
Combined cycle gas turbine	74	79	94
New supercritical coal	68	69	71
Integrated gasification combined cycle	91	92	93
Nuclear	89	86	86

Wind cost are without US PTC. This significantly lowers their costs

Fig. 8. Future levelized cost comparison between different technologies, between 2010 and 2030 [11].

Figs. 10 and 11 show the ranking of the different technologies, both currently and in the future, and it can be observed the expectation about the prospect rapprochement between conventional and renewable energies, being essential the investments in the last ones to achieve it.

3.2. *Wind energy vs. other renewable energies*

Wind energy has been clearly the fastest in its development among all the renewable energies (see Fig. 12), although in this statement hydropower must not be taken into account because of its different origin and way of development in comparison with the other ones. Estimations suggest that global wind energy could generate between 20,000 TWh and 50,000 TWh of electricity each year; and to put that into some perspective, annual global electricity consumptions in 2004 was around 17,000 TWh. Anyway, note that a recent estimate establishes the global offshore resource around 37,000 TWh [12].

The importance of wind energy in comparison with other types of renewable technologies could be explained due to the combination of two factors: the availability of resources and the maturity of the technology in term of cost efficiency. Regarding the first one, it is clear the huge availability of wind energy, but also of solar, wave and current, much more than geothermal, small-scale hydropower and biomass. And regarding the second one, the maturity of wind energy is high because this has been used since olden times in many economic activities: sailing, irrigation, milling, etc., having not so a long evolution other technologies like solar, wave and currents.

Although the push of offshore wind power is clear, and wind technology should take the opportunity of the advantages achieved onshore to move forward in the sea as soon as possible, it would be necessary to push the rest of the technologies (wave, currents, etc.) to achieve a similar evolution as the wind one, although more concentrated in time. This only will be possible with the government support looking for research projects and experimental installations. Regarding the levelized cost (See Fig. 7), nowadays onshore wind is close to the conventional technologies, but offshore is still far, and more even the marine hydrodynamic ones; but in the future it is expected the distances will be reduced.

3.3. *Offshore vs. onshore wind energy*

In 2007, it was the first time that wind energy achieved the 1% of the electricity generated in the world [8], almost all of them corresponding to onshore wind farms. In fact, there were only 2000 MW installed offshore at the end of 2009, certainly a symbolic amount. As it has been exposed in the state of the art, offshore wind energy is being pushed differently depending on the countries and

	€/MWh
Coal lignite	18-150
Oil	26-109
Gas	5-35
Nuclear	2-7
Onshore wind	1-3

Fig. 9. External costs for various power generation technologies within the Europe Union [6].

	2018	2008	2005	Change 2008-2005
Coal	4	1	2	1
Hydropower	1	2	3	1
Gas	3	3	1	-2
Nuclear	2	4	4	0
Onshore wind	5	5	5	0
Biomass	6	6	6	0
Offshore wind	7	7	7	0
Solar	8	8	8	0
Tidal	9	9	-	-

Fig. 10. The relative competitiveness of power generation technologies in 2005, 2008 and 2018 [8].

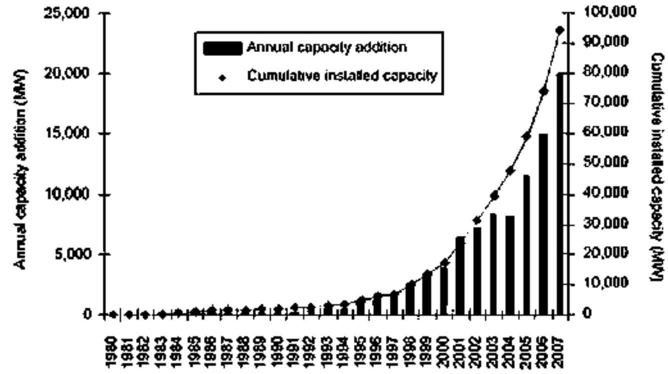


Fig. 12. Annual global wind capacity additions and cumulative installed capacity, in MW, between 1980 and 2007 [8].

the policy approaches. In general, the current growth of offshore wind energy might be explained on the basis of several determining factors, being the most important ones the lack of space in land in some countries for the development of onshore wind farms, sometimes due to the competing site usage, the expected general minor impact in the environment with offshore wind farms in comparison with onshore ones, the government support, etc. Also, the combination of resources availability and technology maturity of offshore wind is closer to onshore wind than other renewable technologies. As a result, offshore wind farms are beginning to form part of the sea and coastal landscape.

The main difference between onshore and offshore wind installations is on their respective environment, which are much more complex in the sea not only for the design but also for the construction and operation works, because of the significant increase of the factors that can condition all of them. In the following paragraphs, the most emphasized advantages and disadvantages of the offshore wind technology in comparison with the onshore one are exposed [13–17].

The first advantage is the better quality of the wind resource in the sea, where wind speed is usually bigger, even increasing with the distance to the coast, and more uniform (softer), leading to less turbulence effects; therefore the fatigue is less important and let to increase the lifetime of the offshore wind turbine generator. Other considerations due to the quality relates to the height at which a wind turbine is placed (the optimum height for a given offshore

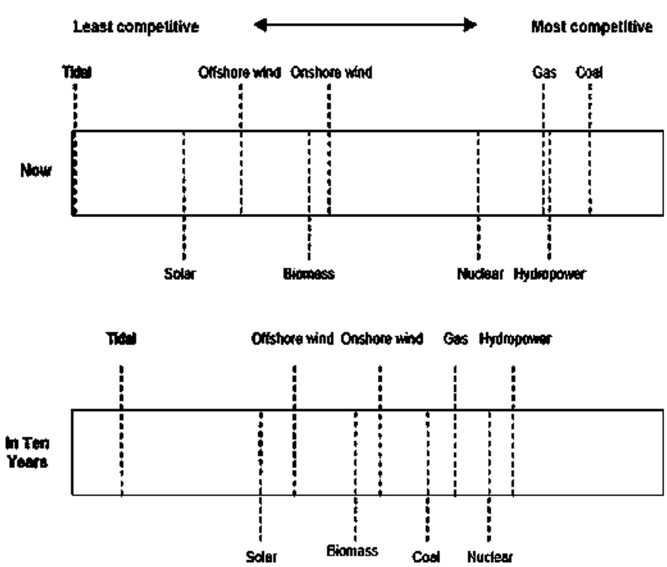


Fig. 11. The relative competitiveness of power generation technologies in 2008 and 2018 [8].

turbine diameter is that whose rotating blades are above the maximum wave height at the site). The characteristics of the layer of turbulent air adjacent to the ground and to the sea surface allow the offshore turbine to be mounted lower than the equivalent onshore machine.

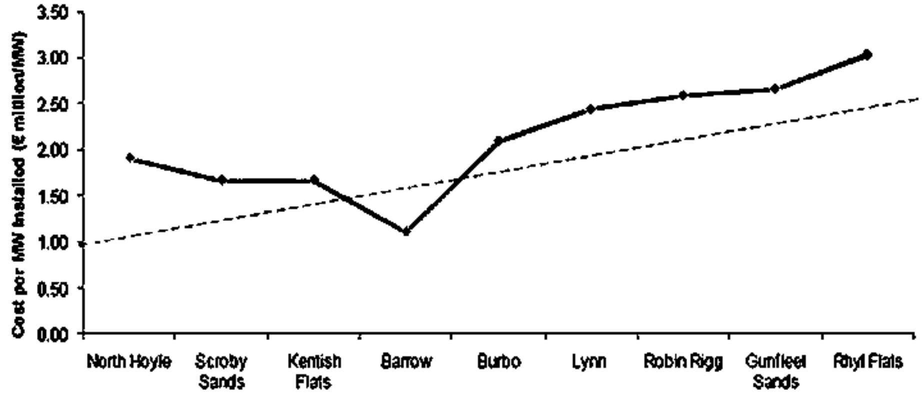
The second advantage becomes from the bigger suitable free areas in the sea where offshore wind farms can be installed, leading to greater installations. Its placement (far from population areas) lets to reduce the environmental regarding the noise emission, nearly all related with the increase of the blade-spit speed. Also, this large distance allows, in some cases, to reduce the visual impact from the coast. All of these statements, together with the not such strict limitations in connection with the load to transport, make possible to install bigger wind turbine units, achieving more production per install unit.

On the contrary, the first disadvantage is the cost of the permitting and engineering process, and of the construction and operation phases. In onshore wind farms, the cost of wind generator turbines is around 75% total cost of the Project, being this percentage in offshore installations approximately 33%, which can be explained as mainly due to the high costs of the sea operations. Besides, unlike onshore wind farms, there are not usually marine electrical infrastructures that connect the highest wind resource areas with the consumer centers, leading to the construction of longer electrical networks, and even to strengthen the existing electrical infrastructures.

The offshore wind farm cost per megawatt was estimated, some years ago, around 2 M€/MW (see Fig. 13), much more than in offshore wind farms. Nevertheless, this cost has increased and nowadays, some offshore wind installations are around 4 M€/MW [18], increase that can be justified because of the learning process still happening.

A second disadvantage is the necessity of a more developed offshore wind farms technology. This is essential for the wind turbine generators (usually similar to onshore ones, but some research projects are trying to decide which is the most suitable wind turbine generator type for offshore wind farm, especially with floating foundation), which will be subjected to high loads and must to adapt themselves to the marine environment and, therefore, to be prepared for the corrosion conditions; also in the foundations, in the marine operations because of the importance of accessibility restrictions and the difficulties existing to work in this environment during the construction and operation phases, etc.

And a third disadvantage is that, due to the limited roughness of the sea surface, the turbulences propagation are higher offshore than onshore; then wake effects provoked by the own wind turbine generators are very important leading to a big impact over the



Construction Year	2003	2004	2005	2006	2007	2008	2008	2008	2009*
Capacity (MW)	60	60	90	90	90	195	180	108	90

Note: *Rhyl Flats anticipated to be complete by year-end 2009. Cost per MW estimated according to investment announcements

Fig. 13. Evolution of cost per megawatt installed offshore in the United Kingdom [19].

lifetime of the wind turbines. To reduce it, the wind turbines must be disposed obeying a minimum separation among them. Also the wind resource evaluation is much more complex and expensive than onshore.

So that although it is evident the difference between the cost of onshore and offshore wind power, some efforts have to be made to push the offshore wind technology, and there will be necessary the improvements of knowledge in several issues like wind turbines, foundations, construction and operation phases, etc.

4. Conclusions

Science and technology have served to the political power, or have changed it, for too long time: then these must collaborate changing the whole consumption paradigm, so that sun light, ocean movements and winds is becoming in necessary power sources.

Offshore wind power is undoubtedly going to constitute an increasing source of power since now, in accordance with the farm settlement feasibility and the improving management capability. Something similar although different in the time will happen with diffuse marine power sources like wave, current and tide/set up; this will happen only when the technical capability for concentration of their power can be developed.

Offshore and onshore wind farms are different in many issues, such as the higher cost of the former, mainly because of the foundations, the electrical networks, and the construction and operation works. It must be emphasized the still necessary knowledge improvements to be acquired in many offshore issues: wind resource, environmental impact, foundation design, optimization of the electrical connection, wind turbines generators, construction and operation phases, etc. So, this technology can be still considered within its learning curve and this could explain the increase of the cost per megawatt installed in the current installations, in comparison with the offshore farms installed some years ago.

Offshore wind can be considered as an incipient market, with only 1500 MW built up to the middle of the year 2009, and with most of the facilities built up to now since 1990 being experimental or pilot projects. Nowadays, offshore wind is not an economically feasible technology yet; it still requires in fact the technical and economical support by Public Administration Agencies for its development. The main offshore wind power development focus is in North Europe, where countries like the United Kingdom and Germany are pushing this technology, taking so the opportunity to push also their national industries.

It is necessary to push this technology to achieve the goals established in the Kyoto Protocol. This is due to the resources availability and the technology maturity, in term of cost efficiency in comparison with other renewable technologies. In fact, the future of this technology can be understood as promising, and it is expected that offshore wind farms are going to begin to form part of the sea and coastal landscape.

Besides, some R&D efforts will have to be made regarding the marine hydrodynamics technologies (wave, tidal and current power) because of its short development up to now, looking to achieve a similar maturity as the wind energy; only so, these renewable sources will be able to take part of the electricity market in the future. Nevertheless, there is still a long way to cover.

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