A preliminary assessment of the long-term prospects for offshore wind farms in Maltese territorial waters

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A Preliminary Assessment of the Long-Term Prospects for Offshore Wind Farms in Maltese Territorial Waters

A dissertation presented in part fulfillment of the requirements for the Degree of Master of Science in Sustainable Environmental Resource Management

By
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November 2010

UNDER THE SUPERVISION OF
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ABSTRACT

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A PRELIMINARY ASSESSMENT OF THE LONG-TERM PROSPECTS FOR OFFSHORE WIND FARMS IN MALTESE TERRITORIAL WATERS

Keywords: WIND; ENERGY; MALTA; OFFSHORE; VIABILITY; MARKET

Almost all of Malta’s current interest in offshore wind development is focused on the development of an offshore wind farm at Sikka L-Bajda in northwest Malta by 2020, to help the country reach its mandated 2020 RES target.

The offshore wind industry is rapidly gaining momentum, with larger projects in deeper waters further offshore being commissioned every year. Countries like Germany and the United Kingdom have actively constructed, or are planning to construct, offshore wind farms at transitional water depths before 2020.

The offshore wind energy market has historically been restricted to the North Sea, the Baltic Sea and the Irish Sea in northern Europe. This geographical barrier has been overcome with the officially commissioning of a wind farm near Shanghai Bridge in China. The industry is poised to expand into the Mediterranean in 2011 with the reported commissioning of Tricase wind farm in Italy. There is significant interest in bringing offshore wind to North America, particularly in the United States.

In order to continue this healthy growth, many companies are developing foundation structures that are stable and cost-effective in deeper waters further offshore. On average, the winds are stronger, more consistent and wind farms further offshore avoid a number of planning and stakeholder issues. Since Maltese waters are very deep, the commercialization of deep water technologies could exponentially increase its wind energy potential.

A systematic approach for evaluating offshore wind farm viability is proposed and tested on three offshore sites proposed in 2005 by the Malta Resources Authority. The system considers a number of technical, planning, environmental and socio-economic issues and rates a given proposal using a weighting system.

The system predicted that is-Sikka L-Bajda is the most viable wind farm proposal in shallow waters in Malta. The wind resource was judged to be adequate and while there were some planning and environmental issues, these are probably relatively easy to mitigate through proper implementation of Marine Spatial Planning. The proposal at Benghajsa Patch was judged to be poorly positioned and would have too many planning issues to be a viable choice. The site at North of Gozo is of marginal capacity and has some grid connection and potential TV and communications issues, but it could be an excellent supplementary project in conjunction with that at is-Sikka L-Bajda.

Since this result is consistent with other studies conducted in Malta, the methodology was judged to be sufficient for evaluating the viability of a wind farms, but requires refinement through a procedure of consultation exercises and questionnaires with experts, authorities, stakeholders and the general public.

Ing. Robert Farrugia
Dr. Jonathan Miles
Dr. Godwin Debono

November 2010
MSc. SERM
Dedications

I would like to dedicate this thesis to my parents, Anthony and Francine, for their dedication and support in helping me achieve my dreams and goals and for encouraging me to be the best I could be at what I do.
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Chapter 1 - The Current State of Wind Energy in Malta

1.1 - Current State of Energy in Malta
To date, Malta is entirely dependent on imported fossil fuels to meet its energy demands. Malta has no refineries and no oil or natural gas resources. Moreover, the Maltese grid is currently isolated with no interconnection or transit of electricity to mainland Europe or any other system, leaving the country vulnerable to surging oil prices and insecurity of supply.

Despite the fact that Malta is obliged by the EU to produce 10% of its energy from renewable technologies by 2020, Malta is the only EU Member State that remains completely dependent on imported fossil fuels for all its energy supply. As a result, the country has received criticism from the European Commission’s top energy civil servant, Mr. Philip Lowe, who stated that Malta is last place in the EU’s renewable energy classification list (1).

Part of the reason for the country’s slow adoption of renewable technologies, according to Energy Commissioner Guenther Oettinger, is because of the country’s size and insularity. For this reason, the commissioner claimed that direct comparison with the other Member States was not a fair comparison (1).

Malta’s renewable energy options are limited to solar photovoltaic, solar thermal energy, onshore and offshore wind energy, and energy from waste. Other renewable energy sources, such as geothermal, hydropower, wave and tidal, have no real potential in Malta. A final solution to achieving energy security would be achieved through diversification of energy supply, utilising as many renewable energy technologies as possible, particular solar and wind.

Wind energy is a crucial element of a renewable energy mix that can be exploited to meet Malta’s renewable energy targets and reduce dependence on fossil fuels. Wind energy is currently the most cost-effective means of generating electricity from renewable sources, with land-based wind energy being cheaper than fossil-fuel generated energy. However, in Malta land space is limited and a previous study has concluded that at most one large-scale farm would be constructed on land (2).

Offshore wind, while not as cost effective as onshore wind, could have the potential to generate a portion of Malta’s electricity consumption and avoids the problem of land use. Unfortunately, Malta’s bathymetry is very deep and there are only a few shallow reefs where large-scale wind farms can be constructed, most notably at Sikka L-Bajda, which could support a wind farm of around 95MW (3). The offshore potential of Malta is currently extremely limited until transitional and deep water technologies emerge on the commercial market.

Since Maltese waters are very deep, with depths exceeding 30 metres only a few hundred metres from the coast in most locations around the islands, any significant offshore wind project beyond is-Sikka L-Bajda would probably be deployed in deeper waters utilizing stronger foundation structures. However, to date there have been limited attempts to deploy wind farms with these support structures because of the higher capital costs. Nonetheless, European countries such as Germany and Norway, whose portion of the North Sea is generally too deep for monopiles, are now planning several deep sea wind farms. In fact, earlier this year Germany opened the Alpha Ventus wind farm using tripod and jacket foundations at 30 metres depth, and currently has active plans to construct in depths of 40 metres. (4)

1 A hybrid offshore wind/wave energy project might be viable, and will be discussed later in the thesis.
If deeper options are considered, the prospects of further offshore wind farms in the Maltese territorial zone increases significantly. However, there are still considerable risks associated with deeper sea technologies, especially in a small country like Malta, which cannot afford to innovate in this industry. First, the North Sea, which has an overall better wind resource than the Mediterranean, has only begun recently to show interest in deeper waters. Furthermore, there are currently no operational offshore wind farms in the Mediterranean, although a wind farm at Tricase (5) is reportedly under construction off the Italian coast. Finally, many of the technologies suitable for deep sea wind farms are still at a prototype stage and are not yet commercially available. For these reasons, the first offshore wind farms in Malta will likely be constructed on the few shallow reefs using well-proven shallow water technology.

1.2 Review of studies carried out to date

1.2.1 Mott Macdonald Reports

So far, virtually all the studies carried on offshore wind is focused on shallow water options for wind farms. In 2005, a report was published by Mott MacDonall and the MRA evaluating the potential of various kinds of renewable energy for the Maltese Islands, and proposed several scenarios and strategies the country could adopt. The study determined that while Malta has significant onshore wind potential, the size of the island’s mean that the visual impacts would be too great for more than one large scale onshore wind farm.

The Mott Macdonald report considered the offshore wind energy potential of Malta. Since the bathymetry of the Maltese archipelago is very deep, the study found that there is only one offshore site, is-Sikka l-Bajda, with marginal potential. However, the report stated that since onshore wind is not viable in Malta, development of this site would be more cost-effective than small-scale renewable. A potential issue could be finding a developer prepared to develop such a marginal site.

The study concluded that with regards to offshore wind viability

“There are likely to be restrictions in the opportunities of offshore wind in Malta. Such restrictions may relate to environmental and cultural designated areas, and to technology viability and increased costs. Potentially the most significant issue may be the competing uses of the sites with seabed characteristics and sea depths suitable for offshore wind turbines. The opportunity costs and associated social impacts of developing offshore wind farms in some areas should be considered carefully.”

The report concludes that in the medium-term, development of offshore wind farms at depths greater than 20 metres are unrealistic. However, development of sites up to 20 metres was considered to be possible in the medium-term (2).

Mott Macdonald Ltd published a report in 2009 providing estimates for the Sikka L-Bajda project. The capacity of the proposal is now estimated to range from 64.8-87MW depending on turbine and spacing. The wind speeds are expected to be lower than for other wind farms in Northern Europe, with higher capital costs than the average. It was concluded that a tariff would be required to construct an offshore wind farm at Sikka L-Bajda. (6)

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2 At the time the report was published, the maximum capacity of the site was through to be around 30MW. Today, it is thought that around 90MW of capacity could be developed at the site, increasing the attractiveness for developers.
1.2.2 – Shallow Offshore Wind Assessment and the Sikka l-Bajda Proposal

In 2005, the Malta Resources Authority (MRA) had identified and assessed a number of sites for their wind potential up to a sea depth limit of 20 metres, which were later reassessed at a depth limit of 25 metres. The MRA plotted a bathymetric map of the Islands up to a depth of 50 metres but excluded the Hurd Bank, which lies 15km east of the main island, mainly because the sea depth was in the range of 35-50 metres; too deep for existing commercial and well-proven technology.

A total of eight individual shallow sites were assessed based on various criteria, as explained in Table 1.1. In the MRA’s assessment, five of the sites were judged to be too close to residential areas or bathing areas for the installation of large wind turbines. Most of the other sites were dismissed for other reasons except the site at Is-Sikka l-Bajda, which was deemed to be the best site for Malta’s first offshore wind farm. Several independent studies have reached similar conclusions (2) (7) (8) (9).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Important Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Criteria</td>
<td>Maximum capacity, expected wind resource, distance to shore, access of the site for connection to the national grid, operation and maintenance</td>
</tr>
<tr>
<td>Planning Criteria</td>
<td>Protected areas (NATURA 2000, SAC and SPA), fishing, boating, yachting, diving and swimming</td>
</tr>
<tr>
<td>Environmental Criteria</td>
<td>Type of benthic environment and its importance to fish and avifauna</td>
</tr>
<tr>
<td>Socio-Economic Criteria</td>
<td>Visual, noise and shadow flicker impact assessments. Impacts on tourist areas, bathing areas and on marine traffic at harbours.</td>
</tr>
</tbody>
</table>

Table 1.1 – The four classes of criteria and some of the important parameters of each

The Sikka l-Bajda site has several key advantages over the other candidate sites. First, it is by far the largest available reef in Malta if the feasibility limit is taken to be 25 metres depth. The wind resource at this site is likely to be superior because the reef is exposed to the prevailing north westerly winds and is far enough from the coast to not be significantly affected by the mainland. The distance to shore is ideal to minimize the visual, noise and shadow flicker impacts onshore, while being close enough to minimize cable connection costs. Finally, the site is not located near any major harbours or airport areas, reducing the risk of interference and/or collision (3).

1.2.3 - Sikka l-Bajda Stakeholder Report

The Ministry for Resources and Rural Affairs appointed a Committee on Wind Energy (CoWE) to address the issues raised against offshore wind development at Is-Sikka l-Bajda by reviewing developments in wind technology, learning from wind farms operating in Europe, and to propose recommendations to resolve conflicts with consulted stakeholders.

The CoWE compiled a report in July 2008 summarizing their findings as a follow-up to the consultation exercise done by the Malta Resources Authority (MRA) in 2005 regarding the Sikka l-Bajda proposal. The committee found that there has been significant stakeholder resistance from various groups and authorities in Malta.

- **Malta Tourism Authority** – expressed concerns that proximity to tourist areas, the negative landscape and visual impacts, infrastructural development, clashes with popular diving areas and interference with recreational marine activities3. However, many operational wind farms in Europe have observed an increase in tourism after the construction of the wind farm, indicating that wind farms could be a tourist attraction.

- **Malta Environment and Planning Authority** – concerned about the risk of collision between birds and wind turbines and disturbances caused to bird nesting areas. Other issues raised by the Authority was disturbances to the marine benthic environment during the construction phase, the

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3 The Royal Malta Yacht Club claims that the wind farm would obstruct several important local races.
footprint taken up by the turbines foundations, visual and coastal impacts, conflicts with coastal activities, and land reclamation issues. The CoWE determined that the primary environmental issues are that reefs and *Posidonia oceanica* meadows are listed in Annex I of the Habitats Directive, the latter as a priority habitat and the reef itself is a candidate Marine Conservation Area and close to a proposed Natural 2000 site⁴.

- **Enemalta** – concerned with grid connection costs and the impacts of the wind farm output on the grid, suggesting that detailed studies be carried out.

- **Malta Maritime Authority** – concerned about increased collision and navigations risks, possible interference with marine navigation and communications equipment, and interaction with leisure and small scale commercial seaborne traffic. The reef is located in Bunkering Area 1, which is designated for bunkering operations under particular weather conditions. There is a need for baseline data to establish maritime traffic patterns on and around Is-Sikka l-Bajda as well as the rest of the islands for the successful development of offshore wind energy generation in Maltese territorial waters.

- **Fisheries Control and Conservation Division** – concerned about the potential loss of fishing grounds and the impacts on fish breeding during foundation construction. There is also the problem of conflicts with fish farm operations and the impact of generated noise on fish populations. The CoWE concluded that while fish populations will diminish during the construction phase, long-term negative impacts are not expected.

The CoWE concluded that the Maltese government should seriously reconsider Is-Sikka l-Bajda as the location for Malta’s first offshore wind farm because of the lack of viable alternative sites in shallow depths, potential volatile oil market and Malta’s need to exploit its renewable energy potential to reach EU targets (10).

### 1.3 – Recent developments for offshore wind in Malta

#### 1.3.1 – Discovery of underwater caves at Sikka l-Bajda

In recent months, the discovery of two underwater ‘caves’ at the Sikka l-Bajda reef has cast doubts on the viability of the project. Dr. Aaron Micallef, a marine biologist, conducted a five day survey, mapping the topography of the seabed in the northeast of Malta using sound pulses to make the discovery. (11) According to Dr. Micallef, the sinkholes were probably formed during an ice age, when the reef was above sea level. The caves were eroded by rainwater, and the thin roof of the caves eventually collapsed under pressure underwater. The larger of the two holes is 240 metres wide, while the other is around half the size. A digital image of one of the sinkholes is shown in Figure 1.1.

While these two sinkholes are not enough to put the project in jeopardy, there is the possibility that there are more sinkholes on the Sikka l-Bajda reef. If it is discovered that the reef could collapse in other areas, the feasibility of the project could be compromised. If this is the case, then this would cripple Malta’s efforts to reach EU targets for 10% renewable energy production by 2020.

⁴ Rdum il-Madonna
Moreover, there may be other issues related to the discovery of the sinkholes. Marine biologist Dr. Alan Deidun stated to *The Sunday Times* (11) that shallow dolines such as the ones discovered at is-Sikka l-Bajda could provide unique habitats to sensitive, shade-seeking species and could also attract rare algae and types of coral.

An Environmental Impact Assessment is currently being carried out on the site to establish whether there are any other similar sinkholes in the area and to identify the areas where wind turbines could be built with minimal risk. A seismic study on the area would provide a clear picture of what lies beneath Sikka il-Bajda and help understand whether other caves have been eroded within the reef. As a result of this development, there have been suggestions that other sites are evaluated, such as northern Gozo.

Despite these difficulties, Resources Minister George Pullicino, claimed that the government is determined to take the necessary action. With regards to wind energy, he said that analysis is currently being done on three sites: Is-Sikka l-Bajda, Hal Far and Bahrija (12).

**1.3.2 – Liability costs for failure of compliance with EU targets and submission of the Renewable Energy Plan**

An estimate of Malta’s potential liability costs for failing to reach EU targets was published in June 2010 by the National Audit Office (NAO). Financial penalties imposed by the European Court of Justice would depend on the seriousness and duration of the infringement. The NAO based their estimates on the basis of financial penalties, statistical transfers and cooperation agreements. For the top end of the worst case scenario, the contingent liability could amount to €2.9 million, €6.5 million and €36.1 million respectively for every 1% shortfall from the renewable energy targets. Moreover, if renewable energy targets remain unattained, there is a risk that Malta could face further non-compliance costs in terms of other EU Directives, such as its CO\(_2\) emissions targets as stipulated in Directive 2001/81/EC (13) (14) (15).

In the National Renewable Energy Action Plan submitted to the European Commission on 6 July 2010, it is forecasted that Malta would be able to surpass the mandated 10% target and reach the 10.2% mark (16). This contrasts Malta’s forecast document released in February, which predicted that Malta would only be able to reach the 9.2% mark (17).
1.4 - Scope of the thesis

This chapter reviewed some of the relevant studies carried out to date on renewable energy from the offshore wind energy perspective. All studies to date have indicated that the only viable offshore project that could come online by 2020 would be Is-Sikka l-Bajda, which is a critical part of Malta’s plan to reach the mandatory RES targets. There have been inquiries into other near shore shallow reefs around the islands, but these would only be able to support few turbines of marginal capacity and the negative impacts would probably outweigh the positive.

In the past five years, significant strides have been made in developing commercially viable foundation structures for deeper waters. The scope of this thesis is to review the developing technologies in conjunction with the wind energy market trends, and then to use this information to reassess the potential for offshore wind farms in deeper water. The reason why this assessment is important for Malta is because of future EU mandatory RES targets beyond the current one for 2020. Assessment of the optimal sites to utilize these upcoming technologies is crucial to keep up with these targets.

The physical characteristics of the Maltese Islands are described in Chapter 2, including the wind resource, geology, bathymetry and marine benthic environment of the country. The potential conflicts and negative impacts of wind farm development are also discussed, particularly focusing on marine traffic, and protected areas and habitats of the Islands.

Foundation technologies are the subject of Chapter 3, which are typically subdivided into groups according to the most suitable depth. The main classes of shallow, transitional and deep water technologies are investigated, followed by a review of the various prototype floating technologies being tested.

The European Wind Energy Association’s offshore wind energy market trends and projections are treated in Chapter 4. All of the major offshore wind farms commissioned since 2002\(^5\) are reviewed in depth to establish what have been done and how the market is changing. The wind farms currently under construction and the wind farms still in an early proposal or planning stage are reviewed.

Finally, in Chapter 5, a simple model is developed to evaluate a number of offshore wind energy proposals in Maltese territorial waters. The model is weighted based on the relative importance of the parameters and is tested on a number of real proposals for the Maltese Islands. The results and conclusions of this study are outlined in Chapter 6 and a couple of hypothetical proposals are suggested.

\(^5\) Up-to-date as of 31\(^{st}\) August 2010
Chapter 2 – Physical characteristics of the Maltese Islands

2.1 – Wind Resource in Malta

One of the most important factors to consider when planning an offshore wind farm is the proper assessment of the wind resource at the site. The development area must have good consistent winds, with a high long-term averaged mean wind speed and a low standard deviation.

For a proper assessment of the wind resource of a potential site, wind measurements should be taken at the site and at the eventual hub height of the turbines, which could be over 100 metres, for a period of not less than 6 months. This is because the wind is a highly variable resource and generally increases with height above the surface and distance from the coast.

2.1.1 – Estimating the wind resource

In the absence of wind data at a site, the wind resource can be estimated by using data from other reference stations and then applying data extrapolation techniques and mathematical models. The Luqa weather station is a useful reference station to use to apply these methods. The Luqa weather station is 11 metres above ground level and 84 metres above mean sea level.

A rough estimate of the wind resource was done by using the daily averaged wind speeds\textsuperscript{6} at the Luqa station from mid-1996 to August 2010\textsuperscript{7}. The wind speeds at this site were increased by a factor of 50\% because the Luqa station is located at the centre of the island and the fact that the wind speed is higher offshore. While this is not a rigorous, nor an accurate analysis of the wind data, it was done to generate an approximation of the distribution of wind data, which is needed to estimate the annual power generation of wind turbines. The data abstracted using this methodology is given in Table 2.1.

2.1.2 – Wind Turbine Power Generation and Wind Farm Economics

Every wind turbine in the market has a power curve, which is in an indication of the power generation rate of a turbine at its operable wind speeds. A power curve is defined by three features; the cut-in speed\textsuperscript{8}, the rated speed\textsuperscript{9} and the cut-out speed\textsuperscript{10}. One of the most utilized turbines in the offshore wind industry today is the Vestas V90-3.0MW, whose power curve is as given in Figure 2.1.

\textsuperscript{6} Typically, using hourly-averaged wind data would give a more accurate evaluation of the wind resource.
\textsuperscript{7} Wind data extracted from \url{http://www.wunderground.com/history/station/16597}
\textsuperscript{8} This is the minimum wind speed required for the wind turbine to start generating electricity.
\textsuperscript{9} This is the wind speed at which the wind turbine is generating electricity at its maximum rate.
\textsuperscript{10} The turbine is switched off automatically at this point, to reduce the wear and tear on the turbine.
Figure 2.1 - Power curve of a Vestas V90-3.0MW wind turbine. The turbine has a cut-in speed of 3.5m/s, a rated speed of 14m/s and a cut-out speed of 25m/s (18).

The wind speeds were grouped into bins of equal value in order to be able to use the bin method for wind turbine generation. If the wind data is separated into $N_B$ bins of width $w_i$, midpoint $m_i$, and frequency $f_i$, then the long-term averaged wind speed, the standard deviation, the average wind power density, the average power generated by a Vestas 90-3.0MW wind turbine and the annual electricity generated can be calculated (19). The electricity generated by the turbine, the cost of the turbine and the price of electricity are used to estimate whether the wind turbine is viable at the location. See Appendix A for more information.

<table>
<thead>
<tr>
<th>$N_B$</th>
<th>$m_i$/ms$^{-1}$</th>
<th>$f_i$</th>
<th>$P_W(m_i)/kW$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; x \leq 1$</td>
<td>0.5</td>
<td>310</td>
<td>0</td>
</tr>
<tr>
<td>$1 &lt; x \leq 2$</td>
<td>1.5</td>
<td>378</td>
<td>0</td>
</tr>
<tr>
<td>$2 &lt; x \leq 3$</td>
<td>2.5</td>
<td>920</td>
<td>0</td>
</tr>
<tr>
<td>$3 &lt; x \leq 4$</td>
<td>3.5</td>
<td>517</td>
<td>50</td>
</tr>
<tr>
<td>$4 &lt; x \leq 5$</td>
<td>4.5</td>
<td>855</td>
<td>250</td>
</tr>
<tr>
<td>$5 &lt; x \leq 6$</td>
<td>5.5</td>
<td>591</td>
<td>450</td>
</tr>
<tr>
<td>$6 &lt; x \leq 7$</td>
<td>6.5</td>
<td>244</td>
<td>700</td>
</tr>
<tr>
<td>$7 &lt; x \leq 8$</td>
<td>7.5</td>
<td>416</td>
<td>900</td>
</tr>
<tr>
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<td>8.5</td>
<td>167</td>
<td>1200</td>
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<td>9.5</td>
<td>288</td>
<td>1600</td>
</tr>
<tr>
<td>$10 &lt; x \leq 11$</td>
<td>10.5</td>
<td>83</td>
<td>2100</td>
</tr>
<tr>
<td>$11 &lt; x \leq 12$</td>
<td>11.5</td>
<td>76</td>
<td>2550</td>
</tr>
<tr>
<td>$12 &lt; x \leq 13$</td>
<td>12.5</td>
<td>89</td>
<td>2800</td>
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<td>34</td>
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<td>49</td>
<td>2950</td>
</tr>
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<td>15.5</td>
<td>13</td>
<td>3000</td>
</tr>
<tr>
<td>$16 &lt; x \leq 17$</td>
<td>16.5</td>
<td>12</td>
<td>3000</td>
</tr>
<tr>
<td>$17 &lt; x \leq 18$</td>
<td>17.5</td>
<td>7</td>
<td>3000</td>
</tr>
<tr>
<td>$x &gt; 18$</td>
<td>18.5</td>
<td>8</td>
<td>3000</td>
</tr>
</tbody>
</table>

Table 2.1 - Wind data for Malta as distributed in bins of equal width, the midpoint of each bin, the frequency and the average power generated by the turbine at the midpoint of each bin.
Using the data in Table 2.1, the mean wind speed was found to be 5.04 m/s with a standard deviation of 3.20 m/s, at around 10 metres above mean sea level. The average wind power density of an offshore location in Malta was estimated to be 191.93 MW/m². A Vestas V90-3.0MW wind turbine is expected to generate electricity at an average rate of 532.41 kW, which is only around 18% of the maximum generating capacity of the turbine, and lower. The turbine is expected to generate around 93.4 GWh over 20 years, the expected lifetime of a wind turbine. Several independent studies have estimated the expected wind resource at is-Sikka l-Bajda, using more accurate methods, as given in Table 2.2.

<table>
<thead>
<tr>
<th>Source</th>
<th>Wind Speed (m/s)</th>
<th>Height above sea level (m)</th>
<th>Expected annual generation of a Vestas V90-3.0MW turbine (GWh)</th>
<th>Net Capacity Factor Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farrugia et al (2000)</td>
<td>7.0 - 8.0</td>
<td>45</td>
<td>6.57 - 9.20</td>
<td>25.1%-35.2%</td>
</tr>
<tr>
<td>Mott Macdonald (2005)</td>
<td>5.7</td>
<td>10</td>
<td>4.161</td>
<td>15.9%</td>
</tr>
<tr>
<td>ALTENER 2002-065</td>
<td>6.5 - 7.5</td>
<td>60</td>
<td>6.13-7.89</td>
<td>23.4%-30.1%</td>
</tr>
<tr>
<td>Mott Macdonald (2009)</td>
<td>6.5 - 7.5</td>
<td>70</td>
<td>5.5-7.04</td>
<td>20.6%-26.8%</td>
</tr>
</tbody>
</table>

Table 2.2 - Expected wind speeds and power generation at Sikka l-Bajda (3)

In order to obtain an estimate for the cost of installing an operating the wind turbine, the Kentish Flats wind farm was used to provide a baseline for cost. The stated project costs for the Kentish Flats wind farm was €125.85 million, around €4.2 million per wind turbine. Since offshore wind is not established in the Mediterranean, and trying to factor in operations and maintenance costs, it is assumed that installing and maintaining the wind turbine in Malta for 20 years would cost around €5.5 million. Electricity is sold at three different rates, €0.105/kWh, €0.12/kWh and €0.18/kWh, the former two figures represent the current electricity rates in Malta while the latter is the expected price of electricity from the Sikka l-Bajda wind farm.

The results of the economic analysis for the three different rates are given in Tables 2.3, 2.4 and 2.5, which show the massive differences in the profitability of a wind farm because of differences in wind speeds. At best, the wind speed at Sikka l-Bajda is projected to be around 8 m/s, at which the turbine is generating at a rate of 1.05 MW, at 35.2% of the maximum generating capacity. The stated Kentish Flats wind farm output corresponds to an average wind speed of almost 10 m/s, almost doubling the power generated and hence the revenue.

The latest estimates from the 2009 Mott Macdonald report indicate that the capital costs are expected to vary between €3.5 million per MW, or €9-10.5 million per Vestas turbine, meaning that the wind farm would require tariffs to be profitable. Other turbines such as the RePower 5M are expected to generate electricity more efficiently, given the wind speeds and hence more feasible.

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11 www.owemes.org
12 The Kentish Flats wind farm comprises of 30 Vestas V90-3.0MW wind turbines and hence is a good example to use for comparison.
13 This number is arbitrary and could be much higher for Malta. If the figures in the Sikka l-Bajda Project Description Statement are accurate, then a 96MW wind farm using Vestas V90-3.0MW turbines would cost €8.75 million per turbine. At these costs, a wind farm is unlikely to be profitable, even at the highest rates.
14 The actual mean wind speed at Kentish Flats is 8.7 m/s at 70 metres above mean sea level.
<table>
<thead>
<tr>
<th>Source</th>
<th>Power generated over 20 years (GWh)</th>
<th>Revenue generated (million €)</th>
<th>Payback Factor</th>
<th>Payback Period (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin data</td>
<td>93</td>
<td>€9.8</td>
<td>1.8</td>
<td>11.2</td>
</tr>
<tr>
<td>Farrugia</td>
<td>131-194</td>
<td>€13.80-19.32</td>
<td>2.5-3.5</td>
<td>5.7-8.0</td>
</tr>
<tr>
<td>Mott Macdonald</td>
<td>83</td>
<td>€8.74</td>
<td>1.6</td>
<td>12.6</td>
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<tr>
<td>ALTENER</td>
<td>123-158</td>
<td>€12.87-16.56</td>
<td>2.3-3</td>
<td>6.6-8.5</td>
</tr>
<tr>
<td>Kentish Flats</td>
<td>320 (stated)</td>
<td>€33.6</td>
<td>6.1</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Table 2.3 - Economics of a Vestas V90-3.0MW wind turbine assuming capital and maintenance costs of €5.5 million at a rate of €0.105 per kWh

<table>
<thead>
<tr>
<th>Source</th>
<th>Power over 20 years (GWh)</th>
<th>Revenue generated (million)</th>
<th>Payback Factor</th>
<th>Payback Period (years)</th>
</tr>
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<tr>
<td>Bin data</td>
<td>93</td>
<td>€11.2</td>
<td>2.0</td>
<td>9.8</td>
</tr>
<tr>
<td>Farrugia</td>
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<td>5.0-7.0</td>
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<td>1.8</td>
<td>11.0</td>
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<tr>
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<td>5.8-7.5</td>
</tr>
<tr>
<td>Kentish Flats</td>
<td>320 (stated)</td>
<td>€38.4</td>
<td>7</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Table 2.4 - Economics of a Vestas V90-3.0MW wind turbine assuming capital and maintenance costs of €5.5 million at a rate of €0.120 per kWh

<table>
<thead>
<tr>
<th>Source</th>
<th>Power over 20 years (GWh)</th>
<th>Revenue generated (million)</th>
<th>Payback Factor</th>
<th>Payback Period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bin data</td>
<td>93</td>
<td>€16.8</td>
<td>3.1</td>
<td>6.5</td>
</tr>
<tr>
<td>Farrugia</td>
<td>131-194</td>
<td>€23.65-33.11</td>
<td>4.3-6.0</td>
<td>3.3-4.7</td>
</tr>
<tr>
<td>Mott Macdonald</td>
<td>83</td>
<td>€14.98</td>
<td>2.7</td>
<td>7.3</td>
</tr>
<tr>
<td>ALTENER</td>
<td>123-158</td>
<td>€22.08-28.38</td>
<td>4.0-5.2</td>
<td>3.9-5.0</td>
</tr>
<tr>
<td>Kentish Flats</td>
<td>320 (stated)</td>
<td>€57.6</td>
<td>10.5</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Table 2.5 - Economics of a Vestas V90-3.0MW wind turbine assuming capital and maintenance costs of €5.5 million at a rate of €0.180 per kWh

2.2 - Bathymetry

The bathymetry is another important factor to consider when planning a wind farm, since it affects both the capital costs and the suitability of a particular foundation structure for that area. For wind farms, a sea depth of less than 30 metres can be considered to be shallow, sea depths ranging from 30-70 metres are transitional depths, and areas with a sea depth greater than 70 metres are deep sea sites. The bathymetry of the Maltese Islands is described in depth.

2.2.1 - North-western Malta

The northwest section of the Maltese coast is shown in Figure 2.2. The bathymetry of this part of the island is shallower than the southern coasts, but is still quite deep for shallow depth wind farm development. The Sikka L-Bajda reef is the country’s largest near shore shallow reef and the prime candidate for Malta’s first wind farm development.

This area is characterized by some major landmarks and designated areas for marine activity. Ahrax Point is an SPA that is very close to the proposed area of development, which also coincides with a well-used bunkering area in Malta. The Firing Practice Area, Delimara Fish Farms, St. Paul’s Bay and Mellieha Bay are all important areas to consider.
2.2.2 - North-eastern Malta
A close-up section of the north-eastern sector of Malta is given in Figure 2.3. The bathymetry is much steeper than for the north-western sector, with virtually no room for shallow wind farm development. Moreover, the coastal zone of this region is an important economic area because of Valletta Harbours and Bunkering Area 2. The wind potential of the region increases significantly for long-term wind farm development, when cost-effective floating foundations enter the wind energy market.
2.2.3 – Eastern Malta and Hurd Bank
The bathymetry of the eastern coast of Malta is given in Figure 2.4. The near-shore is characterized by shallow outcrops that have been considered for wind farm development; Sikka l-Munxar and Benghajsa Patch. These proposals were put on hold on the basis that they would not be able to support more than a few wind turbines. The eastern coast of Malta has some of the shallowest waters in the country and has excellent potential up to the transitional depth limit. Hurd Bank, which is located around 15km off the eastern coast of Malta, is the shallowest part of the region.

The eastern coast is an area of high economic importance, with three designated bunkering areas, an anchoring zone for ships and lies between Valletta Harbour and Marsaxlokk Harbour. Therefore, the potential for stakeholder conflicts and resistance is high when considering wind farm development in this region.
2.2.4 – Southern Malta
The southern coast of Malta is shown in Figures 2.5 and 2.6 and is defined by steep vertical cliffs, designated as an SCI under the Habitats Directive, and the island of Filfla, which is a Nature Reserve under protection by both the Habitats Directive and the Birds Directive. The 50- and 100- metre contour lines are, on average, only a few hundred metres from the coast, leaving virtually no room for shallow or even transitional depth wind farms to be deployed. There may be some potential for deep sea wind farms in the long term, but the southern coast is not well-exposed to the prevailing north westerly winds and is unlikely to be suitable for development.
2.2.5 - Gozo

The bathymetry of Gozo is shown in Figure 2.7, and is generally steeper than the bathymetry of Malta. Sea depths quickly exceed 100 metres in the south and the west and much of the eastern seas is a restricted area. There is a shallow reef in the north of Gozo was considered for offshore wind farm development and could yet be developed. The region east of Marsalforn Bay up to Comino may have some potential for transitional depth wind farms, especially since the region is well-exposed to the north-westerly winds.
2.2.6 – Conclusions of the bathymetry

In general, the northern and eastern coasts of Malta offer much better potential for wind farm development. While the island’s shallow depth potential is extremely limited, the northern sections have much more potential when increasing the depth limit to the upper end of the transitional limit, which is 70 metres. The southern and western coasts should only be reconsidered when floating platforms are commercially viable.

2.3 - Geology

The Maltese Islands are situated on a submarine shallow elevation known as the Malta-Ragusa rise, which extends from the Ragusa peninsula of Sicily to the African coasts of Tunisia and Libya, as shown in Figure 2.8. Geophysically, the Maltese Islands are associated with the Hyblean Plateau of south-eastern Sicily, a region generally regarded as forming part of the African continental plate. The Islands themselves are relatively young on a geological timescale and are composed of Tertiary limestone and marls with subsidiary Quaternary deposits. The succession is a simple “layer-cake” of Lower and Upper Coralline Limestone with an intervening soft Globigerina Limestone, Blue Clay and
The succession is correlated with the end of the Oligocene and Miocene periods, as summarized in Table 2.6 (24).

Each layer has distinct characteristics such as thickness and hardness due to their formation under various conditions such as sea depth, sunlight, distance to the nearest land, the direction and force of sea currents and the presence of different species and organisms. Changes in these physical conditions that resulted in the different strata were caused by the third episode of the Alpine movements.

<table>
<thead>
<tr>
<th>Period</th>
<th>Time Scale</th>
<th>Series</th>
<th>Formation</th>
<th>Geographical State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pliocene</td>
<td>1-11 million years</td>
<td>None</td>
<td>None</td>
<td>Land bridge</td>
</tr>
<tr>
<td>Miocene</td>
<td>11-25 million years</td>
<td>Samartian, Tortonian, Helvetian, Schlier, Burdigalian, Aquitanian</td>
<td>Upper Coralline Limestone, Greensand, Blue Clay, <em>Globigerina Limestone</em>, Lower Coralline Limestone</td>
<td>Epicontinental; 10 metres depth, Epicontinental; uplift of land by Blue Clay and Greensand, Epicontinental; 180 metres depth, Epicontinental; 10-50 metres depth</td>
</tr>
<tr>
<td>Oligocene</td>
<td>25-40 million years</td>
<td>None</td>
<td>None</td>
<td>Epicontinental</td>
</tr>
</tbody>
</table>

Table 2.6 - Summary of the geological formation of the Maltese Islands (24)

Table 2.7 summarizes the stratigraphy of the Maltese Islands in more detail, subdividing each formation its various members. Geological maps of Malta and Gozo are given in Figures 2.9 and 2.10 respectively. These maps can be used to construct a geological profile of a cross-section of the Islands. Then, using the bathymetry off the coast, the profile can be extrapolated offshore to predict the likely geological formations at a particular site.

Outcrops of the Greensand Formation are found only in Gozo.
Figure 2.9 - A geological map of Malta. The Upper Coralline, Greensand and Blue Clay Formations have eroded in many parts of the island, from St. Paul’s Bay in the north to Siggiewi at the southern coast. Members of these formations can be found in the western parts of the island.
2.3.1 - Upper Coralline Limestone Formation
The Upper Coralline Limestone Formation is the youngest rock formation in Malta and gets its name from the abundance of the fossil algal species *Corallina*. While some layers are crystalline and have no traces of the organism of origin, other portions contain casts of shells and other organisms. The Upper Coralline Limestone Formation is subdivided into four members – Gebel Imbark, Tal-Pitkal, Mtarfa and Ghajn Melel.

The Gebel Imbark Member consists of hard, pale-grey carbonates with sparse faunas, deposits now restricted to erosional outliers and synclinal cores. Basal beds consist of cross stratified ooidal and peloidal grainstones.

The Tal-Pitkal Member consists of pale grey and brownish-grey coarse-grained wackestones and packstones containing coralline algal mollusc and echinoid bioclasts. Lower parts of the member show large rhodoliths of *Mesophyllum* and *Lithophyllum*. The upper part consists of patch-reefs and biostromes, which are dominated by peloidal and molluscan carbonate mudstones, with crustose coralline algae and scattered corals.
<table>
<thead>
<tr>
<th>Rock Layer</th>
<th>Maximum Thickness</th>
<th>Rock Members</th>
<th>Age</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Coralline Limestone</td>
<td>175m</td>
<td>Gebel Imbark</td>
<td>Miocene, Early Messinian</td>
<td>4-25m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tal-Pitkal</td>
<td>Miocene, Late Tortonian to Early Messinian</td>
<td>30-50m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mtarfa</td>
<td>Miocene, Late Tortonian</td>
<td>12-16m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ghajn Melel</td>
<td>Miocene, Late Tortonian</td>
<td>0-16m</td>
</tr>
<tr>
<td>Greensand</td>
<td>16m</td>
<td></td>
<td>Miocene, Early Tortonian</td>
<td>0-16m</td>
</tr>
<tr>
<td>Blue Clay</td>
<td>75m</td>
<td></td>
<td>Miocene, Serravallian to Early Tortonian</td>
<td>15-75m</td>
</tr>
<tr>
<td>Globigerina Limestone</td>
<td>227m</td>
<td>Upper Globigerina</td>
<td>Miocene, Aquitanian to Burdigalian</td>
<td>15-38m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle Globigerina</td>
<td>Miocene, Aquitanian to Burdigalian</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower Globigerina</td>
<td>Miocene, Aquitanian</td>
<td>0-80m</td>
</tr>
<tr>
<td>Lower Coralline Limestone</td>
<td>120m</td>
<td>Il-Mara</td>
<td>Oligocene, Chattian</td>
<td>0-20m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Xlendi</td>
<td>Oligocene, Chattian</td>
<td>0-22m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Attard</td>
<td>Oligocene, Chattian</td>
<td>10-15m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maghlak</td>
<td>Oligocene, Chattian</td>
<td>&gt;38m</td>
</tr>
</tbody>
</table>

Table 2.7 - Stratigraphy of the Maltese Islands (26)

The Mtarfa Member comprises of massive to thickly bedded carbonate mudstones and wackestones, which are yellow in the lower third and white and chalky in the upper two-thirds of the eastern outcrops. The lowest beds contain a brachiopod bed up to 1 metre thick containing Terebratula and Aphiesia.

The Ghajn Melel Member is a massive-bedded dark to pale-brown foraminiferal packstones containing glauconite occur above a basal Upper Coralline Limestone erosion surface in western Gozo. Large Clypecaster echinoids and Macrochlamis pectinid bivalves are common in eastern outcrops together with abundant abraded Heterostegina foraminifer bioclasts.

2.3.2 - Greensand Formation
The Greensand Formation is found in western Gozo and comprises of a thickly bedded, friable greyish green, brown or black marly limestone. The rock is granular and non-crystalline with rounded grains cemented together by various chemical substances, such as iron oxide, silica, lime or clay. An abundance of in-situ fauna is present, consisting of Heterosegina costata d’Orbigny, Chlamys multistriatus Poly, Schizaster eurynotus Agassiz, Clypeaster marginatus and articulated bivalves including Glycymeris deshayesi.

2.3.3 - Blue Clay Formation
The Blue Clay Formation is the only significant terrigenous sediment of the Maltese rock succession and directly overlies the Globigerina Limestone Formation. The formation comprises of a sequence of alternating pale grey and dark gray banded marls, with lighter bands containing a higher proportion of carbonate. The formation consists of very fine-grained particles, which have not hardened completely, indicative of land uplift on the Islands. Blue Clay is soft and rich in planktonic material, corals, molluscs, echinoids and pteropods.

2.3.4 - Globigerina Limestone Formation
The Globigerina Limestone Formation is the second oldest rock and outcrops around 70% of the area of the Islands. The rock consists of yellow to pale-grey limestones comprising almost entirely of planktonic globigerinid foraminifera. The presence of thin phosphorite horizons of less than 0.5
metres thick within the formation, comprising of pebbles and nodules of dark brown to black collophanite, allow for the formation to be subdivided in three divisions.

The Upper Globigerina Limestone is a tripartite, fine-grained planktonic foraminiferal sequence comprised of a lower cream-coloured wackestone, a central pale grey marl and an upper pale cream coloured limestone. Pectinid bivalves and echonoids are present and a phosphorite bed containing fish teeth and other macrofossils occurs at the base of the member.

The Middle Globigerina Limestone overlies the lower phosphorite bed and comprise of white to pale grey, marly limestones. The dominant fossils of the layer are the echinoids Brissopsis and Schizaster, the bivalves Chlamys and Flabellipecten, thalassinoidean burrows, and remains of the turtle Tryonyx and the crocodile Tomistoma.

The Lower Globigerina Limestone is composed of massive-bedded, pale yellow, globigerinid biomicrites. The fossils found in the layer are the molluscs Chlamys and Flabellipecten, the echinoids Schizaster and Eupatagus, pteropods such as Cavolina and extensive thalassinoidean burrow systems.

2.3.5 - Lower Coralline Limestone Formation

The Lower Coralline Limestone formation is the oldest exposed formation of the Maltese Islands and is semi-crystalline or crystalline in nature. The formation is characterized by massive-bedded coarse, white-grey limestones and contains many fossil remains, composed of calcareous algae, corals, bryozoa, brachiopods, serpulids and molluscs. The formation is sub-divided into four members: Il-Mara, Xlendi, Attard and Maghlak.

The Il-Mara Member is always found just below the Lower Globigerina Limestone member and comprises of pale-yellow massive-bedded biosparites and biomicrites. The member developed as a result of the subsidence of eastern Malta, where the seafloor was lower than the wave-base and less affected by prevailing currents.

The Xlendi Member is comprised of massive-bedded brown and pale-grey biosparite and biosparrudite. The defining characteristic is the presence of Scutella specimens or fragments at the top of the highest horizon. The abundance of larger benthonic foraminifera indicates that the member was formed under high-energy, sub-littoral shoal environments in water depths of around 5 metres.

The two dominant algal species present in the Attard Member are Archaeolithothamnion intermedium and Lithothamnion, indicating that the sediments accumulated in a sub-littoral open shoal-water environment of less than 25 metres depth.

The Maghlak Member comprises primarily of benthonic foraminifera and microfossils such as the miliolid Austrotrillina and the soritid Praerhapydionina. A key feature of this member is the absence of planktonic foraminifera. (27)

2.3.6 – Unconfined Compressive Strength of the Maltese Rock Formations and Geological Profiles of Is-Sikka l-Bajda

A table summarizing test results of the unconfined compressive strength of the various rock formations found in the Maltese Islands is given in Table 2.8. The Globigerina Formation is the softest of the rock formations found in Malta, while the Upper Coralline Limestone, particularly the Tal-Pitkal and Gebel Imbark members, is the hardest. These two formations are the most likely geological formations to be found at the seabed of potential wind farm sites.
While the properties of the seabed of a potential wind farm development are usually determined by geotechnical studies of the area, the most likely formation can be predicted by extrapolating a geological profile taken from a cross-section of the island to the potential development site. A geological profile of northwest Malta as indicated by the line AB in Figure 2.8 is extended to is-Sikka i-Bajda to predict the likely formation of the area. The profile and extrapolation are given in Figure 2.11.

The geological formation of the Sikka L-Bajda reef and the surrounding sea is the Upper Coralline Limestone Formation. The most probably member is Tal-Pitkal, since the member is the most prevalent in this region. However, there is a small possibility of Gebel Imbark or Mtarfa Member. Since Tal-Pitkal is, on average, the hardest rock in the Maltese Islands, drilling would be required for all turbines installed at this location using foundation structure such as monopiles. While the hardness of the rock increases costs and duration of installation, the rock is extremely stable, which is an advantage when compared to the sandy and gravelly composition of the North Sea seabed, in which sediment movement could be an issue.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Member</th>
<th>Unconfined Compressive Strength results (MPa)</th>
<th>Expected Range (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCL</td>
<td>Wied</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maghlak</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attard</td>
<td>6.92</td>
<td>25.6</td>
<td>15.0</td>
</tr>
<tr>
<td>Xlendi</td>
<td>30.75</td>
<td>6.2</td>
<td>11.45</td>
</tr>
<tr>
<td>Il-Mara</td>
<td>6.48</td>
<td>5.67</td>
<td>7.52</td>
</tr>
<tr>
<td>Globigerina</td>
<td>Lower</td>
<td>5.14</td>
<td>14.18</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>3.2</td>
<td>4.95</td>
</tr>
<tr>
<td></td>
<td>Upper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UCL</td>
<td>Mtarfa</td>
<td>3.2</td>
<td>4.95</td>
</tr>
<tr>
<td>Tal-Pitkal</td>
<td>4.62</td>
<td>14.7</td>
<td>14.8</td>
</tr>
<tr>
<td>Gebel Imbark</td>
<td>40.63</td>
<td>62.1</td>
<td>37.05</td>
</tr>
</tbody>
</table>

Table 2.8 - Unconfined Compressive Strength of the Maltese Rock Formations
Figure 2.11 - Schematic geological cross-section of AB over Mellieha Ridge, extrapolated to Sikka L-Bajda. The reef is of the Upper Coralline Limestone Formation, likely Il-Pitkal Member, the hardest of the Maltese rocks.
2.3.7 - Typical seabed characteristics of the North Sea

The North Sea has been the leader of offshore wind farm development because the physical conditions are optimal. Besides having a good wind resource and a shallow bathymetry, the North Sea has the ideal seabed characteristics for installing the monopile, which is the most cost-effective foundation for shallow depth sites. A summary of some of the operational wind farms and the relevant seabed geology is given in Table 2.9.

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Foundation Type</th>
<th>Seabed Geology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horns Rev 1</td>
<td>Monopile</td>
<td>Sand, gravel and pebble gravel (28)</td>
</tr>
<tr>
<td>North Hoyle</td>
<td>Monopile</td>
<td>Sand, sandy gravel and clay (29)</td>
</tr>
<tr>
<td>Nysted</td>
<td>Monopile</td>
<td>Holocene sand, gravel and grit (30)</td>
</tr>
<tr>
<td>Scrabo Sands</td>
<td>Monopile</td>
<td>Sand</td>
</tr>
<tr>
<td>Kentish Flats</td>
<td>Monopile</td>
<td>Sand and clay (21)</td>
</tr>
<tr>
<td>Barrow</td>
<td>Monopile</td>
<td>Sand and gravel (31)</td>
</tr>
<tr>
<td>Burbo Bank</td>
<td>Monopile</td>
<td>Holocene sands with variable gravel and mud content (32)</td>
</tr>
<tr>
<td>Rhyll Flats</td>
<td>Monopile</td>
<td>Mostly sand and some gravel (33)</td>
</tr>
<tr>
<td>Horns Rev 2</td>
<td>Monopile</td>
<td>Sand and gravel</td>
</tr>
<tr>
<td>Alpha Venus</td>
<td>Tripod and Jacket</td>
<td>Sand and Gravel (34)</td>
</tr>
<tr>
<td>Gunfleet Sands</td>
<td>Monopile</td>
<td>Sand (35)</td>
</tr>
</tbody>
</table>

Table 2.9 - A list of the various wind farms commissioned in the North Sea and the seabed geology at these sites

The seabed geology of virtually every offshore wind farm development in northern Europe using the monopile foundation is characterized by thick, sandy or gravelly sediments, often more than 20 metres thick. The seabed geology of Malta is completely different than the North Sea, and this will have significant impacts on the planning and construction phases of wind farm development in Malta. While drilling into the rock will be required in Malta, the stability offered by the Maltese geology could be advantageous, since there is little risk of significant sediment movement during the operation phase, which has proved to be a challenge for some wind farms listed in Table 2.9.

2.4 - Marine Habitats in Malta

The marine habitats in Malta are subdivided into four coastal littoral zones: the supralittoral, mediolittoral, infralittoral, and circalittoral zones. Each zone is relatively homogenous and is distinguished by different environmental conditions such as light, wetness, salinity, hydrodynamism, nutrients and typology of substratum. In particular, zones are distinguished by the range of depths in which different organisms survive, which each zone being characterized by different species (36).

2.4.1 - Supralittoral Zone

The supralittoral zone is characterized by organisms that require some wetting with seawater but not immersion. The substrata of this zone are rocky shores, sandy shores and *Posedonia oceanica* banquettes. While this zone contains important habitats for several species, the zone is unlikely to be affected by offshore wind farm development.

2.4.2 - Mediolittoral Zone

The mediolittoral zone is colonized by organisms that tolerate regular immersion in seawater but not continuous submersions. The mediolittoral zone extends from 10-150cm depth, occasionally up to 200cm, depending on the degree of exposure. The zone is divided into several substrata – the upper/middle/lower mediolittoral zone of rock shores, coralline algal ‘trottoir’ and soft substratum shores. Due to the steep bathymetry of Malta and the extreme shallow depth range of the zone, this zone is unlikely to be of concern in any offshore wind farm development projects.
2.4.3 - Infralittoral Zone

The infralittoral zone extends from the lower limits of the mediolittoral at around 1.5 metres depth to around 50 metres at the lower limit. The zone can be divided into two substrata, hard bottom assemblages and soft bottom assemblages.

The hard bottom assemblages are vegetated by photophilic macroalgae in the upper regions and sciaphilic communities in shady areas. The dominant communities in this zone are the brown algae *Cystoseira* spp. and *Dictyopteris membranacea*. *Cystoseira* is a genus of tough brown seaweeds and *Cystoseira* forests usually exhibit a four-storey structure. The algal beds provide a number of microhabitats for invertebrate and fish species, sponges and bivalves. The larger algae provide another kind of microhabitat for many sessile animals, as well as a surface for attachment of other algae or sessile fauna. Additionally some marine animals feed, shelter, or lay eggs in the algal beds.

The soft bottoms assemblages are dominated by sea grasses, particularly *Posidonia oceanica* and *Cymodocea nodosa*, which are probably the most important marine habitat type in the Maltese Islands. In shallow and sheltered waters around 5-10 metres deep, the meadows are mainly *Cymodocea nodosa*. In deeper waters, the endemic species *Posidonia oceanica* is prominent. The seagrass meadows are highly important because of their productivity, high species-richness, their role in stabilising sediments, nutrient cycling and as refuges, breeding and nursery grounds for a number of marine species.

The *Posidonia oceanica* sea grass meadows are a protected species as specified in Annex A of the Habitats Directive. Since the optimal sea depth conditions coincide with the optimal depth ranges for current wind farms, the potential impacts of offshore wind farm development on this ecosystem needs to be well studied and mitigated. A baseline survey of the *Posidonia* meadows was carried out in 2002 by GAS s.r.l. using a side scan sonar and the results are shown in Figure 2.12.

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16 These algal forests comprise of a basal structure of encrusting species, a second storey with low growing erect species, a third storey with tall forms of larger plants, with the large *Cystoseira* forming the last layer.

17 Ephiphytes

18 Bryozoans
2.4.4 - Circalittoral Zone
The circalittoral zone extends from the lower limit of the infralittoral zone down to a depth of around 200 metres, the maximum depth where multicellular photosynthetic organisms can exist. The zone is divided into two substrata: the hard substrata are dominated by attached forms, such as encrusting algae, tubeworms, bryozoans, sponges and corals. The soft substrata are inhabited by burrowing animals and species that live on or partly embedded in the sediment.
The defining Mediterranean circalittoral communities are the coralgal, which are massive bioconstructions formed by coralline algae, such as *Mesophyllum lichenoides*, *Neogoniolithon mamillosum*, and *Peyssonnelia rosa-marina*. The result is a complex architecture that becomes settled by sponges, hydroids and bryozoans, which can form massive reefs or maerl (37).

2.4.5 - Marine Habitats Listed in Annex I of the Habitats Directive
There are several other marine habitats found in the Maltese archipelago that are listed under Annex I of the Habitats Directive (38).

- **Permanently submerged sublittoral sandbanks** – This habitat type occurs in shallow water bays, smaller embayments, creeks and harbours in the Maltese Islands. The sandbanks may be vegetated or non-vegetated and can comprise of sandy muds, fine sands, coarse sands, gravels or rocks.

- **Beds of *Posidonia oceanica*** - This habitat type is listed as a priority habitat and can exist on both hard and soft substrates, withstand variations in temperature and water movement, but are sensitive to desalinization and vulnerable to anthropogenic influences. In the Maltese Islands, *Posidonia oceanica* meadows occur as two main subtypes: the continuous meadows and the reticulate meadows, the latter in which the beds are intermixed with channels and areas of bare sand or bedrock. Posidonia ‘barrier reefs’ occur at Mellieha Bay and Salina Bay and are characterized by a thick layer of matte and *Posidonia oceanica* shoots forming bands over areas of the matte.

- **Coastal lagoons** – Coastal lagoons are a priority habitat and are defined to be areas of shallow, coastal salt water, partially or wholly separated from the sea by natural barriers. There are several approximate lagoonal environments in the Maltese Islands, which vary in physical characteristics, as well as salinity.

- **Large shallow inlets and bays** – These are complex systems composed of an interdependent system of sublittoral, littoral and adlittoral biotypes, several of which are habitat types included in Annex 1, such as sandbanks and seagrass meadows. For Malta, it was proposed that the lower limit for ‘shallow’ to be taken as 40 metres, close to the maximum depth at which the *Posidonia* meadows are normally found.

- **Reefs** – Reefs are rocky marine habitats or biological concretions that rise from the seabed. While they are sublittoral, they may extend into the littoral zone. Reefs are therefore composed of a complex of different biotopes, some of which are included in Annex I of the Habitats Directive, such as *Posidonia* ‘barrier reefs’. In Malta, only a few species are capable of developing biogenic reefs and so the extent of rocky reefs is far greater and range from vertical rock walls rising from the seabed to the surface, underwater cliffs, rocky shoals, and boulder fields.

- **Submerged or partially submerged sea caves** – both submerged and partially submerged caves are common in the Maltese Islands, and can be formed by marine or terrestrial processes, sometimes a combination of both. Marine caves are generally subdivided into three zones; an outer section, where light penetrates allowing for the growth of photophilic algae, a middle section dominated by sessile invertebrates such as sponges and corals and a completely dark inner section largely devoid of sessile organisms (39).

---

19 Non-continuous
20 At least 1 metre thick
21 Encrusting coralline algae, bryozoans and vermetid gastropods can contribute to these structures.
22 The underwater continuation of coastal cliffs.
2.4.6 – Threats to marine habitats in Malta

Table 2.10 gives an overview of the main threats that can affect marine habitats in the Maltese Islands. Several of these threats could be brought about during wind farm development and operation, meaning that a plan to mitigate the threats should be implemented prior to development.

<table>
<thead>
<tr>
<th>Marine Habitat</th>
<th>Examples of Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seagrass meadows</td>
<td>- Mechanical damage</td>
</tr>
<tr>
<td></td>
<td>- Activities that result in habitat loss and degradation</td>
</tr>
<tr>
<td></td>
<td>- Increase in water turbidity</td>
</tr>
<tr>
<td></td>
<td>- Terrestrial run-off of effluents</td>
</tr>
<tr>
<td></td>
<td>- Invasion by non-native species</td>
</tr>
<tr>
<td></td>
<td>- Bottom trawling</td>
</tr>
<tr>
<td></td>
<td>- Anchoring</td>
</tr>
<tr>
<td></td>
<td>- Dredging</td>
</tr>
<tr>
<td></td>
<td>- Thermal effluents</td>
</tr>
<tr>
<td></td>
<td>- Deleterious effects that may arise from fish farm and tuna pens</td>
</tr>
<tr>
<td>Cystosiera Communities</td>
<td>- Organic pollution</td>
</tr>
<tr>
<td></td>
<td>- Dumping</td>
</tr>
<tr>
<td></td>
<td>- Fishing</td>
</tr>
<tr>
<td></td>
<td>- Changes in sedimentation/current regime due to developments</td>
</tr>
<tr>
<td>Cladocora caespitose Banks</td>
<td>- Over-collecting</td>
</tr>
<tr>
<td></td>
<td>- Pollution</td>
</tr>
<tr>
<td></td>
<td>- Mechanical damage by anchors and fishing gear</td>
</tr>
<tr>
<td></td>
<td>- Smothering by sedimentation from development</td>
</tr>
<tr>
<td>Coralligene Communities</td>
<td>- Bottom trawling</td>
</tr>
<tr>
<td></td>
<td>- Dumping</td>
</tr>
<tr>
<td></td>
<td>- Changing in sedimentation regime due to land-use change</td>
</tr>
<tr>
<td>Maerl Communities</td>
<td>- Bottom trawling</td>
</tr>
<tr>
<td></td>
<td>- Dumping</td>
</tr>
<tr>
<td></td>
<td>- Pollution</td>
</tr>
<tr>
<td></td>
<td>- Invasion by non-native species</td>
</tr>
</tbody>
</table>

Table 2.10 - A list of threats to various marine habitats in the Maltese Islands. The habitats most likely to be impacted by wind farm development are the seagrass meadows, Cystoseira Communities and the Cladocora caespitose Banks.

2.5 - Marine Traffic-Related Barriers to Offshore Wind Farm Development in Malta

Malta is an island and therefore heavily exploits the Mediterranean Sea for resources and trade. Historically, Malta has always played an important and strategic role in the Mediterranean and this role has been maintained in the modern global economy.

Maltese territorial waters are used for bunkering services, ferry services between the islands, military activities, cruise liners and other marine tourism activities, commercial and recreational fishing, shipping, repairs to vessels and other similar activities. Many of the marine activities in Maltese territorial waters are governed and regulated by the Malta Maritime Authority (MMA), established in 1992. The MMA’s activities involve the monitoring, development and growth of the country’s ports, ship registration, and yachting activities. The MMA is responsible for enhancing navigational safety, vessel traffic monitoring and ensuring the protection of the marine environment while creating equal economic opportunities.
The number of vessels calling in Malta increased from under 7,000 vessels in 2000 to almost 11,000 in 2008. The number of vessels calling in Malta decreased to around 5,000 vessels in 2009, but this is more likely the outcome of the global economic crisis and is likely an anomaly. The overall increase in activity within Maltese territorial waters indicates the strategic location of the country on major trade routes. As such, Malta is an ideal location for ships calling for bunkering, crew changes, to carry out works and surveys, or to load ship stores, equipment and provisions (41).

![Number of Vessels Calling in Malta](image)

**Figure 2.13 - Number of vessels calling in Malta from 2000-2009. 2009 data unpublished and obtained courtesy of the Malta Maritime Authority. (41)**

2.5.1 - Bunkering Zones

Bunkers cover the quantities of fuels delivered to sea-going ships of all flags, including warships. There are six designated bunkering zones throughout the Maltese Islands: is-Sikka l-Bajda, south-east of Valletta Harbour, Hurd Bank, East of Hurd Bank, North of Marsaxlook and East of Mellieha. Several of these bunkering zones, particularly Area 1 at Sikka l-Bajda and Area 3 (east and west), are also areas of interest for offshore wind farms. Statistics of the various marine activities in the bunkering zones for 2009 is given in Table 2.11.
It is clear that bunkers are an important economic activity in Maltese territorial waters, accounting for 2,549 of the 4,944 (51.6%) registered vessels calling in 2009. According to the MMA’s 2008 annual report, 20% of the activities were bunkers, around 2,200 bunkers. This indicates that while there was less traffic overall in the year 2009, bunkering activities actually increased.

Bunkering Area 4 is the most heavily utilized bunkering area on the Islands, accounting for averaging 2.76 marine activities a day, most of which are bunkering activities. The Sikka l-Bajda and Hurd Bank bunkering zones are also heavily utilized, and are of the most interest for this thesis, because of the relatively shallow depth for Malta and good exposure to the prevailing winds.

There could be significant stakeholder resistance due to proposals for wind farm development whose development area overlaps part of, or all of, the bunkering areas. It may be possible to relocate the bunkering areas to other locations on the island, or increase activities in the other zones. A list of ports in Malta and bunker suppliers, traders and brokers for these ports are given in the link in the footnote.\(^{23}\)

2.5.2 - Port Approaches
There are two areas designated as port approach areas – the Grand Harbour at Valletta and Marsaxlokk Bay. The two ports are essential for the Maltese economy and are not suitable for wind farm development.

2.5.3 - Nature Reserves
Natura2000 sites under the Bird Directive and/or the Habitats Directive are priority areas, as shown in Figure 2.14. By definition, an area listed as a Natura2000 sites does not exclude the region from human activity or development, including offshore wind farms. However, the proper measures should be taken to identify and mitigate the risks of wind farm development during the planning phase. Two possible mitigation measures include the choice of foundation structure and planning the construction phase during parts of the year where bird nesting is not disturbed.

2.5.4 - Restricted Areas
There are two areas that are restricted for commercial vessels and vessels over 50 metres long. The areas are the Gozo and Comino Channels between the two main islands; Malta and Gozo and Hamrija Bank in southern Malta. These regions can be immediately excluded for potential wind farm development because of the large vessels that are required during the construction phase. In the north of Gozo, there is a disused explosives dumping ground, which is also unsuitable for wind farm development.

2.5.5 - Fishing and Fish Farming
There could be significant stakeholder conflicts if a proposed offshore wind farm is too close to fish farms or popular fishing grounds, because of the negative impacts on marine life, including fish, from noise during the construction and operation phases. If this happens, the lives of the people who depend on the fish produce of that area would be inadvertently affected.

2.5.6 - Other Conflicts
In 2006, the Malta Resources Authority (MRA) carried out a consultation exercise with some key Government entities and authorities to identify potential stakeholder conflicts. The results were published in the form of a map, with the identified areas labelled as ‘no-go zones’, as shown in Figure 2.15.
Significant portions of the Maltese coastline has been designated by various authorities as ‘no-go zones’, signalling that there will be considerable stakeholder resistance against any proposed wind farm close to Malta’s coast. However, this does not mean that wind farm development is not possible in these areas, but proper coastal zone management, particularly marine spatial planning is recommended to help resolve these issues.

2.6 - Risk assessment for ship-turbine collisions

Collisions of ships with offshore wind energy turbines can be significant threat to the economy and the environment. In a collision incident, the ship’s structure will be damaged, causing possible leakage of supplies or cargo, such as oil. In the worst-case scenario, the ship could break apart and sink. Collisions can occur because of engine failure, causing the ship to drift into a turbine.

To calculate the risks, a stochastic analysis of the probability of collisions as well as consequence analysis is required. While not much work has been done on developing models to predict the probability of collision, simulations on the consequence of collision have been done. The risk of a devastating ship-turbine collision can be evaluated using a risk matrix, which combines the consequence of collision and the probability of collision to calculate the risk (42).

2.6.1 - Consequence of collision

The consequence of collision can be simulated by developing numerical models using methods such as the finite element method to model the colliding ship, the offshore wind turbine and its foundation structure, the surrounding water and immediate seabed. The colliding ship, which would drift into the turbine at a certain velocity, depending on sea conditions, has an initial kinetic energy. During
collision, much of the energy is transferred to the turbine, some of which results in deformation of the turbine\textsuperscript{24}. The remaining energy results in damage to the ship.

Simulation results of double-hull tankers colliding in wind turbines with different foundation structures in the German part of the North Sea indicate that collisions with monopiles and jacket structures cause relatively little damage to the ship. However, in the case of collision with a tripod, there was significant damage to the ship structure, especially if the ship collided with a tripod leg. In most of the simulations, there was minor damage to the turbines, except for the monopile, which was ripped from the seabed.

The grade of consequence is not easy to define because there can be many consequences in the case of a collision. The environmental consequences are probably the most considered and publicized consequence for these scenarios, but potential damage to the turbines, the ship, the potential loss of human lives and the economic ramifications are equally important.

It may prove to be too difficult to try and evaluate the cumulative degree of consequence at once – one possible alternative is to assign a grade for each individual consequence and aggregate them later for the overall degree of consequence. The consequence grade and description for environmental damage is given in Table 2.12 (42).

<table>
<thead>
<tr>
<th>Consequence Grade</th>
<th>Environmental Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor</td>
<td>No damage to the marine environment</td>
</tr>
<tr>
<td>Significant</td>
<td>Minor spillage from supplies in wing tanks</td>
</tr>
<tr>
<td>Severe</td>
<td>One or more holds penetrated causing cargo to flow into the sea</td>
</tr>
<tr>
<td>Catastrophic</td>
<td>Ship breaks apart and sinks causing all the cargo to flow into the sea</td>
</tr>
</tbody>
</table>

Table 2.12 - Consequence Grades for environmental damage after a ship-turbine collision (42).

Similar consequence grading systems could be defined for the other consequences. For example, a basic grading system for wind turbine damage is defined in Table 2.13.

<table>
<thead>
<tr>
<th>Consequence Grade</th>
<th>Turbine Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor</td>
<td>No apparent loss in generation capacity of the turbine</td>
</tr>
<tr>
<td>Significant</td>
<td>Some deformation of the turbine seen, reducing generating capacity of the turbine</td>
</tr>
<tr>
<td>Severe</td>
<td>Significant damage caused to the turbine, requiring immediate shutdown for repairs</td>
</tr>
<tr>
<td>Catastrophic</td>
<td>Foundation ripped from the seabed, causing the tower and hub to topple and fall into sea</td>
</tr>
</tbody>
</table>

Table 2.13 - Consequence Grade for the wind turbine after collision

2.6.2 - Probability of Collision

The probability of collision is only a proposal and not much work has been done to accurately calculate this. The probability of a collision would be determined on a number of factors, such as the actual location of a proposed wind farm, marine activity in the area, and the sea current. The probabilities can be graded into frequency grades, such as given in Table 2.14.

\textsuperscript{24} The rest is transferred to the ground and soil.
The combination of both a consequence grade and a probability grade can be combined to yield a position in the risk matrix, as shown in Table 2.15. In the system below, a risk factor of less than 3 could be considered acceptable.

### Table 2.14 - Frequency Grades for the probability of a collision in the case of engine failure of a ship (42).

<table>
<thead>
<tr>
<th>Frequency Grade</th>
<th>Probability $p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent</td>
<td>$p &gt; 2 \times 10^{-1}$</td>
</tr>
<tr>
<td>Reasonably Probable</td>
<td>$2 \times 10^{-1} \geq p &gt; 2 \times 10^{-2}$</td>
</tr>
<tr>
<td>Remote</td>
<td>$2 \times 10^{-2} \geq p &gt; 2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Extremely Remote</td>
<td>$2 \times 10^{-3} \geq p &gt; 2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 2.14 - Frequency Grades for the probability of a collision in the case of engine failure of a ship (42).

### Table 2.15 - The probability of collision and the consequence of collision are combined to get the risk factor (31).

<table>
<thead>
<tr>
<th>Consequences</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Severe</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 2.6.3 - Marine Spatial Planning Initiative

Marine spatial planning (MSP) is a public process of analyzing and allocating the spatial and temporal distribution of human activities, including wind farms, in marine areas to achieve ecological, economic, and social objectives that usually have been specified through a political process. Effective MSP is ecosystem-based, integrated, area-based, adaptive, strategic and participatory.

MSP is a continuing, iterative non-linear process that learns and adapts over time. The development and implementation of MSP involves a number of steps and is summarized in Figure 2.16. There are many environmental, economical and social benefits in successful implementation of MSP, as listed in Table 2.16.

A comprehensive MSP is usually implemented through a zoning map or permit system. It is similar in many ways to integrated coastal zone management (ICZM). However, the range of ICZM only extends to the edge of the continental shelf, which in many countries is only a kilometre or two off the coast. MSP is focused on the human use of marine spaces and can be used for integrated planning beyond the territorial limit into the Exclusive Economic Zone (43).

MSP is a useful tool with significant potential in resolving many marine spatial issues, including those involved with offshore wind farm development. However, MSP is a public team-orientated activity intended to be used by all the involved stakeholders and will not be pursued further in this dissertation.
Environmental Benefits - Identification of important biological and ecological areas.
- Incorporation of biodiversity objectives into planned decision-making.
- Identification and reduction of conflicts between human use and nature.
- Allocation of space for biodiversity and nature conservation.
- Planning of a network of marine protected areas.
- Identification and reduction of the cumulative effects of human activities on marine ecosystems

Economic Benefits - Greater certainty of access of desirable areas for investments.
- Identification of compatible uses within the same area of development.
- Reduction of conflicts between incompatible uses.
- Improved capacity to plan for changes in human activities, including the emerging technologies.
- Better safety during operation of human activities.
- Promotion of efficient use of resources and space.
- Streamlining and transparency in permit and licensing procedures.

Social Benefits - Improved opportunities for community and citizen participation.
- Identification of impacts of decisions on the allocation of ocean space for communities and economies onshore.
- Identification and improved protection of cultural heritage.
- Identification and preservation of social and spiritual values related to ocean use.

Table 2.16 - List of the possible environmental, economic and social benefits of successful implementation of MSP (44).

Figure 2.16 - MSP is a team-orientated exercise and usually follows the procedure described in the figure (44)
Chapter 3 - Offshore Wind Turbine Foundation Structure Technologies

3.1 - Introduction

With offshore wind turbines getting larger and heavier, and being sited further offshore and in deeper waters, it is a challenge to develop innovative and cost effective foundations to support these structures.

An offshore wind turbine is massive in size – from the root of their foundations to the top of the nacelle, the wind turbines can reach a height of 250 metres. (45). Many wind turbines being built today are rated at 5 MW and larger turbines up to 10MW are being developed. As the turbines’ size increase, the importance of developing cost-effective foundations that can safely support these turbines increases.

To date, almost all the wind farms in operation or in construction in Europe use monopile foundations. Monopile foundations are a tried and tested technology that has found many uses in marine construction, including offshore wind and the oil and gas industry. The monopile has found success in its simplicity and minimal footprint on the seabed.

However, while the monopile has been an essential technology in kicking off the offshore wind industry, the technology is reaching its limit. While proving to be cost effective and efficient in shallow waters, the simplicity of the structure means that they cease being cost efficient in waters greater than 20 metres for a 5 MW wind turbine. Moreover, if placed in waters as deep as 30 metres, monopiles cannot support turbines that are rated at MW capacity.

The wind industry has been considering other options, including adaptations of the monopile foundation. Tripod and jacket structures are two such adaptations and are well-proven in the oil and gas industry. For deep waters exceeding 60 metres depth, floating foundation structures are being developed.

In 2008, the Carbon Trust suggested that the estimated $75 billion for offshore wind could be reduced by almost 20% with two parallel strategies – choosing optimal sites and RD&D to reduce the cost of technology. From fifty technology areas, the Carbon Trust found foundations, access, electrical connections and wake effects to be the most promising areas (46). From these four areas, foundations are perhaps the most important, since it is almost half the capital costs. The Carbon Trust held an open competition for developers to submit their concepts, selecting seven designs to fund (47). One of the selected designs, the Titan 200 tripod, is discussed later on in the chapter.

In general, wind turbines can be classified into three different classes depending on the water depth as shown in Figure 3.1, which are

- **Shallow Waters** – 0 to 30 metres
- **Transitional Waters** – 30 to 60 metres
- **Deep Waters** – 60 to 900 metres
The chapter shall continue with a brief overview of shallow water technologies before moving on to transitional deeper water technologies. There are many upcoming transitional and deepwater prototypes and concepts to choose from; many of these are discussed at the end of the chapter.

3.2 - Shallow Depth Foundations

Figure 3.2 shows the shallow water foundations that are currently being deployed. Monopiles, depicted on the left hand side of Figure 3.2, has been highly utilized in the industry to date because of their simplicity and minimal design changes required to transition from onshore to offshore. The central foundation is a gravity base foundation. Such foundations have been successfully deployed in wind farms at Nysted and Samsoe in Denmark. Gravity base foundations are more flexible than monopiles, but the costs increase rapidly with depth.

The final shallow depth technology considered is called the suction bucket or suction caisson. While they have not been actually deployed in a wind farm to date, the technology has some promise in waters around 20-30 metres deep, where the viability of monopile and gravity foundations is questionable.

Figure 3.2 - The three main kinds of shallow depth foundations – the monopile, gravity base caisson, and suction bucket caisson (49)
3.2.1 – Gravity Base Caisson
Gravity foundations were the first type of foundation used by the offshore wind energy industry. Gravity foundations can be made from steel or concrete and use gravity to keep the wind turbine stable and can be seen in Figure 3.3. Gravity foundations are built onshore, then are transported and lowered into place using cranes. Some sea bed preparation is required – silt must be removed and the sea bed must be smooth before the foundation can be lowered. Once in place, the foundation is filled with sand or gravel to achieve the required weight to achieve stability. This foundation structure is usually limited to depths of less than 10 metres because the foundations are too heavy and expensive to install in greater depths.

![Figure 3.3 - A typical gravity base caisson foundation for shallow depths (50)](image)

3.2.2 - Monopile
Monopile foundations are the most commonly and widely known foundation in the offshore wind industry. Monopiles are typically hollow, steel cylinders with a diameter between 3.5 and 4.5 metres and a surface thickness of around 5cm. The length of a pile can vary, depending on the site, but is normally around 30-50 metres long.

Some seabed preparation might be required, such as the laying of gravel to prevent erosion. The piles are typically driven into the seabed, using specialized vessels called jack-up barges. Jack-up barges are mobile, self-elevating platforms able to rest on the sea floor, resting on a number of supporting legs. The barges are equipped with large, hydraulic hammers, which are used to drive the pile to the design depth.

After the pile has been driven in, a transition piece is attached on top of the pile in a special concrete casting process. The transition piece is usually pre-installed with various features including boat landing arrangement, cable ducts for the submarine cables and turbine tower flange for the bolting of the turbine tower. A typical monopile foundation can be seen in Figure 3.4.
The monopile foundation has been critical in the early years in the development of the offshore wind energy industry. This is because the monopiles are a technological and economical solution for wind turbines at shallow depths. The foundation has also been an attractive choice because the sandy and gravelly composition of the North Sea seabed makes it possible to drive the piles to their required depth with minimal drilling.

While the monopile has been widely used in the offshore wind industry to date, there are several key limitations to this technology. First of all, monopiles require specialized vessels to pound the piles into the seabed. Secondly, the single column structure of a monopile foundation wind turbine is subject to large horizontal forces, due to wind, waves and current, exerting turning moments at the foundation level. The foundation is not strong enough to be stable in deeper waters and is not considered to be viable at depths greater than 30 metres. Finally, the monopile is not an ideal foundation in locations with large boulders in the seabed, which must be drilled into and blasted with explosives.

3.2.3 - Suction Caissons

Suction caissons were first used by the company Senpere and Aubergne for mooring anchors for large tankers off the coast of Denmark and are a staple of the offshore oil and gas industry. While traditional used only in shallow waters, the offshore oil and gas industry has deployed suction caissons in deep waters.

Suction caissons are simple steel fabrications that look like upside down buckets which can be designed to be lighter than the steel required for an equivalent monopile foundation. The installation method is simple and quick – a single unit can be deployed and installed in a few hours as a single operation using only a crane of sufficient capacity to lift the foundation into place. The caisson is allowed to settle into the seabed and a pump attached to the head. The pump is used to apply suction to help the caisson to pull itself deeper into the seabed. Auxiliary equipment and consumables such as hydraulic hammers and grouting spreads are not required. Finally, at the end of the turbine’s life, a suction caisson can be removed completely from the seabed by reattaching the pumps and applying pressure inside the caisson, leaving little trace that it was ever there. The installation procedure can be seen in Figure 3.5.
Suction caissons have several advantages over the monopile including higher durability, no need for specialized vessels, the ease of installation, and the structure’s greater resistance to vertical and lateral loads due to their larger diameters. Suction caisson foundations are being considered for a 200 MW offshore wind farm in Hong Kong, in waters around 30 metres deep (54).

3.3 – Transitional Depth Technologies
In deeper waters between 30 to 60 metres, shallow water foundation structures can be replaced by fixed bottom systems that use a wider base with multiple anchor points, similar to what is done in the oil and gas industry. Transitional substructure technologies are typically most viable at depths up to 60 metres. Various transitional substructure technologies can be seen in Figure 3.6.

Transitional depth technology is an important step in the progression towards floating systems and access to the full offshore wind resource. Estimates in the United States have shown that the transitional depth resource for Class 5 winds and above exceeds 250 GW (55).

The first offshore wind turbines in transitional water depths were deployed at Beatrice, off the coast of Scotland. The demonstration project consists of two 5-MW turbines at 42 metre depths in the North Sea (56).
3.3.1- Tripod
The tripod foundation is a transitional depth foundation for offshore wind turbines that are based off similar foundations used in the oil and gas industry. The turbine tower rests upon a steel pile, similar to a monopile foundation. A steel frame is attached to the pile which distributed the loads from the tower onto three steel piles. These piles are driven into the sea bed to a certain depth, depending on the sea bed geology and water depth. A typical tripod structure is shown in Figure 3.7.

![Figure 3.7 - A typical tripod support structure for offshore wind turbines (50)](image)

The design of the tripod foundation gives it sufficient strength to be placed in deeper waters than the monopile foundation, while maintaining the advantage of minimal sea bed preparation. However, the bulky frame means that the tripod is unsuitable for shallow waters, since service vessels would have difficulties in approaching the turbine. However, since the tripod foundation is designed for transitional water depths, they are not expected to be deployed in waters where this may become an issue.

The major disadvantage to using the tripod foundation is the fact that the tripod legs are anchored into the seabed with steel piles. This makes the tripod foundation unsuitable for areas with large amounts of boulders in the seabed, which would have to be drilled into and blasted with explosives to remove them (57).

The tripod foundation has been utilized for the first time in the Alpha Ventus Offshore Wind Farm, which is located in the Exclusive Economic Zone of Germany. The wind farm was fully commissioned in the first half of 2010 and will provide valuable information regarding the viability of offshore wind farms in transitional water depths (58).

![Figure 3.8 - Installation of the world's first tripod foundations at Alpha Ventus (58)](image)
3.3.2 - Jacket Foundation
A jacket foundation is a very large multi-chord base formed of multiple sections of structural tubing or pipe that are welded together. The jacket is prefabricated onshore and placed upon a large transport barge to be transported to the installation site. The size of the jacket depends on the depth of the water in which it is to be placed. In the oil and gas industry, jacket foundations have been installed at sites hundreds of metres deep.

The jacket is a semi-submerged structure, with a small portion of the jacket extending slightly above the surface of the water. This exposed portion of the jacket is the portion upon which the turbine tower can be mounted, as seen in Figure 3.9. For this reason, wind turbines with a jacket foundation are called jacket-tubular structures, since the tower is a tubular structure.

![Figure 3.9 - A typical jacket-tubular foundation structure (50) ![Figure 3.9 - A typical jacket-tubular foundation structure (50)](image)

These towers have already started going under intensive modelling and testing and so far can be installed in waters as deep as 60 metres. At this point natural frequencies, static stresses and buckling have been tested and the results were satisfactory. Studies have shown that truss towers have also been shown to weigh half of what a monopile tower would. This decrease in weight can also play a large role in the reduction of cost in transportation and installation. One other advantage to the jacket foundation is that minimal seabed preparation is required (59).

3.3.3 - Truss Tower
Trusses, or lattice towers, are an alternative foundation substructure to tubular towers and can be seen in Figure 3.10. Truss towers were not developed for onshore wind turbines mainly because of their aesthetic appearance and complex fabrication process. However, the truss tower has several key advantages over tubular towers, namely having less weight and a more flexible design. The open sections of the truss tower allow waves and winds to flow through the structure, reducing the loads. In addition, wind farms utilizing truss towers as the foundation structure can be placed far enough offshore to reduce the visual impacts.
Truss substructures have been utilized in two demonstration 5 MW wind turbines in the Beatrice project (61). The feasibility of this kind of structure was evaluated based on the economic impact and the structural behaviours. In tubular-jacket substructures, transient pieces could have stress concentration issues. This disadvantage is avoided in truss towers and when considering the material-saving property in conjunction with this advantage, this could mean that a truss tower is more optimal than a tubular-jacket structure (62).

3.4 - Floating Deepwater Technologies
In the next few years, large offshore wind farms in very deep waters are expected to be built, particularly within the German part of the North Sea. As discussed in Section 3.2.1 the costs of those support structures get prohibitively high at these depths. Fortunately, as depth increases, alternatives for supporting the turbine increases, including floating support structures.

Floating structures must have enough buoyancy to support the weight of the turbine and to restrain pitch, roll, and heave motions within acceptable limits. The most important loads to consider are wind turbine thrust, wave loads, wind turbine torque and drift forces. There are some key differences in the load characteristics of floating wind turbines to that of floating oil rigs. While floating oil rigs are payload and wave driven, the floating turbine loads are primarily wind-driven overturning moments.

Floating support structures have some immediate advantages – probably the most attractive is that it will allow for the offshore wind industry to expand to new sites and countries such as the Mediterranean, Norway, the United States and East Asia. There is a wide variety of technology solutions proposed as a result of the number of choices of concept available and corporate interest. Finally, many floating concepts are easier to construct and install than fixed structures – the removal and decommissioning process is easier as well.

However, floating support structures have several key challenges to overcome, one of which is the stability of the turbine. Floating support structures must be designed in a way that they can support wind turbines rated in the MW class, while minimising turbine and wave-induced motion. The added complexity in the design process, including understanding the coupling between the support structure and the wind turbine is another hurdle the industry must overcome. There are significant concerns to the design and costs of the electrical infrastructure. Finally, there is a lack of experience in deep
offshore wind farms and care must be taken during the construction, installation and O&M procedures.

While no full-scale floating systems have been deployed, a number of companies have deployed full-scale prototypes. A number of other companies are still in the concept development stage. Floating support structures can be classified into three main classes

- **Buoyancy stabilized** – uses the water plane area to achieve stability, similar to the way a barge does. Simple moorings are used to keep the structure in place.
- **Ballast stabilized** – uses a very large weight deep under water, providing a counterbalance to the loads. Simple moorings are used to keep the structure in place.
- **Tension-Leg Platform** – uses tensioned mooring arrangements to keep the structure stable.

Each class is technically and practically viable and are actively being pursued, each having their advantages and disadvantages. Several concepts, such as SWAY’s concept, are a combination of these three classes. Some examples of proposed deep water concepts are shown in Figure 3.11.

![Figure 3.11 - Floating deepwater platform concepts: Semi-submersible tri-floater, barge, spar-buoy with two tiers of guy-wires, three-armed mono-hull tension leg platform (TLP), concrete TLP with gravity anchor, deep water spar (49)](image)

Some preliminary studies have been done already to assess floating systems but none of the public studies to date have attempted to optimize the platform cost and geometry (63) (64).

The wind turbine platform and mooring system should provide the most potential for system cost reduction because the application is new and the most significant cost saving design tradeoffs have not yet been explored. However, a solid basis from which to determine the optimum design has not yet been established.

The commercial investment of floating wind turbines is a technological challenge, but a necessary one if the full wind potential is to be exploited, especially in regions like the Mediterranean where there are precious little shallow waters.

3.4.1 – Ballast-Stabilized

Foundations commonly known as spar buoys, ballast stabilized foundations are one of the concept offshore foundations currently being researched. A spar buoy is a tall, thin buoy that floats upright in the water. It is characterized by a small water plane area and a large mass. Adjustment of these two
parameters tunes the spar buoy to reduce the response to wave forcing. Spar buoys are traditionally known for their use in making oceanographic measurements.

There have been significant technical challenges in the attempt to use spar buoys to support large wind turbines. The structure must be able to support major horizontal loads centred at heights well above sea level. The centre of gravity of the vessel must be lowered to below sea level, which can take up to 2,400 tonnes of ballast to stabilize the structure for a utility-sized turbine (65). While this has proven to be a major engineering challenge, the major issue with spar buoys has been balancing the conflicting requirements of the main design drivers, namely

- Maximizing pitch stiffness to minimize vessel heel
- Maximizing the natural heave period to reduce wave-induced motion
- Minimizing cost (66)

The drivers impose conflicting demands on the water plane area, vessel mass and vessel dimensions to be simultaneously as large as possible to minimize heel and motion, and as small as possible to minimize cost. It is this conflict that greatly reduces the viable design space for spar buoys.

Despite these challenges a ballast stabilized concept has been developed by the company StatoilHydro. The concept is currently being tested in the Hywind pilot project over a two-year period. The current turbine is shown in Figure 3.12 and rated at 2.3MW and is designed to operate in water depths between 120-700 metres (67). This project will provide valuable information as to how the wind and waves affect the structure, which will help in the improvement of the design, in particular in reducing the cost.

![Figure 3.12 - StatoilHydro's spar buoy concept (68)](image)

3.4.2 - Tension Leg Platforms
Tension leg platforms (TLP) are also called mooring-line stabilized foundations and are similar to spar buoys. The mooring line stabilized turbines are fixed in place with tension leg platforms and suction gale anchors. These turbines are somewhat lighter than ballast stabilized wind turbines which allows for more motion of the tower. If the motions of the tower are not controlled they can lead to catastrophic impacts. Currently the mooring line stabilized foundation requires extremely expensive and heavy foundations in order to prevent motion

The challenges in developing a successful design are
• Installing the structure safely, reliably and cost effectively while maintaining stability throughout the entire process, which includes towing, preparation, tensioning of the cable and during submersion of the structure.
• Developing anchoring for ground conditions at the site. Gravity anchors, piled anchors and suction anchors have all been considered but none are easy or cheap to design and handle (66).

Despite the challenges, TLPs are considered to have the most potential for success over the other two classes from both a technical and economic point of view. The TLP concept experiences relatively little tilting motions. Results published and financed by the Research Fund for the Italian Electrical System in 2007 indicate that TLP systems could be less expensive compared to the other floating concepts (69).

A study presented in the Conference Proceedings OWEMES 2009 Brindisi, Italy, concluded that there are considerable offshore wind resources (around 2000-4000 MW) available in waters deeper than 60 metres off the Italian coasts of Sardinia, Sicily and Apulia. These regions are technically exploitable by means of floating wind systems, particularly TLPs.

A preliminary design was developed and evaluated from a technical and economic feasibility standpoint with reference to a large offshore wind farm with 24 turbines rated at 6MW each. The turbines were arranged in four rows of six turbines each, placed around 20km offshore in waters 200 metres deep. A general evaluation of the possible unit cost of the 144MW wind farm was calculated, and an offshore production cost of around 150€/MWh was calculated. Typical onshore wind farms have production costs of around 120€/MWh. However, this general calculation is just an estimate, since annual operation and maintenance costs and the annual energy production of offshore wind farms are still uncertain (70).

3.4.2 - Buoyancy Stabilized
Buoyancy stabilized foundations or hydrostatic turbines are one of the lesser known foundations still being researched. It has also been called the floating jacket concept. The foundation uses a stabilized barge on the surface of the ocean in order to support the wind turbines. The barge is stabilized with cantenary mooring lines attached to anchors on the seabed.

This type of foundation has not found wide practical use yet due to its susceptibility to large waves and large motions due to waves. The major challenges in developing a successful design are minimizing wave loads, motion response and structural loads of the floater. The design of catenary moorings suitable for shallow waters is another engineering challenge for buoyancy stabilized systems (66). Foundations have been designed, derived from the oil and natural gas industry, but the gyroscopic motion of the turbine made this difficult.

3.5 – Transitional and Deepwater Foundation Concepts and Prototypes
In recent years, several companies have been developing new foundation concepts and prototypes for wind turbines in transitional and deep water depths. A total of eight concepts/prototypes are reviewed, one of which is a tripod while the others are floating concepts based on one or more of the principles described above.
3.5.1 - Titan 200
The Titan 200 offshore wind foundation was developed by Offshore Wind Power Systems of Texas. The Titan design is one of the designs selected by the UK Carbon Trust in the Offshore Wind Accelerator Program Round 3 (71).

The Titan 200 design is a tripod foundation designed to economically support a wind turbine in water depths deeper than 14 metres and can be deployed in waters up to around 60 metres deep. The platform is capable of floating with the wind turbine installed and the legs retracted. This assembly can then be towed to its destination and put into service.

At the site where the turbine is to be placed, the legs are lowered to the sea floor and ballasted down. This causes the legs to sink further into the seabed until they reach their proper depth. The vessel holding the turbine then begins to raise the turbine above the water line, causing an air gap between the turbine and the water. The practice is used in the oil and natural gas industry and is proven to be reliable.

This method of installation is a major advantage since specialized vessels are not required. The Titan design can be moved to another site or towed back onshore for maintenance and repairs, eliminating the need to repair on site, which is expensive. Moreover, the Titan design is versatile, allowing for use in uneven seabeds, different soil conditions, and obstructions below the surface. If necessary, the Titan legs can be rotated or repositioned on the same centreline (71).

3.5.2 - WindFloat
WindFloat is a floating support structure for large offshore wind turbines designed and patented by Marine Innovation & Technology, which is owned by Principle Power. The features of WindFloat dampen wave and turbine induced motion, enabling wind turbines to be sited in locations where water depths exceeds 50 metres and wind resources are superior. Finally, economic efficiency is maximized by reducing the need for offshore operations during final assembly and commissioning. A diagram highlighting several key features of the structure is given in Figure 3.14.
There are three advantages to the WindFloat foundation. First, its static and dynamic stability provides sufficiently low pitch and yaw performance enabling use of existing commercial wind turbine technology. Second, its design and size allow for onshore assembly thereby eliminating the need for expensive specialized vessels like jack-up barges. Onshore assembly expands the installation weather window – offshore assembly is usually too dangerous during the winter. Finally, its shallow draft allows for depth independent siting and wet tow to sites not visible from shore.

The WindFloat is fitted with patented water entrapment plates at the base of each column. The plates improve the motion performance of the system significantly due to additional damping and entrained water effects. This stability performance allows for the use of existing commercial wind turbine technology. In addition, WindFloat’s superior stability is augmented by a closed-loop active ballast system. This additional ballast system mitigates mean wind-induced thrust forces, restoring the system to optimal efficiency following changes in wind velocity and direction. The catenary mooring systems employs conventional components such as chain and polyester lines to minimize the cost associated with the mooring system. Through the use of prelaid drag embedded anchors, site preparation and impact is minimized.

The current WindFloat model has been designed for implantation at a 150 MW floating wind farm situated off the coast of Portugal. An artistic rendering of the wind turbines is given in Figure 15.
3.5.3 - SWAY Prototype

The SWAY prototype is currently being developed by the SWAY Corporation. This prototype is a hybrid, ballast stabilized and a mooring line stabilized platform. This prototype foundation is currently being tested for a 5 MW wind turbine, although SWAY intends to deploy turbines rated up to 10 MW. This turbine is expected to be installed in waters between 80 and 300 metres deep (74).

The tower for the SWAY turbine is set to extend 100 metres underwater from the surface and will require a ballast of about 2,000 tons at the bottom in order to stabilize it. Attached to the bottom of the wind turbine is a single tension leg line that holds the turbine in the correct position. The tower’s centre of gravity is far below the centre of buoyancy of the tower – this gives the tower the stability needed to support the large wind turbines to be mounted on it.

The SWAY system is designed to align itself with the wind direction. This is achieved by placing the rotor downwind of the tower. When the wind changes direction, the entire tower turns around a subsea swivel. Moreover, the tower is designed to be reinforced with a tension rod system, further reducing stresses on the system, allowing for the mounting of large turbines.

SWAY’s technology has significant medium to long term potential and can open new offshore wind energy markets in many countries like Norway, the United States, Japan, Ireland, Spain, Portugal and Italy.25 SWAY estimates that 50km off the Norwegian coast, where the water depth is in the range of 100-300 metres, the power production from each turbine would be 20-30% higher than the same wind turbine located at Horns Rev, which is around 15km off the west coast of Denmark.

SWAY’s technology has several advantages compared to alternative energy sources, such as onshore wind power and shallow water wind parks. Wind farms using SWAY’s floating concept could be located far offshore, eliminating any noise and visual impacts. Moreover, the SWAY concept is flexible with respect to water depth and seabed conditions, requiring only one single vertical anchor leg to hold the platform in position. This reduces any potential conflicts with the fishing industry.

In February 2010, SWAY received a €17.2 million reward from Enova to test their prototype. SWAY will test the 10 MW test turbine for two to five years onshore to gather performance data. SWAY is

25 Since the bathymetry of Malta is similar to that of Italy, floating foundations such as the SWAY model would significantly improve the exploitable wind in Malta as well.
also testing a floating tower using a modified Areva Multibrid M5000 turbine, 7km off the coast of Karmoy (76). Although a commercial model is still some years away, there is significant interest in the concept, which should speed its development (74) (77).

3.5.4 - The Semi-Submersible Multiple Wind Turbine System
The Submersible Multiple Wind-turbine System (SMWS) concept has been developed by Moellgaard Energy. While the SMWS concept is not novel and the triangle has been used in previous concepts, the company believes that it has discovered the necessary innovations to make the SMWS feasible. (78).

One particular arrangement for the SMWS is shown in Figure 3.17, which consists of three wind turbines with a 126 metre rotor. The illustrated SMWS comprises wind turbines mounted on columns penetrating the sea surface, connected by pontoons submerged below the sea surface and a position system of turret mooring type.

![Figure 3.17 - One possible configuration for the SMWS concept (79)](image)

The floating mechanism is kept in position by the turret mooring system and rotated around the turret to head the wind. The turret is situated inside the front column and each of the six mooring lines connects to the turret at one end and to the sea floor at the other end.

The SMWS can be constructed onshore and installed at sea without the use of specialized vessels and with a minimum of hazardous operations. The SMWS is almost fully assembled with wind turbines and electrical systems when towed offshore. During SMWS construction, the anchors, mooring lines and the turret are prepared offshore by anchor handler vessels. The array cables and flexible power cable extending from the seabed to the SMWS are prepared offshore by cable layer vessels.

The SMWS is towed from port to final offshore location in lightweight condition and positioned above the turret at the centre of the mooring spread by towing vessels. The turret is hoisted in place and mounted in to the SWMS. The flexible array cable is hoisted in place in to centre of the turret and connected to the power swivel in the SMWS.

The SMWS has several key design advantages which include less motion and inclination, allowing for better directional stability, which could reduce costs and would allow for different turbine designs to be mounted on the foundation. The concept is versatile and applicable to virtually any site. Wind turbines mounted on SMWS foundations may not need active yawing mechanism, further reducing the costs, weights and technical issues. The concept provides an incentive for centralized systems, in
particular the electrical systems such as common transformers, emergency start systems and control systems.

Despite these advantages, there are a few key areas in which the SMWS concept requires attention. The power produced the SMWS will need to be transferred to cables on the sea bed by a rotating electrical junction. While there are several possible solutions to this issue, including rotating transformers, mechanical step junctions and slip rings, none of these have been applied on this scale. Moreover, the electrical cable extending from the seabed to the SWMS will need to be flexible and durable to extend the fatigue life.

The economic potential of the SMWS is demonstrated by comparison between a fixed installation (jacket foundation) and the SMWS at a UK Round 3 location in the North Sea at a depth of 40 metres. The Indexed Capital Cost of the SMWS installation was estimated to be 84 while that of the fixed foundation was around 106. The Cost of Energy (COE) in terms of €/kWh of the SMWS should therefore be lower than that of the fixed installation (79).

3.5.5 - Poseidon Floating Power Plant
Poseidon is a floating foundation designed to work as a platform for extracting energy from both wind and wave power. Poseidon is developed by Floating Power Plant A/S (FPP), which has designed and tested various scale models over the past ten years to come up with the current demonstration model Poseidon 37.

Poseidon is based on a hydraulic power take-off system and is designed for locations offshore with considerable flux and has a significantly higher installed effect, efficiency and production compared to other wave energy systems. The Poseidon concept combines known and mature technologies and opens up the possibility for the wind industry to capture the wind energy within deep water environments, by utilizing a floating platform as foundation for wind turbines.

Some of the innovative technological features leading to Poseidon’s positive results are the dynamic ballasting of the floats, the profile of the floats, the anchor system, and the possibility of integration of wind turbines on the platform. The float absorbs the inherent energy from the waves. A piston pump is used to convert the energy into water pressure, which is used to drive a turbine, generating electricity. The design of the floats ensures maximum absorption of wave energy. The anchor buoy system is designed to ensure that the waves always meet the front of the plant. The front of the wave plant is 230 metres long and consists of 10 floats, as shown in Figure 3.18.
Poseidon 37 is a 360 tonnes, 37-metre wide and 25-metre long hybrid renewable energy demonstration plant. Poseidon was tested off the coast of Lolland in southern Denmark in 2008. The goal of the test was to document the utilization rate in offshore conditions and the use of the system as a floating foundation for wind turbines.

Poseidon 37 was towed back to the test site on the 14th June 2010 for a second test phase. In testing so far, the stability of the platform was perfect even when the turbines were operating at peak performance. The second test phase is designed to provide the data required for the commercial design phase.

The Poseidon concept is designed to be anchored in the open sea with deep waters, high flux and good wind conditions. A 240 metre wide platform can produce over 50 GWh a year, equivalent to the power consumption of around 12500 – 15000 households. Ideally, commercial versions of the Poseidon concept should be as large as possible, which would help reduce the total investment costs, particularly infrastructure costs.

By combining wind and wave power FPP is attempting to address the problem of end-user power demand and supply not being synchronized. Since waves are more stable and predictable than the wind, especially in deep waters, and they continue to roll along after the wind has subsided, the Poseidon should provide more consistent electricity all year round. FPP predicts that their solution would cost between 10-15 Euro cents per kWh, which would be competitive for Europe (81).

3.5.6 - Asymmetric Floating Tower

The Asymmetric Floating Tower (AFT) has been developed by NauticaWindPower and has been designed to address the offshore wind energy industry’s paradigm of rigid-hub rotors positioned upwind of the tower. Modern turbine designs are focused on minimizing the material used, which can cause the turbines, particularly the blades, to become deflection-limited. Commercial land-based turbines have suffered failures from this design in the past, when the blades bent back and hit the tower. With stronger winds and additional tower motion offshore, the probability of the blades colliding with the tower is increased. Moreover, the rigid rotor system can result in fatigue failures in the gearbox due to cyclic bending loads from the rotor. Offshore turbines will incur even more damaging dynamic loads from the gyroscopic forces during motion.
A typical AFT-based turbine configuration is shown in Figure 3.19, which has a rotor located downwind of the tower reducing the risk of blade/tower interference under wind gusts and tower motion. The turbine’s teetered hub uses a pivot point in the hub to allow the blades to move relative to the plane of rotation, effectively decoupling the plane of rotation from the tower motion.\(^26\)

![Figure 3.19 - Typical AFT configuration compared to standard upwind turbine designs (82)](image)

The AFT’s fundamental design characteristic is increased deflection capability and decoupling the rotor from the foundation and tower motions. The downwind articulated rotor integrates with the AFT to exploit this characteristic. Despite these differences to other designs, the majority of components including the rotor blades, gearbox, generator, nacelle and electrical subsystems can be integrated with the AFT.

The AFT has several design advantages aimed at reducing costs as illustrated in Figure 3.20. With a flexible design, the AFT will move in response to extreme wind and wave conditions, translating much of the external loads into motion that is dissipated into inertia, improving durability. The reduced load requires less material to be used in the structure, eliminate the need for some components\(^27\) and reduces fatigue wear on the blades and gearboxes. As with most other floating wind turbine systems, the AFT can be assembled entirely onshore, reducing the costs incurred from on site construction and the use of specialized vessels. The design requires a single tether anchor point, which causes minimal disruption to the seabed and reduces the cost of decommissioning.

Three generations of AFT designs have been developed and tested to date, and all have demonstrated positive clearances between the blades and the water surface with wave heights corresponding to hurricane waves for multi-megawatt size turbines. Data from these designs and tests were used to verify coupled aero-elastic and hydrodynamic analysis and design tools (82).

\(^26\) This is a technology commonly used in helicopters

\(^27\) The AFT design may not need an active yaw subsystem
3.5.7 - Blue H Submerged Deepwater Platform

The Blue H prototype was designed by the Blue H Group and can be installed in waters between 10 and 15 miles from shore in depths between 50 metres and 200 metres. Blue H’s system is better known as the Submerged Deepwater Platform (SDP) and uses a tension leg platform adapted from the oil and natural gas industries technology. The prototype, which is shown in Figure 3.21, uses a two blade rotor design.

The SDP foundation technology comprises of four elements and can be seen in Figure 3.22. The first element is the fabricated steel structure containing six separate airtight compartments and six open, floating, interlinked compartments. These compartments serve as the SDP foundation counterweight. The second element is the heavy-duty chain attached to the six sides of the structure. During transportation to the offshore site, the floating compartments are filled with gravel, and the additional mass sinks the structure to the seabed. The third element is the partly submerged platform. The steel structure made up of six interconnected hollow pipes provides the required buoyancy during transport and operation. The fourth element is the wind turbine, which is placed on a tubular steel tower on the platform.
Once the platform with the fully assembled turbine has arrived at the destination, the assembly is temporarily ballasted to force the platform down into the water. The six chains attached to the counterweight are then attached to the platform and the temporary ballast is removed. The resulting buoyancy creates an upward force, forcing the chains to get tensioned so that the counterweight, chains and platform form a ‘semi-stiff system’. The procedure requires no seabed preparation, no specialized equipment and vessels and the assembly can be done onshore.

The Blue H prototype has been tested at a deepwater site in Italy at the Tricase. Tests with the prototype were successful and hence Blue H is planning to proceed with its intention to expand the Tricase site by 25 more units, for a total capacity on 92 MW, making it the first deepwater farm in the world. (83) (84).

3.5.8 – Hywind

The Hywind floating structure was developed by the Norwegian company StatoilHydro and consists of a steel cylinder filled with a ballast of water and rocks, extending 100 metres below sea level and fixed to the seabed by a three-point mooring spread. The current model is designed for turbines rated at 2.3 MW and can be deployed in water depths ranging from 120-700 metres. The structure with turbine can be seen in Figure 3.23.

The Hywind pilot is currently being tested over a two-year period at an offshore location 10km off the coast of Karmoy, Norway, as shown on Figure 23. The purpose of the pilot is not to generate revenues from power generation, but to discover how the wind and waves affect the structures. Statoil will use the data collected from the pilot project to commercialize their concept, reducing costs to make floating wind power competitive in the energy market. Statoil is investing around NOK 400 million in the construction and development of the wind turbine concept. The public corporation Enova SF granted NOK 59 million in support of the Hywind project. The project was officially inaugurated on the 8th September 2009 (86) (85).
3.5.9 - Summary of Floating Offshore Wind Technologies

A summary highlighting the key properties of the reviewed technologies and concepts is given in Table 3.1. While all eight designs are derived from a few basic concepts, each company has developed a unique design, trying to optimize the stability and cost. There are many permutations of offshore deepwater wind turbine support structures that haven’t been tried yet, leaving a large window of opportunity for improvements in the technology.

<table>
<thead>
<tr>
<th>Technology</th>
<th>WindFloat</th>
<th>Hywind</th>
<th>Blue H</th>
<th>SWAY</th>
<th>Titan 200</th>
<th>SMWS</th>
<th>Poseidon</th>
<th>AFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundation Type</td>
<td>Semi-submersible moored with 4-6 lines</td>
<td>Spar, moored with 3 lines</td>
<td>Semi-submerged Tension Leg Platform</td>
<td>Hybrid Spar/Tension Leg Platform with single tendon</td>
<td>Floating Tripod with retractable legs</td>
<td>Semi-submersible turret mooring with 6 lines</td>
<td>Buoyancy-stabilized</td>
<td></td>
</tr>
<tr>
<td>Water Depths (metres)</td>
<td>&gt;40</td>
<td>&gt;100</td>
<td>&gt;40</td>
<td>100-400</td>
<td>14-60</td>
<td>&gt;30</td>
<td>&gt;30</td>
<td>&gt;30</td>
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<tr>
<td>Turbine</td>
<td>3-10 MW</td>
<td>2.3 MW Siemens</td>
<td>2-bladed “Omega” for testing purposes</td>
<td>3.6 MW and 5.0 MW</td>
<td>3.5 MW</td>
<td>Up to three turbines rated up to 2 MW each</td>
<td>2-bladed downwind</td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td>Tow-out, fully commissioned</td>
<td>Dedicated vessel tow out and upending</td>
<td>Tow out on buoyancy modules until connection</td>
<td>Tow out on buoyancy until legs lowered and moored to seabed</td>
<td>Tow out on ballast until connection</td>
<td>Tow out and moored to seabed</td>
<td>Tow out on buoyancy until moored to seabed</td>
<td></td>
</tr>
<tr>
<td>Turbine Installation</td>
<td>Onshore</td>
<td>Offshore</td>
<td>Onshore</td>
<td>Offshore</td>
<td>Onshore</td>
<td>Onshore</td>
<td>Onshore</td>
<td></td>
</tr>
<tr>
<td>Strengths</td>
<td>Dynamic motions, installation, simplicity of design</td>
<td>Existing turbine and hull technology, well funded</td>
<td>First sub-scale demo deployed</td>
<td>Low steel weight</td>
<td>Can be used in shallow depths and is not sensitive to seabed conditions</td>
<td>Multiple wind turbines per platform allows for integration of several subsystems</td>
<td>Virtually zero down time due to multiple turbines and integration of wave and wind</td>
<td>Improved durability, reduced risk of blade-tower collisions</td>
</tr>
<tr>
<td>Challenges</td>
<td>Steel cost</td>
<td>Dynamic motions, installation</td>
<td>Mooring cost, turbine design, turbine coupling with tendons</td>
<td>Installation and maintenance; downwind 3-blade turbine</td>
<td>Limited depth range where the technology is viable</td>
<td>Installation and electrical subsystems</td>
<td>Installation</td>
<td>Downwind 2-bladed turbines</td>
</tr>
<tr>
<td>Stage of Development</td>
<td>Ready for prototype testing</td>
<td>Full-scale prototype installed in 2009</td>
<td>Half-scale prototype installed in 2008</td>
<td>Ready for prototype testing</td>
<td>Ready for pilot project</td>
<td>Patent Pending</td>
<td>Prototype testing using 11kW turbines</td>
<td>Concept design</td>
</tr>
</tbody>
</table>

Table 3.1 - Summary of the state of the reviewed prototypes and concepts

One of the key advantages of floating wind turbine support structures is the ability to assemble the turbine entirely onshore. This is a huge advantage because construction onshore is less risky, cheaper.
and can be done all year round. Out of the eight concepts reviewed, only two, the WindFloat and SWAY concepts, require significant installation work offshore.

Another cost-cutting advantage in favour of floating wind turbine support structures is that there is no need for specialized vessels, such as jack-up barges, for installation. These vessels can cost hundreds of thousands of Euros a day to rent and if the vessel breaks down, the entire construction procedure comes to a halt.

There are still some areas for improvement in floating support structures, and while simulations and small-scale demonstration projects have proven to be successful and stable, they remain unproven technology for performance, reliability and cost on a larger, commercial scale. However, a couple of concepts are currently being tested, while others, like the SWAY concept and the Titan 200, have received the necessary financial support to start demonstration projects.
Chapter 4 - Review of the Offshore Wind Energy Industry

4.1 - European Offshore Wind Energy Market Trends and Projections
The offshore wind energy market, while still not yet mainstream, has been experiencing healthy growth over the past few years. A total of 366 MW of offshore wind capacity was installed in 2008 in the EU, taking the total installed capacity to 1471 MW in eight Member States, led by the United Kingdom and Denmark. Among the major offshore wind projects completed in 2008 were the Lynn and Inner Dowsing wind farms in the UK and Princess Amalia in the Netherlands (87).

In addition to these large projects, Phase 1 of Thornton Bank in Belgium was developed together with two near-shore projects, one in Finland and one in Germany. In addition, an 80 kW turbine was piloted on a floating platform in a water depth of 108m in Italy28, the first offshore wind turbine in the Mediterranean Sea. Offshore wind energy development in the Mediterranean, together with further developments in the Baltic Sea, North Sea and Irish Sea, is a crucial step forward in establishing offshore wind as a mainstream industry.

The offshore wind energy market continued to experience strong market growth in 2009, with a large number of projects that commenced construction, were under construction or were completed during the course of the year. The European Wind Energy Association (EWEA) expected 420 MW increase in capacity by the end of 2009, including the first large-scale floating prototype off the coast of Norway29. The total installed offshore capacity was just under 2000 MW by the end of 2009 (87).

Barring any financial crisis limiting offshore wind development, 2010 is expected to be a historic year for offshore wind power in Europe, with an estimated market of over 1 GW, bringing the total installed capacity to around 3000 MW. Europe’s 2010 offshore market could make up around 10% of Europe’s total annual wind market, indicating that the offshore industry is well on its way to becoming mainstream.

4.1.2 - Offshore Wind Growth in the first half of 2010
The EWEA reported that during the first half of 2010, 118 new offshore wind turbines were connected to the grid, adding another 333 MW capacity. At this rate, the total installed capacity will exceed the 577 MW installed offshore in 2009. The wind farms that became fully operational so far in 2010 are Alpha Ventus in Germany, Poseidon in Denmark, and Gunfleet Sands and Robin Rigg in the UK (88).

Additionally, 151 wind turbines were installed but were not fully connected to the grid. Much of the turbines were installed in British waters (Greater Gabbard, Thanet, Sheringham Shoal, Walney I) and Germany (BARD Offshore I and Baltic I), but Denmark has also been constructing a wind farm at Rodsand, while Belgium is primed to fully commission its first offshore farm at Belwind. Preliminary work was carried out on four other offshore wind farms but no foundations or turbines have been installed so far30.

28 This is the Blue H pilot project discussed in the previous chapter.
29 The Hywind pilot project
30 The four wind farms are Global Tech 1 and Nordergrunde in Germany and Ormonde and the London Array in the UK
4.1.3 – Offshore Wind Market beyond 2020
The EWEA expects that the offshore wind energy market will continue to grow and that the total installed capacity in 2020 will be around 40 GW\textsuperscript{31}, producing enough electricity to meet between 14.3% and 16.9% of the EU’s total electricity demand (89).

The offshore wind market is expected to continue to grow beyond 2020 to around 13.6 GW in 2030, for a total capacity of 150 GW, meeting between 12.8% and 16.7% of the total EU electricity demand. 2027 should be the first year in which the market for offshore wind turbines will exceed the market for onshore wind in the EU, establishing offshore wind as a mainstream industry in renewable energy (90).

4.2 - Current Operational Offshore Wind Farms
The entire offshore wind energy market focused primarily Northern Europe, particularly the North Sea, the Baltic Sea and the Irish Sea. While there is interest in expanding the market to the Mediterranean, the United States, there are currently no operational offshore wind farms in these regions. There is one operational offshore wind farm in Asia, located east of the Shanghai Bridge in China.

In this section, the current operational large scale wind farms are briefly reviewed in chronological order. While the exact figures will vary depending on the average consumption per household, every additional MW of generating capacity is enough to provide electricity for around 700-1000 households. Generally, a grid formation is preferred with at least 500 metres separating wind turbines, to reduce interference and improve efficiency.

4.2.1 - Horns Rev 1
Horns Rev 1 is one of the world’s largest offshore wind farms and is located 14 to 20km off the west coast of Denmark’s Jutland Peninsula, close to Blavands Huk in the North Sea, as shown in Figure 4.1. The wind farm consists of eighty Vestas V80-2MW wind turbines for a total capacity of 160MW. The wind farm cost around DKK 2 million (€270 million) and became fully operational in the summer of 2002.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{HornsRev.png}
\caption{Location of Horns Rev 1}
\end{figure}

\textsuperscript{31} This represents a twenty-fold increase from today’s 1.5 GW capacity
The site was chosen because of ideal wind resources, which is consistent and has an average speed of 9.7m/s at 62 metres height and shallow water depths ranging between 6 to 14 metres deep. The wind speed and direction distributions, as seen in Figure 4.2, are ideal to exploit the wind resource.

The Horns Rev landscape is stable and has not changed its position since its formation. Horns Rev consists of sand, gravel, pebble gravel and stones with a few pockets of fine materials. The results of a geotechnical survey of this region influence the choice of the monopile foundation for the wind farm. (91) (92) (28)

![Wind speed and wind direction distributions measured at 62 metre height at Horns Rev 1](image)

**Figure 4.4.2 - Wind speed and wind direction distributions measured at 62 metre height at Horns Rev 1 (28)**

### 4.2.2 - North Hoyle

North Hoyle offshore wind farm is Wales’ first offshore wind farm, and the UK’s first major offshore renewable power project. The wind farm was built in 2003 and is located 7km off the North Wales coast between Rhyl and Prestatyn and covers an area of approximately 10km$^2$, as shown in Figure 4.3. The site offers combinations of shallow waters, strong wind conditions and close proximity to the national grid. The total project costs are estimated to be around £80 million (€97 million).

The North Hoyle Offshore Wind Farm comprises of 30 Vestas V80 2.0MW turbines, mounted on monopile foundations in waters around 12 metres deep. The electricity generated is transferred to a substation in Rhyl via subsea cabling, where the power is transmitted to the national grid. The configuration and connection to the substation can all be seen in Figure 4.3.

![North Hoyle Offshore Wind Farm showing the interconnections between turbines and the connection to shore](image)

**Figure 4.4.3 - North Hoyle Offshore Wind Farm showing the interconnections between turbines and the connection to shore (93)**

A joint investigation into the assessment of marine radar, communications and positioning systems was undertaken at North Hoyle during 2004. Two complementary trials were completed, utilising local vessels and radar systems to focus on two main areas – general marine systems and marine radar...
systems. The trials concluded that the wind farm had no noticeable effects on GPS, voice communications systems, compasses and other systems. There was some minor interference for small vessel radars, where the turbine generators produced blind and shadow areas in which other turbines or vessels could not be detected unless the observing vessel was moving. This issue had been identified during theoretical studies prior to construction and was not considered to be a huge problem moving forward. (93)

4.2.3 - Nysted

Nysted Wind Farm, also known as Rødsand I, is one of the world’s largest wind farms, and is owned by DONG Energy (80%) and E.ON Sweden (20%). The wind farm was commissioned in 2003 and is made up of 72 Siemens 2.3MW turbines, placed in a parallelogram of eight rows of nine turbines, the nearest of which is 10km offshore. The turbines are built to the so-called “Danish concept”32. The wind farm has a total generating capacity of 165.6MW. The wind farm is in shallow water depths between 6-9 metres and covers an area of around 26km².

The Nysted Wind Farm at Rødsand lies about 10km south of Nysted and around 13km west of Gedser. The offshore wind farm is close to four wildlife reserve areas. The entire area to the north of the wind farm has been designated as a Ramsar and EC bird protection area as well as an EU habitat area. Although the Rødsand area was once dry land around 13,000 years ago, no evidence of human activity was discovered during an archaeological survey of the area (30) (94).

4.2.4 - Arklow Bank

Arklow Bank Offshore Wind Farm is the first Irish wind farm and the first wind farm to utilize wind turbines rated at 3MW or higher. The farm consists of seven GE 3.6MW wind turbines, for a total generating capacity of 25MW, and was fully commissioned in June 2004. Originally, the wind farm was intended to be built in two phases, the second phase was to add a further 193 turbines. However, the project was cancelled in 2007.

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32 Three-bladed turbines that turn clockwise.
The wind park is located 10km off the coast of Arklow on the Arklow Bank and was connected to the Arklow National Grid substation via submarine and underground cables. The turbines are supported by steel monopile foundations that were driven into the seabed by a hydraulic hammer. (96)

4.2.5 - Scroby Sands
Scroby Sands Wind Farm is located 2.5km offshore Great Yarmouth on the coast of East Anglia. The wind farm utilizes thirty Vestas V80-2.0MW wind turbines, mounted on monopile foundations. The wind farm cost £75.5 million, including a decommissioning provision of £1.617 million, leading to a cost of £1.259 million/MW. The wind farm has become a local attraction, with around 35,000 visitors a year.

The Scroby Sands wind farm was a challenging project because it was built on a sandbank that moves up to 3 metres per day. Procurement of the wind farm started in 2003 and construction in November. Commissioning and handover of E.ON UK was in late 2004.

CEFAS monitored sedimentary, hydrological and benthic processes in 2005 to determine the wind farm’s effects on the seabed and on coastal processes. No problems were identified although there was some scouring around the turbine. Aerial surveys have shown no effect on common seal populations and an increase in the grey seal population. E.ON UK is monitoring the depth of the subsea cables to ensure that they stay buried (97).

4.2.6 - Samsø
Samsø offshore wind farm is a community owned wind farm, around 3km south of the ‘renewable energy island’ Samsø in northern Denmark. The offshore wind farm, which consists of ten 2.3MW turbines, was constructed to offset the emissions produced by transportation and the electricity is exported to the mainland, as shown in Figure 4.6. Each offshore wind turbine cost around €1.4 million per MW, nearly double that of the land-based turbines33. However, power generation at sea is much higher: the land-based turbines generate 2,300MWh per installed MW capacity, while the offshore turbines produce 3,500MWh per installed MW capacity, which helps to offset the initial capital costs.

33 The land-based turbines cost about €800,000 per MW.
The offshore wind turbines were finished in 2002. Most of the turbines were purchased collectively by the community. It is estimated that around 450 of Samso’s residents own shares in the offshore turbines, who receive annual checks depending on how much their turbine has generated (100) (101).

![Image](image.png)

**Figure 4.6 – Samso offshore wind farm layout. The electricity generated is sold to the mainland (101)**

### 4.2.7 - Kentish Flats

The Kentish Flats offshore wind farm is located on the southern side of the outer Thames estuary, on a large, flat and shallow plateau just outside the main Thames shipping lanes, some 8.5 km north of Herne Bay and Whitstable on the North Kent coast, as shown in Figure 4.7. The farm comprises thirty Vestas V90-3.0MW wind turbines. The wind resource at the site is good, with a mean wind speed of 8.7m/s at 70 metres height.

The wind farm is arranged in a regular grid of five east-west rows each of six turbines, sited in an area of 10km². The water depth is on average 5 metres with a variable thickness of seabed sand, underlain by soft to firm clays, on top of the London clay formation, which favours a monopile foundation design.

The Kentish Flats offshore wind farm project was fully consented in March 2003. Geotechnical surveys were carried out in the first half of 2004 and construction began that summer. Construction of the wind farm was completed by August 2005, with commissioning and testing of all turbines completed by September.

An EIA carried out on the project concluded that the wind farm will contribute to the British government’s commitment to emissions reduction, climate change control, energy diversity and security. The farm was deemed to have minimal social impacts, would not block established shipping routes and would not impact the local fishing industry long term (102).
4.2.8 - Barrow Wind Farm
Barrow offshore wind farm is a 90MW offshore wind farm in the East Irish Sea approximately 7.5km southwest of Wainey Island, near Barrow-in-Furness, as shown in Figure 4.8. The wind farm’s rectangular site covers around 10km$^2$ and comprises of thirty Vestas V90-3.0MW wind turbines, delivering power to the grid system at Heysham via buried subsea and offshore cables. Construction of the wind farm started in April 2005 and became fully operational in June 2006.

The wind turbines are arranged in four rows, two with seven turbines and two with eight. The turbines are mounted on monopile foundations in waters around 15-20 metres deep and the mean wind speed at 75 metres height is approximately 9m/s. (31)
4.2.9 - Beatrice Wind Farm Demonstrator Project
The Beatrice Wind Farm Demonstrator Project was a joint venture between Scottish and Southern Energy and Talisman Energy to build a deep water wind farm close to the Beatrice Oil field in the North Sea, as shown in Figure 9. The project was constructed in 2007 and consists of two REpower 5MW turbines mounted on jacket foundations and is expected to run for five years. The wind farm generates around one-third of the electricity needed to operate the adjacent Beatrice platform. The wind farm is located more than 23km from shore in a water depth of around 45 metres. The total cost of the Beatrice Wind Farm Demonstration Project was £35 million. Funding was provided by the EU (£6 million), DTI (£3 million) and Scottish Executive (£3 million) (103).

If successful, the site will be further developed into a 900MW wind farm as part of the Crown Estate’s Round 3 developments.

4.2.10 - Egmond aan Zee
Egmond aan Zee wind farm is the first Dutch offshore wind farm based off the coast of Egmond aan Zee around 10-18km offshore and started operation in October 2007. The wind farm consists of 36 Vestas V90-3.0MW wind turbines for a total generating capacity of 108 MW. The wind farm takes up a total area of 27km$^2$ and cost around €200 million.

The Dutch government started the tender process in 2001 and the contracts were signed in 2005 in a joint venture by Shell and Nuon under the name NordzeeWind. Surveys of the seabed and wind measurements were taken and steel monopiles were selected for the foundations structure.

The Egmond aan Zee wind farm is being used in a comprehensive Monitoring and Evaluation Programme (NSW-MEP) to collect data on the potential impacts of offshore wind farms on nature and the environment in the Netherlands.
The Dutch Ministry of Economic Affairs has designated the Egmond aan Zee wind farm as a demonstration project. The Dutch government has supported the project by inclusion in the Environmental Quality of Electricity Production (MEP) scheme, by investment subsidies under the CO₂ reduction plan and tax relief (104) (105).

4.2.11 - Burbo Bank Wind Farm

The Burbo Bank Offshore Wind Farm is located on the Burbo Flats in Liverpool Bay at the entrance of the River Mersey, around 6.4km from the Sefton coastline and 7.2km from North Wirral. Burbo Banks Wind Farm has 25 Siemens 3.6MW wind turbines and takes up an area of around 10km². Each turbine is anchored to the seabed by a 529metre long steel monopile foundation. Burbo Bank wind farm was officially inaugurated on 18 October 2007.

This location was chosen for many reasons. Firstly, Burbo Bank is exposed to the full force of the westerly winds (averaging around 9m/s) and has shallow water depths (2-8 metres). There were no perceived environmental issues with constructing a wind farm. The seabed geology was ideal for the monopile foundations and the location is close to an onshore electricity connection. Finally, the wind farm is within Port Authority jurisdiction and the local familiarity with wind power further reduced potential barriers. (32) (107)

4.2.12 - Princess Amalia

The Princess Amalia Offshore Wind Farm the second Dutch offshore wind farm in the North Sea and is located in block Q7 of the Dutch Continental Shelf. Princess Amalia is the first offshore wind farm to be constructed outside the territorial zone and in such deep waters, which varied from 19 to 24 metres deep. The wind farm is located 23km from the shore and takes up a total area of 14km², as seen in Figure 4.11. The wind farm consists of 60 Vestas V80-2.0MW wind turbines mounted on monopile foundations. Princess Amalia became fully operational in June 2008. (108)

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34 For safety reasons
35 Seaforth Docks Wind Farm
36 Within 12 nautical miles of the coast as established by the UN Law of the Sea.
Since it is the first offshore wind farm to be built outside the 12 nautical mile territorial zone, the wind farm makes for an interesting case study in terms of environmental impacts. An extensive monitoring programme is being run, which will continue during the first five years after the construction of the wind farm. The potential impacts of the wind farm on birds, fish, marine mammals and the absence of fishing in the area are all under evaluation. The impacts of the foundations on various local morphological processes are being mapped using various techniques.

4.2.13 - Lillgrund

Lillgrund is Sweden’s biggest investment in offshore wind power and is also one of the largest in the world. The offshore project is located in a shallow area of Oresund, 7km off the coast of Sweden and 9km off the coast of Denmark, as shown in Figure 4.12. The wind farm comprises of 48 Siemens 2.3 MW MK II wind turbines for a total production capacity of 110 MW. The wind farm has been fully operational since December 2007 and officially opened in June 2008.

The water depth at the Lillgrund wind farm site varies between 4-13 metres deep. The wind resource at the site was measured to be around 8.5m/s at 65 metres height and a prevailing wind direction of 225 to 255 degrees.

The wind turbines are connected to each other and to the substation in five radials as shown in the figure. The ‘hole’ in the farm is because the water there is too shallow for the navigation of vessels. There were many constraints limiting the wind farm layout, including a gas pipe north of the site, proximity to a major shipping lane through Oresund, proximity to the Danish border and constraints limiting turbine height. This led to a layout where the turbines are very close to each other, and could possibly reduce the efficiency. (109)
4.2.14 - Lynn and Inner Dowsing

Lynn and Inner Dowsing are two adjacent wind farms that have been built 5km off the Lincolnshire coast, east of Skegness, as shown in Figure 4.13. The wind farms consist of 54 Siemens-3.6MW wind turbines and are mounted on cylindrical steel foundations driven into the seabed. The wind farms are located in water depths ranging from 18.6 metres to 26 metres. The turbines cover an area of 20km² with the closest row being 5km from the coast and the furthest being 9km offshore. Both wind farms are connected to an onshore substation at Middlemarsh, Skegness via submarine cables. Offshore construction began in 2007 and the wind farms reached full generating capacity in March 2009. (110)

4.2.15 - Thornton Bank 1

Thornton Bank is Belgium’s first offshore wind farm and was officially inaugurated in early 2009. The wind farm currently has a generating capacity of 30MW, with six Repower turbines in the 5MW class erected according to the first stage of development. Another three sections are to be added by 2013, bringing to total capacity up to 300MW.
The first six turbines are mounted on gravity base foundations in water depths between 12 to 27.5 metres around 30km off the coast near Zeebrugge. The first phase investment amount is about €150 million. (111)

Figure 4.14 – A map of the Thornton Bank development site, turbine layout and submarine cables to the onshore grid

4.2.16 - Robin Rigg Wind Farm
The Robin Rigg Offshore Wind Farm is located in the middle of the Solway Firth, approximately 11km from the Dumfries and Galloway coastline in Scotland and 13.5km from the Cumbrian coastline in England, as shown in Figure 4.15. The wind farm consists of sixty 3MW wind turbines and an offshore substation with interconnecting cables. The substation sits on two platforms connected by a short bridge and is connected to the local electricity distribution system via two 132kV cables which come ashore near Seaton, Cumbria.

The first turbine was turned on in September 2009 and since then the wind farm has become fully operational. The wind farm is one of the largest in the UK and the estimated investment costs were around €500 million. Work commenced by preparing the onshore substation at Seaton for connection with the windfarm at the beginning of 2007. The monopole foundations were installed in the summer of 2007 using a jack-up barge. The array cables, wind turbines and the 132kV cables were installed from 2008 to summer 2009. (112)
4.2.17 – Hywind
The Norwegian energy giant StatoilHydro has launched the Hywind pilot project, the world’s first full scale floating wind turbine, located in the North Sea. The pilot project is located six miles off the coast of southwest Norway, in water depths over 120 metres for a cost of around $67 million. The 2.3MW Siemens wind turbine is currently being tested for a two-year period. (113)

4.2.18 - Rhyl Flats
The Rhyl Flats Offshore Wind Farm is one the largest offshore wind farms in the UK and became fully operational in December 2009. The project was initially developed by Celtic Offshore Wind Limited, which received full consent in 2002, but was sold to and developed by RWE Npower.

The wind farm is located to the west of Rhyl Flats, on the eastern end of the Constable Bank between Abergale and Rhos-on-Sea, approximately 8km off the coast of North Wales. The area of the wind farm is approximately 10km². It comprises 25 3.6MW wind turbines mounted on monopile foundations and has a maximum installed capacity of 90MW.
Subsea cables were used to connect the turbines together and to carry the electricity to shore at the substation at Towyn, which steps up the voltage and transfers the power into the main grid. The greatest challenge endured during the construction of the wind farm was the weather, which was responsible for many delays during the construction stages. Environmental constraints further reduced the working window for construction of the wind farm. (33)

4.2.19 - Horns Rev 2
In 2002 and 2004, the Danish government and several political parties signed an agreement to build a 200MW offshore wind farm. DONG Energy was selected by the Danish Energy Agency to construct the Horns Rev 2 offshore wind farm. Preliminary studies commenced in 2005 and an EIA was prepared. The Horns Rev 2 project was approved in March 2007. Construction commenced from April 2008 to December 2009 and was opened for commercial operation in January 2010.

Horns Rev 2 is further offshore than Horns Rev 1 and in water depths of around 9-17 metres. The wind farm consists of 91 Siemens SWP 2.3-93 wind turbines for a total farm capacity of 209MW. Monopile foundations were used for the Horns Rev 2 wind farm. Stones were dumped on the seabed to limit the movement of the sand and to reduce erosion.

A total of 70km of buried submarine cables were laid at Horns Rev 2. The turbines were interconnected from west to east between rows and the cables contained fibre optics, which transmits communication and control to and from the various wind turbines. The transformer platform, which is used to collect and transmit the generated power onshore, is located east of the wind farm, as shown in Figure 4.18. (114)
4.2.20 - Alpha Ventus

The Alpha Ventus offshore wind farm is Germany’s first offshore wind farm and is a pioneering project undertaken jointly by EWE, AG, E.ON Climate & Renewables, and Vattenfall Europe Windkraft. The wind farm is located around 45km north of the island of Borkum, within the Exclusive Economic Zone (EEZ) of the Republic of Germany and outside of the Wadden Sea National Park as shown in Figure 4.19. Since the area lies in the EEZ, the UN Law of the Sea permits economic utilisation by the Federal Republic of Germany, and is subject to a special legal regime.

The wind farm consists of twelve 5MW wind turbines arranged in a 4x3 grid formation and has a total surface area of 4km², as seen in Figure 4.19. The Alpha Ventus has a good wind resource, with an average wind speed of around 10m/s prevalent from the south-west. The wind is consistent and...
planners anticipate around 3800 full operating hours a year\textsuperscript{37}. The farm lies in waters 30 metres deep and was fully commissioned in April 2010\textsuperscript{38}.

The Alpha Ventus offshore wind farm is an important pioneering project and its success is crucial for the expansion of the European offshore wind market to deeper waters farther off the coast. The northern half of the wind farm’s turbines are mounted on jacket foundations using REpower 5M wind turbines. The southern half of the wind farm comprised of AREVA Multibrid M5000 turbines mounted on tripods. The work for both types of foundation started in June 2009 and all the wind turbines were fully assembled by mid-November. The foundations can be seen in Figure 4.20. (118)

![Jacket (left) and tripod (right) foundations used at Alpha Ventus.](image)

4.2.21 - Gunfleet Sands Wind Farm
Gunfleet Sands wind farm is a British offshore wind farm operated by DONG Energy and is located in the Thames Estuary, around 7km off the Essex coast. The wind farm covers an area of around 17.5km\textsuperscript{2}. The wind farm comprises of 48 Siemens SWT-3.6M-107 turbines mounted upon monopile foundations with a scour protection of gravel and rock. The water depth at the site varied between 0 and 15 metres. The wind farm has a total capacity of 172MW and came fully online on 15 June 2010. The stated cost for the wind farm was £297.50 million. (35)

The Gunfleet Sands Offshore Wind Farm was built in two phases, Gunfleet Sands 1 and 2. The original Gunfleet Sand 1 project received the necessary approvals and permits in 2003-2006, but a second formal EIA was carried out to consider the proposed Gunfleet Sands 2 project.

Construction commenced in September 2008, but was mired by many delays. The crane vessel installing the turbine blades broke down in April 2009. In May 2009, Oceanteam, the company building the wind farm, went into liquidation and terminated funding for the project. The wind farm, expected to be completed in August 2009, was finally completed in April 2010. (121)

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\textsuperscript{37}This is approximately half the year. Typical onshore sites have wind speeds of 5m/s and only around 2200-2500 full operating hours.

\textsuperscript{38}Due to the distance and the curvature of the Earth, Alpha Ventus is not visible from shore.
4.2.22 - Shanghai East Sea Bridge Wind Farm
Shanghai East Bridge Wind Farm is China’s first commercial offshore wind farm and is located off Shanghai’s coast, on the east side of the bridge. The wind farm comprises 34 Sinovel 3MW wind turbines for a total generating capacity of 102MW. The wind farm started transmitting power to the main grid on July 6, 2010. (122)

The wind farm cost around $337 million to complete, which is about double the cost of an onshore plant with the same capacity. However, since the offshore wind resource is higher and since the farm is expected to operate for 25 years, the costs are expected to be relatively low across its lifetime. Shanghai is planning to construct a second phase of the East Sea Bridge Wind Farm on the west side of the bridge, adding another 150MW of generating capacity. (123) (124)

4.2.23 - Thanet
The Thanet project is located 11.3km from Foreness Point, on the eastern part of the Kent coastline as shown in Figure 4.22. The wind farm will comprise 100 Vestas V90-3.0MW wind turbines and have a total capacity of 300MW September 23, 2010. (125) The wind farm covers an area of 35km² and is located in water depths of 20-25 metres. An interesting feature of the wind farm is that the offshore substation was placed at the centre of the farm. However, Ole Bigum Nielson, the UK offshore wind power director at Vattenfall, claimed that this arrangement led to complications during installation. (126) The total investment for completing the wind farm is estimated to be around £780 million. (127)
4.2.24 – Analysis of offshore wind farms constructed to date

A summary highlighting some of the main parameters of offshore wind farms constructed since 2003 is provided in Table 4.1. When Horns Rev 1 was commissioned in 2003, the offshore wind industry were deploying 2MW turbines. Today’s wind farms are using turbines of the 3MW and 3.6MW variety. Monopile foundations are the most popular choice for offshore wind farms up to September 2010, although the first ventures with jackets and tripods in Germany was commissioned earlier this year.

The wind farms commissioned in the early part of the decades are typically in water depths of less than 15 metres. The offshore wind energy market has been slowly transitioning to deeper depths, with many recent wind farms being constructed in water depths approaching 30 metres. A similar trend can be seen in the closest distance to shore. The first offshore wind farm constructed outside the territorial zone[39] was Princess Amalia in 2007. Since then, three other wind farms: Thornton Bank, Horns Rev 2, and Alpha Ventus, have been constructed outside the territorial zone.

The main challenge in the offshore wind industry today it to expand the market while keeping costs as low as possible. When analyzing the costs, the most important parameters are the cost per MW capacity and the cost per kWh of electricity produced. From the cost per MW capacity perspective, the most cost effective offshore wind farms is the Nysted wind farm in Denmark, at €0.69 million per MW. This is probably because the gravity base foundations are the most cost effective option for water depths of less than 10 metres.

[39] This is 12 nautical miles, or 22.2km off the coast.
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<th>Distance to shore (km)</th>
<th>Cost (million €)</th>
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<td>Kentish Flats</td>
<td>30</td>
<td>3</td>
<td>90</td>
<td>Monopile</td>
<td>5</td>
<td>8.5</td>
<td>119.2</td>
<td>3.973</td>
<td>1.32</td>
</tr>
<tr>
<td>Barrow</td>
<td>30</td>
<td>3</td>
<td>90</td>
<td>Monopile</td>
<td>15-20</td>
<td>7.5</td>
<td>158.8</td>
<td>5.29</td>
<td>1.76</td>
</tr>
<tr>
<td>Beatrix</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>Jacket</td>
<td>45</td>
<td>23</td>
<td>35</td>
<td>17.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Egmond aan Zee</td>
<td>36</td>
<td>3</td>
<td>108</td>
<td>Monopile</td>
<td>N/A</td>
<td>10</td>
<td>200</td>
<td>5.56</td>
<td>1.85</td>
</tr>
<tr>
<td>Burbo Bank</td>
<td>25</td>
<td>3.6</td>
<td>90</td>
<td>Monopile</td>
<td>2-8</td>
<td>6.4</td>
<td>181</td>
<td>7.24</td>
<td>2.01</td>
</tr>
<tr>
<td>Princess Amalia</td>
<td>60</td>
<td>2</td>
<td>120</td>
<td>Monopile</td>
<td>19-24</td>
<td>23</td>
<td>380</td>
<td>6.33</td>
<td>3.167</td>
</tr>
<tr>
<td>Lillgrund</td>
<td>48</td>
<td>2.3</td>
<td>110</td>
<td>Monopile</td>
<td>4-13</td>
<td>7</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Lynn and Inner Dowsing</td>
<td>54</td>
<td>3.6</td>
<td>194.4</td>
<td>Monopile</td>
<td>18-26</td>
<td>5</td>
<td>341</td>
<td>6.31</td>
<td>1.75</td>
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<tr>
<td>Thornton Bank</td>
<td>6</td>
<td>5</td>
<td>30</td>
<td>Gravity Base</td>
<td>12-27.5</td>
<td>28.7</td>
<td>150</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>Robin Rigg</td>
<td>60</td>
<td>3</td>
<td>180</td>
<td>Monopile</td>
<td>N/A</td>
<td>11</td>
<td>500</td>
<td>8.33</td>
<td>2.78</td>
</tr>
<tr>
<td>Hywind</td>
<td>1</td>
<td>2.3</td>
<td>2.3</td>
<td>Hywind Floater</td>
<td>&gt;120</td>
<td>9.7</td>
<td>67</td>
<td>67</td>
<td>29.13</td>
</tr>
<tr>
<td>Rhy l Flats</td>
<td>25</td>
<td>3.6</td>
<td>90</td>
<td>Monopile</td>
<td>N/A</td>
<td>8</td>
<td>225</td>
<td>9</td>
<td>2.5</td>
</tr>
<tr>
<td>Horns Rev 2</td>
<td>91</td>
<td>2.3</td>
<td>209</td>
<td>Monopile</td>
<td>9-17</td>
<td>30</td>
<td>722</td>
<td>7.93</td>
<td>3.45</td>
</tr>
<tr>
<td>Alpha Ventus</td>
<td>12</td>
<td>5</td>
<td>60</td>
<td>Jacket &amp; Tripod</td>
<td>30</td>
<td>45</td>
<td>250</td>
<td>20.83</td>
<td>4.17</td>
</tr>
<tr>
<td>Gunfleet Sands</td>
<td>48</td>
<td>3.6</td>
<td>172</td>
<td>Monopile</td>
<td>0-15</td>
<td>7</td>
<td>297.5</td>
<td>6.19</td>
<td>1.73</td>
</tr>
<tr>
<td>Shanghai Bridge</td>
<td>34</td>
<td>3</td>
<td>102</td>
<td>N/A</td>
<td>N/A</td>
<td>243.6</td>
<td>7.16</td>
<td>2.39</td>
<td></td>
</tr>
<tr>
<td>Thanet</td>
<td>100</td>
<td>3</td>
<td>300</td>
<td>Monopile or Gravity Base</td>
<td>20-25</td>
<td>11.3</td>
<td>886.8</td>
<td>8.87</td>
<td>2.96</td>
</tr>
</tbody>
</table>

Table 4.1 - Summary of some of the vital statistics of the large scale wind farms and pilot projects operational to date.

The key wind farms to analyze from a cost perspective are those that break new grounds in the energy market in terms of depth, distance from shore and foundation structure. The crucial wind farms are Princess Amalia\(^{41}\), Horns Rev 2,\(^{42}\) Alpha Ventus\(^{43}\) and in all three cases the cost per MW installed

\(^{40}\) No information was found to confirm which foundation structure was used
\(^{41}\) Outside the territorial limit and in water depths over 20 metres.
\(^{42}\) 30km off the Danish coast, well outside the territorial zone.
\(^{43}\) Tripod and Jacket structures 45km offshore in 30-metre deep waters.
capacity is over €3 million. The parameter that likely explains the increase in capital costs seems to be the distance to shore. The Lynn and Inner Dowsing wind farm in the UK achieved far better numbers than Princess Amalia in similar depths, but is only 5km off the coast.

Energy yield per annum data was available for Horns Rev 1 (600GWh), Kentish Flats (280GWh), Barrow (305GWh) and Gunfleet Sands (570GWh). At these figures, the cost per kW of electricity over 1 year is €0.45, €0.425, €0.52 and €0.522 respectively, without factoring in operations and maintenance costs. The Horns Rev 1 farm uses smaller, less cost-effective turbines and is further offshore than the other wind farms and are in similar depths, while achieving similar cost effectiveness per kWh. This would seem to indicate that the farm is located in a better location with a very good wind resource.

4.3 - Offshore Wind Farms Under Construction and Planned Windfarms

4.3.1 – Wind Farms under Construction

There are currently eight offshore wind farms under construction in Europe, as summarized in Table 4.2. There are several wind farms scheduled to come online in the next couple of years that are of significant importance to the development of offshore wind.

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Number of Turbines</th>
<th>Size of Turbines (MW)</th>
<th>Capacity (MW)</th>
<th>Distance from Shore (km)</th>
<th>Depth (m)</th>
<th>Foundation</th>
<th>Start of Construction</th>
<th>Expected Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>EnBW Windpark Baltic (129)</td>
<td>21</td>
<td>2.3</td>
<td>48.3</td>
<td>16</td>
<td></td>
<td>March 2010</td>
<td>End 2010</td>
<td></td>
</tr>
<tr>
<td>Rødsand II* (130)</td>
<td>90</td>
<td>2.3</td>
<td>200</td>
<td>5-12</td>
<td>Gravity Base</td>
<td>2008</td>
<td>End 2010</td>
<td></td>
</tr>
<tr>
<td>BARD Offshore 1 (4)</td>
<td>80</td>
<td>5</td>
<td>400</td>
<td>90</td>
<td>40</td>
<td>Tripile</td>
<td>March 2010</td>
<td>2011</td>
</tr>
<tr>
<td>Sheringham Shoal (131)</td>
<td>88</td>
<td>3.6</td>
<td>317</td>
<td>17</td>
<td>Monopile</td>
<td></td>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>Tricase (132)</td>
<td>24</td>
<td></td>
<td>92</td>
<td>19.6</td>
<td>108</td>
<td>Blue H floater</td>
<td>2010</td>
<td>2011</td>
</tr>
<tr>
<td>Walney (133)</td>
<td>102</td>
<td>3.6</td>
<td>367.2*</td>
<td>15</td>
<td>Monopile</td>
<td>2010</td>
<td>2012</td>
<td></td>
</tr>
<tr>
<td>Greater Gabbard (134)</td>
<td>140</td>
<td>3.6</td>
<td>504</td>
<td>25</td>
<td>24-34</td>
<td>Monopile</td>
<td>2010</td>
<td>2012</td>
</tr>
<tr>
<td>Ormonde</td>
<td>30</td>
<td>5</td>
<td>150</td>
<td>10</td>
<td>17-21</td>
<td>Jacket</td>
<td>Autumn 2009</td>
<td>2012</td>
</tr>
</tbody>
</table>

Table 4.2 - Summary description of the offshore wind farms currently under construction. Out of the eight farms, two are being constructed in transitional depths, while another in deep seas.

The major investor in offshore wind in the next few years is the United Kingdom, which has plans to aggressively exploit their shallow portion of the North Sea. Wind farms are being constructed at Sheringham Shoal, Walney and Greater Gabbard for a total capacity of around 1.5GW and are expected to be fully operational by 2012. Since all three wind farms are being constructed using monopiles, the expected water depths of the development area is less than 25 metres. The locations and layout of the wind farms can be seen in Figures 4.23, 4.24 and 4.25 respectively.

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* Expected to cost around €435 million.
* Constructed in two phases of 51 turbines each.
Figure 4.23 - Sheringham Shoal map (131)

Figure 4.24 – Walney Offshore wind farm location, layout and submarine cables to the onshore connection points. The wind farm will be constructed in two phases, and 51 of the monopile foundations were installed for Walney 1 (blue) by the end of August, 2010. (133) (135)

Figure 4.25 – The Greater Gabbard wind farm development area is divided in two areas (136)

Perhaps the most important wind farm to monitor for Malta is Tricase offshore wind farm that is reportedly being constructed by Blue H Technologies around 19.6km off the oast of Tricase, Italy. This wind project is a followup to the successful prototype launched during 2007-2008 by the same company. The wind farm is located in deep waters of around 108 metres, around the average depth of
the northern Maltese coast. The layout of the wind farm can be found in Figure 4.26. The wind farm is expected to be completed in 2011. (132)

![Figure 4.26 - Tricase wind farm location, layout and submarine cable connection to onshore connection point. The performance of this wind farm once completed would be of great interest to Malta. (5)](image)

Germany is following up the Alpha Ventus wind farm with an eighty turbine, 400MW capacity windfarm called BARD Offshore 1, scheduled to come online in 2011. This wind farm is larger, further offshore and in deeper waters than Alpha Ventus and highlights the interest in bringing wind energy into transitional depths. The turbines will be mounted on a foundation structure called a tripile, which can be seen in Figure 4.27 as well as the location of the farm itself.

![Figure 4.27 - (left) The position of BARD Offshore Wind Farm development area is in light-blue. (right) The tripile foundation structure is similar to a tripod. (4)](image)
The extension to the Nysted wind farm of 2004, Rodsand 2, is expected to be completed by the end of 2010 and is shown in Figure 4.28. Like the first wind farm, concrete gravity foundations are being deployed. The 200MW extension will cost an estimated €435 million, around €4.83 million per turbine and €2.175 million per MW capacity. (130)

Figure 4.28 - The 200MW extension of Nysted Wind Farm will use the same foundations and is in the immediate vicinity of the original wind farm. (137)

The last offshore wind farm currently in the construction phase is Ormonde Wind Farm which is located 10km off the Irish coast, as shown in Figure 4.29. The wind farm was originally a hybrid wind and natural gas project, but was switched to wind only when Vattenfall purchased the project in 2008. The wind farm will utilize 5MW turbines mounted on four-legged jacket foundations in water depths of around 17-21 metres. (138)

Figure 4.29 - Ormonde Wind Farm is under construction in the East Irish Sea and is expected to be completed in 2012. The wind farm will be one of the first to use turbines rated at 5MW. The wind farm will be mounted on jacket structures even though the farm is in shallow water depths. (139)
4.3.2 - Proposed Wind Farms

*The Crown Estate Round 2 Tender Process*

The United Kingdom has the most well-established program for offshore wind energy development in Europe, which is managed by the Crown Estate. The Crown Estate, which owns 55% of the foreshore and all of the seabed within the 12 nautical mile territorial limit, has adopted a strategy of leasing rounds under which areas of the seabed were made available for offshore wind farm development. The first round was announced in December 2000 and mostly consisted of demonstration scale projects of up to 30 turbines. Eleven sites were developed including Scroby Sands, Kentish Flats, Lynn and Inner Dowsing, Rhyl Flats, North Hoyle, Burbo Bank, Barrow and Robin Rigg. The Teesside wind farm is the last wind farm from Round 1 that has not yet been constructed.

The Round 2 tender process was announced in July 2003 with the objective of leasing areas of the seabed for commercial scale wind farms. Fifteen sites were leased, amounting to 7.2GW capacity, including sites outside the territorial limit. Out of these sites, Gunfleet Sands and Thanet are now fully operational while, Greater Gabbard, Sheringham Shoal and Walney 1 are currently under construction. The other ten Round 2 sites are still at a proposal stage in varying stages of development and are summarized in Table 4.3.

The remainder of the Round 2 sites are all larger wind farms than which has been previously constructed, with the exception of Lincs. While the development areas are still in shallow waters, the size of the turbines, the size of the farms themselves and the amount of money being spent on development all indicate the push of the industry to make offshore wind energy a mainstream industry for energy. (140)

*The Crown Estate Round 3 Tender Process*

The Energy Act of 2004 gave the Crown Estate rights to issue leases for development beyond the 12 nautical mile territorial limit within Renewable Energy Zones up to 200 nautical miles. The proposals for the third round of offshore wind farm leasing was announced on 4 June 2008, with the Crown Estate planning on taking a more active role by co-investing with developers. Nine zones have been designated as Round 3 zones for offshore wind farms, potentially adding 25GW offshore capacity to the grid. Many of the larger wind farms lie outside of the territorial zone, as shown in Figure 4.30. (141)

A summary of the wind farms planned in Round 3 is provided in Table 4.4. The size of these planned wind farms is massive, with the smallest one being capable of powering all of Malta if generating at its full capacity. The Round 3 development sites, along with several German wind farms planned for transitional depths, will establish commercial wind energy in transitional water depths. While many of these wind farms are tentatively scheduled to be completed by 2018, delays are not uncommon in the offshore wind energy industry.

The Moray Firth development site is also known as the Beatrice Offshore Wind Farm, located just north of the two current demonstration turbines, around 13.5km off the Caithness coast. The wind farm will comprise of around 184 wind turbines with a total generating capacity of around 920MW. Since the site lies in waters between 35-50 metres deep, the turbines are expected to be mounted on open lattice towers similar to those currently being tested in the demonstrator project. The planning consents are to be submitted in 2012, with construction commencing in 2014 and completion in 2018. (142)
Table 4.3 - Summary of the Crown Estate’s Round 2 sites that are still in the planning phase.

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Number of Turbines</th>
<th>Turbine Size (MW)</th>
<th>Capacity (MW)</th>
<th>Distance from Shore (km)</th>
<th>Depth (m)</th>
<th>Foundation</th>
<th>Cost (£ million)</th>
<th>Start of Construction</th>
<th>Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Docking Shoal</td>
<td>83-177</td>
<td>3 or 6</td>
<td>540</td>
<td>20</td>
<td>3-14</td>
<td>Monopile</td>
<td>£1500</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>(143) (144)</td>
<td>(145)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lincs</td>
<td>75</td>
<td>3.6</td>
<td>270</td>
<td>8</td>
<td>10-15</td>
<td>Monopile</td>
<td>£725</td>
<td>End 2010</td>
<td>2012</td>
</tr>
<tr>
<td>(146) (147)</td>
<td>(148)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Race Bank</td>
<td>88-206</td>
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<td>620</td>
<td>27</td>
<td>4-22</td>
<td>Monopile</td>
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<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>(149)</td>
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</tr>
<tr>
<td>Gwynt y Môr</td>
<td>160</td>
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<td>576</td>
<td>13</td>
<td>12-28</td>
<td>N/A</td>
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<td>2011</td>
<td>2014</td>
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<tr>
<td>(150)</td>
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<td></td>
</tr>
<tr>
<td>London Array</td>
<td>175</td>
<td>3-7</td>
<td>630</td>
<td>20</td>
<td>Up to 23</td>
<td>Monopile</td>
<td>£3000</td>
<td>End 2011 (Phase 1)</td>
<td>N/A</td>
</tr>
<tr>
<td>(151) (341)</td>
<td>(152)</td>
<td>(1000)</td>
<td></td>
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<tr>
<td>Galloper</td>
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<td>3.6 or 7</td>
<td>504</td>
<td>N/A</td>
<td>N/A</td>
<td>Undecided</td>
<td>N/A</td>
<td>2014</td>
<td>2016</td>
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<tr>
<td>(153)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Triton Knoll</td>
<td>150-333</td>
<td>3 or 8</td>
<td>1200</td>
<td>33</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>2018</td>
<td>2020</td>
</tr>
<tr>
<td>(154)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>West Duddon</td>
<td>139</td>
<td>3.6</td>
<td>500</td>
<td>14</td>
<td>17-21</td>
<td>Undecided</td>
<td>N/A</td>
<td>2012</td>
<td>N/A</td>
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<tr>
<td>(155) (156)</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Humber Gateway</td>
<td>42-83</td>
<td>N/A</td>
<td>300</td>
<td>8</td>
<td>11-18</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>(157)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dudgeon East</td>
<td>Up to 168</td>
<td>N/A</td>
<td>540</td>
<td>32</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>(158)</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Westermost Rough</td>
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<td>3 or 7</td>
<td>N/A</td>
<td>8</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>2014</td>
</tr>
<tr>
<td>(159)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4 - Summary of the Crown Estate’s Round 3 sites. The potential size of the wind farms, their distance to shore and the depths of these areas will usher a new area for offshore wind farms.

<table>
<thead>
<tr>
<th>Wind Farm</th>
<th>Size of Turbines (MW)</th>
<th>Capacity (MW)</th>
<th>Distance from Shore (km)</th>
<th>Depth (m)</th>
<th>Start of Construction</th>
<th>Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beatrice (142)</td>
<td>5</td>
<td>920</td>
<td>13.5</td>
<td>35-50</td>
<td>2014³⁷</td>
<td>2018</td>
</tr>
<tr>
<td>Firth of Forth (160)</td>
<td>5</td>
<td>1075</td>
<td>40</td>
<td>31-62</td>
<td>2015</td>
<td>2018</td>
</tr>
<tr>
<td>Dogger Bank (161)</td>
<td>N/A</td>
<td>9000</td>
<td>125</td>
<td>18-63</td>
<td>2015</td>
<td>2023</td>
</tr>
<tr>
<td>Hornsea (162) (163)</td>
<td>N/A</td>
<td>4000</td>
<td>80</td>
<td>24-59</td>
<td>2014</td>
<td>2018</td>
</tr>
<tr>
<td>Norfolk (164) (165)</td>
<td>7</td>
<td>7200</td>
<td>24.1</td>
<td>N/A</td>
<td>2015</td>
<td>Undecided</td>
</tr>
<tr>
<td>Hastings (166)</td>
<td>5</td>
<td>500</td>
<td>19.8</td>
<td>19-63</td>
<td>2014</td>
<td>2018</td>
</tr>
<tr>
<td>Isle of Wight (167)</td>
<td>900</td>
<td></td>
<td></td>
<td>2013-2015</td>
<td>2018³⁸</td>
<td></td>
</tr>
<tr>
<td>Bristol Channel (168) (169)</td>
<td>N/A</td>
<td>1500</td>
<td>14</td>
<td>23-56</td>
<td>2014</td>
<td>2018³⁹</td>
</tr>
<tr>
<td>Irish Sea³⁹ (170) (171)</td>
<td>4200</td>
<td>15</td>
<td></td>
<td>2016</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4 - Summary of the Crown Estate’s Round 3 sites. The potential size of the wind farms, their distance to shore and the depths of these areas will usher a new area for offshore wind farms.

---

³⁶ Will be constructed in two phases, the total numbers are in parentheses.
³⁷ To use the open lattice towers used in the Beatrice demonstration project.
³⁸ The wind farm is expected to cost around £3 billion.
³⁹ Expected to cost around £4.5 billion.
⁴⁰ The developers, Centrica has not revealed any detailed about the project.
The largest Round 3 site is Dogger Bank, with a target installed capacity of 9GW. In the EWEA’s proposed ‘Super Grid’ for wind energy, Dogger Bank is considered to be a potential central node within the grid system. The reported distance to shore is around 125km, covering an area of 8535km² in water depths ranging from 18-63 metres. Construction of the wind farm is expected to start in 2015 and completed in 2023 in three 3GW phases. (161)
Other European Proposed Wind Farms

The Republic of Ireland is another country with good experience in the offshore wind energy industry. The country has plans or is constructing six small scale wind farms and four larger wind farms. The major wind farms proposed in Ireland are Codling (173), the Dublin Array (174), Oriel (175) and Sker Rocks (176). While not as ambitious as the Crown Estate’s Round 3 programme, these four wind farms are expected to add around 2GW capacity to the national grid on completion.

Denmark is expected to continue to be a leader in offshore wind energy development, highlighted by a 400MW wind farm off the island Anholt, expected to be completed in 2013. (177) Denmark has a number of wind farms at an early planning stage including further 200MW extensions at Horns Rev, Jammerbugten, Krieger’s Flak and Ringkobing. (178)

Norway has not been a major player in the offshore wind energy industry although its seas have the best wind resource in Europe. The reason for this is that the Norwegian portion of the North Sea is very deep and the required foundation technology is only now starting to reach a point where they can be deployed on a large, commercial scale. The 350MW wind farm Havsul 1 has been authorized and another 200MW farm, Siragrunnen is currently waiting for approval. Several larger scale wind farms of over 1GW capacity are still in an early planning stage, several of which could use be hybrid wind/wave energy project using floating platforms such as Poseidon. (178)

The rest of northern Europe, including Germany, Sweden, the Netherlands and Belgium are all showing increasing interest in offshore wind energy development. The Swedish government has authorized three wind farms for a total capacity of 1300MW, but are currently on hold due to the economic crisis. Germany has almost 9GW, distributed over 28 wind projects that have been approved by the German government, reinforcing the recent German push towards offshore wind energy development. The Belgian and Dutch governments have pushed for further offshore wind development authorizing four and twelve wind farms for 651MW and 3250MW of installed capacity respectively. (178)

Several Mediterranean countries have also expressed interest in offshore wind. The Italian government has authorized a wind farm project at San Michele (162MW) and consent applications for wind farms at Chieuti (150MW), Golfo di Manfredonia (300MW), Gargano North/South (600MW/855MW), Torro San Gennaro (150MW), Golfo di Gela (137MW) and Golfo di Trieste (30MW) have been submitted. While the Spanish government has not approved or received applications for wind farm development in Spanish Seas, 42 potential sites are in an early planning stage51. Finally the Greek government, while not formally approving any projects to date, have received consent applications for 38 individual projects for a total of almost 6GW. While many of these potential projects are of marginal capacity, several large scale wind farm have been proposed. (178)

While there is no present guarantee of significant offshore wind development in the Mediterranean, it is important for Malta to monitor Mediterranean countries because the wind resource and bathymetry are similar. It may be an option for the Maltese government to invest in some of these projects, should they be developed, particularly Italian projects.

United States and Canada

While the United States is not currently operating or constructing any offshore wind farms, a good number of wind farms are in the proposal/planning stage, as can be seen in Figure 4.31. The primary

---

51 For many of these sites, the potential capacity has not yet been determined
hurdle that has stalled offshore wind in the United States to date is public backlash and stakeholder resistance due to the aesthetical impacts of offshore wind farms.

Among the wind farms proposed are Buzzards Bay (300MW), Cape Wind (420MW), Delaware (200MW), Evanston, Illinois (200MW), Hywind II – Hywind-M (unknown capacity), Maine floating-turbine wind farm (unknown), Wasatch Wind (4,400MW) and Far Rockaway (700MW). Canada has several offshore wind farms at a proposal stage, notably the Great Lakes Array (1,600MW), NaiKun Wind (400MW), Superior Array (650MW) and Trillium Power Wind 1 (414MW) and 2 (740MW).

![Map of various offshore wind farm proposals in the United States](http://offshorewind.net/)

**4.4 – Important wind farms to monitor for Malta**

While this chapter has shown how the wind energy market is expected to develop over the coming 10-15 years, there are several wind projects and developments that are of more strategic importance to the Maltese Islands than others. Since Malta has little shallow waters and is too small to afford to construct massive wind farms up to GW capacity, these farms are of little interest.

The performance of wind farms extending into transitional depths and eventually deep seas are the most important projects to monitor, because their successful implementation will open these depths to Malta. In Northern Europe, Germany appears to be aggressively pushing into sea depths greater than 30 metres, with the commissioning of Alpha Ventus and construction of BARD Offshore 1. The United Kingdom is expected to continue to exploit its shallow waters for the next 5-8 years, but the Round 3 projects are planned in depths of up to 70 metres. Norway is currently developing foundation structures suitable for deep sea wind farms; since the depths are comparable to Malta, developments in Norway should be closely monitored.

However, the most important region to monitor is the Mediterranean itself, because the establishment of commercial offshore wind in the Mediterranean will help reduce installation costs and improve the economies of scale. At the moment, Italy would appear to be leading the way in bringing offshore

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52 Joint project with Canada
wind to the Mediterranean, with Tricase wind farm due to be commissioned in 2011 and several other wind farms having received government approval.

4.5 - Conclusions

The movement towards offshore wind energy was initiated by the European nations Denmark and the United Kingdom, with a vast majority of operational wind farms in their territorial waters. Other European nations, particularly Germany, the Netherlands, Belgium and Sweden have developed offshore wind farms of their own.

Moreover, the offshore wind industry is showing signs of expanding out of the North and Baltic Sea into East Asia, North America, and the Mediterranean. China has one operational wind farm and several others in development, Italy is expected to open the Tricase wind farm in 2011 and North America have proposed several large scale farms throughout the United States and Canada.

Perhaps the most promising sign for the offshore wind industry is the significant interest to begin a movement towards transitional and deep sea locations. This is highlighted by Alpha Ventus and BARD Offshore 1 wind farms in Germany, Tricase in Italy and the Crown Estate’s Round 3 development sites. Many of these wind farms are tentatively scheduled to be fully commissioned before 2020, and their overall performance would be of great interest to the Mediterranean, including Malta.
Chapter 5 - Development of a systematic model to evaluate the viability of offshore wind farm proposals in Maltese territorial waters

In this chapter, a simple model is established to test the viability of offshore wind farm proposals in the Maltese Islands. The viability of an offshore wind farm is deemed to be dependent on four ‘pillars’ – technical, planning, environmental and socio-economic, all of which can be evaluated based on the specifications of a given proposal. Since not all the factors involved are equivalently significant to the viability of a proposal, each factor within a pillar is given a weight based on the perceived importance. The higher the overall score of a proposal, the higher its viability.

After the system of evaluation is established, it is tested on three sites previously considered for offshore wind farm development; Is-Sikka L-Bajda, Benghajsa Patch and North of Gozo.

5.1 - Model Development

5.1.1 - Technical

The technical aspect of a wind farm proposal is probably the most important of the four pillars. It is a measure of the technical and economic feasibility of a proposal. The total weight of the technical pillar is 80, which is almost 40% of the total weight of the systematic model. This pillar was given the highest weighting because if the farm is not technically feasible, then the project is not worth pursuing, regardless of the degree of planning, environmental and socio-economic issues.

The parameters considered in evaluating the technical feasibility are the maximum capacity, the expected wind conditions, the accessibility of the farm, the depth and the geology of the wind farm. Each of these parameters is determined by a number of sub-parameters, as shown in Figure 5.1. The weight of each sub-parameter and justification for this weight is given in Table 5.1.

5.1.2 - Planning

Planning is the second of the four pillars and the model is an attempt to evaluate the potential planning issues, such as conflicts with other industries as well as NATURA 2000 sites, archaeological sites and areas of historical significance. Proper implementation of Marine Spatial Planning is aimed towards the reduction, or complete elimination, of clashes between the proposal and these various issues.

As with the technical section, the value of each parameter is determined by a number of related sub-parameters. Since utilisation of the site may be permanent, such as bunkering, or temporary (cruise liner), these are considered separately. Finally the risk of collision is factored into the planning score. While it may not be possible in this dissertation to derive an accurate assessment of the risk, it is an important part of the evaluation of the proposal. A chart illustrating the main parameters of the planning score is given in Figure 5.2, while the scores are allocated in Table 5.2.

5.1.3 - Environmental

The third pillar considers the benthic environment and the impact on birds and fish species during the construction and operation phases of the proposed wind farm. The most important environmental issues are the presence of Posidonia oceanica meadows in the benthic environment, and the impact of noise during the construction phase on birds and fish. The degree of impact is highly dependent on the foundation structure due to varying footprints and methods of installation. Since many EIAs for wind farms have reported minimal long-term environmental impacts of wind farm development, this pillar is given the least weight in this initial assessment model. The breakdown of parameters and sub-parameters and the associated weights and justifications are given in Figure 5.3 and Table 5.3.
5.1.4 - Socio-Economic
The socio-economic pillar is concerned with the profitability of the proposal as well as the social and economic impacts. Some of the major social parameters considered in this evaluation model include the visual, noise and shadow flicker impacts, as well as public opinion. In particular, since offshore wind energy competes with other alternative energy sources, public support is critical.

The development of offshore wind farms in Maltese territorial waters is likely to clash with other important industries in the Islands, particularly the tourism industry and marine vessels entering and leaving major ports. The two main ports, Grand Harbour and the Freeport, are critical to the Maltese economy and are of high priority in the model.

Finally, the actual profitability of the wind farm is factored into the model. The profitability of a wind farm is dependent on the capital costs, operations and maintenance costs, the annual energy yield and the price of electricity. While higher electricity prices would increase the profitability, high prices would decrease public support of the project. The breakdown of the parameters and the weights are explained in Figure 5.4 and Table 5.4.

5.1.5 - Viability Score
The final step is to add up the scores of each of the four pillars to get a final viability score for the proposal. The range of possible values is given in Table 5.5. The viability is assessed based on the percentage of the maximum number of points obtained, as summarized in Table 5.6.

Since the model is designed to be used after all possible information is gathered, including EIAs and accurate wind data, it was not possible to fully test every parameter listed. Moreover, the model, and the weights associated with each parameter, could be highly subjective, especially when designed by a single individual, and should be re-evaluated by a number of experts to readjust the weights based on a collaborative effort. There may be some parameters that are underrepresented or even left out altogether, but the parameters and associated weights are expected to vary from project to project.

Despite the model’s potential limitations, there are some key advantages in this systematic evaluation. First of all, it allows decision-makers to choose between different proposals. Secondly, this system can be used by non-experts in the field during consultation exercises, who could give a score based on their opinions. Finally, the system was designed to allow for distinction between variations in the proposal, such as varying number, size and spacing between turbines.

The latter feature will be tested in the next section of the thesis, which is based on the 2009 Mott Macdonald report on the Sikka L-Bajda project.
Figure 5.1 - Chart showing the parameters and sub-parameters of the technical pillar.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sub-parameter</th>
<th>Maximum Score</th>
<th>Minimum Score</th>
<th>Justification &amp; Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Capacity</strong></td>
<td>Area of Site</td>
<td>4</td>
<td>0</td>
<td>A larger area allows for more turbines to be deployed.</td>
</tr>
<tr>
<td></td>
<td>Size of Turbines</td>
<td>6</td>
<td>0</td>
<td>Larger wind turbines increase the potential of the proposal. Turbines rated less than 2MW are no longer used in the offshore wind industry.</td>
</tr>
<tr>
<td></td>
<td>Number of Turbines</td>
<td>6</td>
<td>0</td>
<td>More wind turbines increase the maximum potential of the proposal</td>
</tr>
<tr>
<td><strong>Expected Wind Conditions</strong></td>
<td>Exposure to NW winds</td>
<td>10</td>
<td>1</td>
<td>The prevailing NW winds is the most important wind resource to monitor</td>
</tr>
<tr>
<td></td>
<td>Exposure to other winds</td>
<td>5</td>
<td>1</td>
<td>Good exposure to the other winds minimizes non-operating hours</td>
</tr>
<tr>
<td></td>
<td>Distance to shore</td>
<td>4</td>
<td>1</td>
<td>The further offshore the wind farm is, the better the wind resource is likely to be</td>
</tr>
<tr>
<td></td>
<td>Hub Height</td>
<td>4</td>
<td>1</td>
<td>A wind turbine with a hub height of 100 metres will have better winds than one with a hub height of 70 metres.</td>
</tr>
<tr>
<td></td>
<td>Distance between turbines and rows</td>
<td>6</td>
<td>0</td>
<td>If placed too close to each other, the wind turbines interfere with each other and reduce efficiency. The threshold at which this effect is apparent depends on the size of the turbine.</td>
</tr>
<tr>
<td><strong>Accessibility</strong></td>
<td>Distance to shore</td>
<td>5</td>
<td>1</td>
<td>Proposals that are far away from the coast have significant costs due to the length of submarine cable required.</td>
</tr>
<tr>
<td></td>
<td>Distance to grid connection point</td>
<td>2</td>
<td>0</td>
<td>An onshore substation placed in the centre of the mainland is not strategically suitable for a wind farm proposal in the North of Gozo.</td>
</tr>
<tr>
<td></td>
<td>Nearest port of access</td>
<td>4</td>
<td>0</td>
<td>Is the wind farm accessible by the local ports and can it be reached quickly in case of emergency?</td>
</tr>
<tr>
<td><strong>Depth</strong></td>
<td>Foundation suitability</td>
<td>10</td>
<td>0</td>
<td>Is the foundation suitable for the depth of the proposed site?</td>
</tr>
<tr>
<td></td>
<td>Costs</td>
<td>8</td>
<td>0</td>
<td>Some foundations structures, notably floating platforms, cost the same irrespective of the depth. Others, such as the gravity base are much more expensive in deeper seas.</td>
</tr>
<tr>
<td><strong>Geology</strong></td>
<td>Ease of installation</td>
<td>2</td>
<td>0</td>
<td>Some foundations structures may require drilling into solid rock, prolonging the construction phase.</td>
</tr>
<tr>
<td></td>
<td>Cost of installation</td>
<td>2</td>
<td>0</td>
<td>Time spent drilling holes into the rock for the foundations increases costs.</td>
</tr>
<tr>
<td></td>
<td>Stability of foundation</td>
<td>2</td>
<td>0</td>
<td>Foundations installed in solid rock are more stable than foundations installed on sands, which may be prone to damage from sediment movement.</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>80</td>
<td>5</td>
<td>Table 5.1 - Breakdown and weights of the technical pillar</td>
</tr>
</tbody>
</table>
Figure 5.2 - Chart showing the parameters and sub-parameters of the planning pillar

- Protected Areas
  - NATURA 2000 - SPA
  - NATURA 2000 - SAC

- Permanent Utilisation of the site
  - Bunkering
  - Fish farming
  - Archaeological site and/or shipwrecks
  - Area of Historical Significance

- Temporary Utilization of the site
  - Fishing
  - Boating
  - Yachting
  - Diving
  - Cargo Ships
  - Cruise Liners

- Risk of collision with turbines
  - Proximity of the wind farm to main shipping routes
  - Average size of vessels
  - Sea currents
  - Ship type
  - Foundation structure
  - Drift speed
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sub-parameter</th>
<th>Maximum Score</th>
<th>Minimum Score</th>
<th>Justification &amp; Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protected Areas</td>
<td>NATURA 2000 - SPA</td>
<td>5</td>
<td>0</td>
<td>A proposal that is within 2-3km of such an SPA could have impacts on the SPA</td>
</tr>
<tr>
<td></td>
<td>NATURA 2000 - SAC</td>
<td>5</td>
<td>0</td>
<td>A proposal that is within 2-3km of such an SAC could have impacts on the SAC</td>
</tr>
<tr>
<td>Permanent utilization of the site</td>
<td>Bunkering</td>
<td>4</td>
<td>0</td>
<td>Bunkering is a very important marine activity in the Maltese Islands</td>
</tr>
<tr>
<td></td>
<td>Fish Farming</td>
<td>4</td>
<td>0</td>
<td>It may be difficult for wind farms and fish farms to co-exist in the same region due to impacts on the fish due to noise</td>
</tr>
<tr>
<td></td>
<td>Archaeological Site</td>
<td>1</td>
<td>0</td>
<td>While this is not a significant concern, archaeological sites must not be damaged by wind farm development.</td>
</tr>
<tr>
<td></td>
<td>Shipwrecks</td>
<td>1</td>
<td>0</td>
<td>Similar reasoning to that for archaeological sites.</td>
</tr>
<tr>
<td></td>
<td>Area of Historical Significance</td>
<td>2</td>
<td>0</td>
<td>Such areas must not be significantly altered by the construction of a wind farm.</td>
</tr>
<tr>
<td>Temporary utilization of the site</td>
<td>Fishing</td>
<td>2</td>
<td>0</td>
<td>Cruise liners, cargo ships and fishing vessels are the main vessels of concern, but boating, yachting and diving are also important activities.</td>
</tr>
<tr>
<td></td>
<td>Boating &amp; Yachting</td>
<td>1</td>
<td>0</td>
<td>Other temporary uses of the site could be small tourist vessels, such as the line taking tourists from Sliema to Comino and Gozo along the northern coast of Malta.</td>
</tr>
<tr>
<td></td>
<td>Diving</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cargo Ships</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cruise Liners</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Risk of collisions (Probability)</td>
<td>Proximity of wind farm to main shipping routes</td>
<td>5</td>
<td>-5</td>
<td>The closer a wind farm is to a major shipping route, the greater the probability of collision.</td>
</tr>
<tr>
<td></td>
<td>Average size of sea vessels</td>
<td>2</td>
<td>0</td>
<td>Larger vessels increase the probability of collision.</td>
</tr>
<tr>
<td></td>
<td>Sea currents</td>
<td>2</td>
<td>-5</td>
<td>If the sea current tends to push a sea vessel into the wind farm, the probability of a collision increases significantly</td>
</tr>
<tr>
<td>Risk of collision (Consequence)</td>
<td>Ship types</td>
<td>2</td>
<td>0</td>
<td>The hull structure of a vessel determines the impact it can take before breaking apart.</td>
</tr>
<tr>
<td></td>
<td>Foundation type</td>
<td>3</td>
<td>0</td>
<td>A monopile would be torn from the seabed before major damage to a ship is done, but a tripod could cause heavy damage.</td>
</tr>
<tr>
<td></td>
<td>Drift speed</td>
<td>2</td>
<td>0</td>
<td>A fast-moving vessel has more energy, therefore causing more damage.</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>50</td>
<td>-10</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 - Breakdown and weights of the planning pillar
Figure 5.3 - Chart showing the parameters and sub-parameters of the environmental pillar.
### Parameter Sub-parameter Maximum Score Minimum Score Justification & Reasoning

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sub-parameter</th>
<th>Maximum Score</th>
<th>Minimum Score</th>
<th>Justification &amp; Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of benthic environment</td>
<td>Presence of <em>Posidonia oceanica</em> meadows</td>
<td>2</td>
<td>0</td>
<td>These seagrass meadows are listed as a priority habitat under the Habitats Directive and wind farm development on such sights need to be carefully monitored.</td>
</tr>
<tr>
<td></td>
<td>Impact on the <em>Posidonia</em> meadows</td>
<td>10</td>
<td>0</td>
<td>The impact on the <em>Posidonia</em> meadows can be affected during the construction phase, but is largely dependent on the footprint of the foundation.</td>
</tr>
<tr>
<td>Impact on fish – construction</td>
<td>Noise</td>
<td>4</td>
<td>0</td>
<td>The noise generated during the construction phase significantly affect fish and other marine species living in the area.</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>2</td>
<td>0</td>
<td>Disturbances of the benthic environment during construction could have short-term impacts on fish and other marine species.</td>
</tr>
<tr>
<td>Impact on fish – operation</td>
<td>Noise</td>
<td>2</td>
<td>0</td>
<td>The impact of noise is possible but the risk is significantly less than during the construction phase.</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>1</td>
<td>0</td>
<td>Other impacts on fish, such as the potential impacts of the electromagnetic fields generated, should be considered.</td>
</tr>
<tr>
<td>Impacts on birds – construction</td>
<td>Noise</td>
<td>4</td>
<td>0</td>
<td>The impact of the noise generated during construction, particularly during the nesting season, could disturb birds. The issue is easily avoided by planning the construction phase for other parts of the year.</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>2</td>
<td>0</td>
<td>If the wind farm is too close to bird nesting sites, there could be physical disturbances during construction.</td>
</tr>
<tr>
<td>Impacts on birds – operation</td>
<td>Noise</td>
<td>2</td>
<td>0</td>
<td>The impact of generated noise during operation is significantly less than during construction, but should not disturb birds.</td>
</tr>
<tr>
<td></td>
<td>Collisions with turbine blades</td>
<td>1</td>
<td>0</td>
<td>Studies have shown that the collision of birds and wind turbines is not high enough to warrant concern.</td>
</tr>
</tbody>
</table>

**Total** 30 0

Table 5.3 - Breakdown and weights of the environmental pillar
Figure 5.4 - Chart showing the parameters and sub-parameters of the socio-economic pillar
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sub-parameter</th>
<th>Maximum Score</th>
<th>Minimum Score</th>
<th>Justification &amp; Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual, noise and shadow flicker</td>
<td>Visual</td>
<td>4</td>
<td>0</td>
<td>Visual impact is dependent on the distance of the farm to the nearest settlement and its inclination with respect to the settlement.</td>
</tr>
<tr>
<td></td>
<td>Noise</td>
<td>2</td>
<td>0</td>
<td>The impact of noise is mitigated more rapidly with distance than for visual impacts.</td>
</tr>
<tr>
<td></td>
<td>Shadow Flicker</td>
<td>2</td>
<td>0</td>
<td>The shadow flicker effect dissipates rapidly with distance.</td>
</tr>
<tr>
<td>Tourism &amp; Recreation</td>
<td>Beaches and bathing areas</td>
<td>3</td>
<td>0</td>
<td>Beaches and bathing areas are an important part of Malta’s tourism industry.</td>
</tr>
<tr>
<td></td>
<td>Tourist centres</td>
<td>2</td>
<td>0</td>
<td>A wind farm placed too close to tourist-heavy localities could harm the industry.</td>
</tr>
<tr>
<td></td>
<td>Tourist attraction</td>
<td>1</td>
<td>0</td>
<td>Several wind farms across Europe have reported interest from tourists.</td>
</tr>
<tr>
<td>Impact of wind farm on marine traffic at harbours</td>
<td></td>
<td>8</td>
<td>-10</td>
<td>Before the global economic recession, over 10,000 vessels called in Malta. Therefore any wind farms that impedes such vessels entering Maltese ports, particularly the Grand Harbour and the Malta Freeport, are deemed to be unacceptable.</td>
</tr>
<tr>
<td>Public opinion</td>
<td>Acceptance</td>
<td>2</td>
<td>0</td>
<td>Offshore wind energy must compete with other energy solutions, such as onshore wind, solar photovoltaics and fossil fuels.</td>
</tr>
<tr>
<td></td>
<td>Perception on impacts</td>
<td>3</td>
<td>0</td>
<td>Includes public perception on the impacts on birds and underwater marine life.</td>
</tr>
<tr>
<td></td>
<td>Willingness to pay</td>
<td>4</td>
<td>-4</td>
<td>Since wind farm development in the short-term is unlikely to be competitive with oil and gas in Malta, it is especially important the public accepts higher electricity prices.</td>
</tr>
<tr>
<td></td>
<td>Willingness to move further offshore to reduce some impacts</td>
<td>2</td>
<td>-4</td>
<td>Building wind farms further offshore would reduce several impacts, but would increase costs, incurring further costs on the public.</td>
</tr>
<tr>
<td>Profitability</td>
<td>Cost per MW capacity</td>
<td>8</td>
<td>0</td>
<td>Based on evidence derived from European wind farms, capital costs of around €1-2 million per MW is good, anything above €4 million is probably too expensive, except for pilot projects and pioneering wind farms such as Alpha Ventus.</td>
</tr>
<tr>
<td></td>
<td>Expected energy yield</td>
<td>6</td>
<td>0</td>
<td>Depends on a good, consistent wind resource that sufficiently exploits the chosen turbine's power curve. The net capacity factor is an important figure to consider.</td>
</tr>
<tr>
<td></td>
<td>Operations and maintenance costs</td>
<td>3</td>
<td>0</td>
<td>While largely an unknown quantity for offshore wind, these costs need to be accounted for in wind farm evaluation.</td>
</tr>
<tr>
<td></td>
<td>Expected price of electricity</td>
<td>6</td>
<td>0</td>
<td>A higher price increases profitability, but there is a trade-off with the “Willingness to pay” and “Willingness to move further offshore” sub-parameters.</td>
</tr>
<tr>
<td>Other</td>
<td>Navigation</td>
<td>2</td>
<td>0</td>
<td>Studies have shown that wind farms could have minor interference with the navigation equipment of smaller vessels</td>
</tr>
<tr>
<td></td>
<td>Communication</td>
<td>2</td>
<td>0</td>
<td>While wind farms are not likely to impair communications, it still needs to be considered.</td>
</tr>
<tr>
<td></td>
<td>Air traffic</td>
<td>2</td>
<td>0</td>
<td>There may be some concerns because of the potential for collisions of wind turbines in certain parts of Malta that are in the direct path of runways, but this is not considered to be an extreme danger. Could be an issue for low-flying aircraft.</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>60</td>
<td>-18</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4 - Breakdown and weights of the socio-economic pillar
<table>
<thead>
<tr>
<th>Percentage</th>
<th>Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% - 49%</td>
<td>(-23)-108</td>
<td>Proposal is rejected with zero possibility of reconsideration.</td>
</tr>
<tr>
<td>50% - 64%</td>
<td>109-141</td>
<td>Proposal is considered to have minimal viability, but some major revisions of the fundamentals of the proposals are required. Implementation is doubtful, even after revision.</td>
</tr>
<tr>
<td>65% - 74%</td>
<td>142-163</td>
<td>Proposal is viable but has several key flaws that reduce the attractiveness. This could be because the proposal involves using technologies that are not yet available, or there are some socio-economic or environmental issues that may be difficult to overcome. In terms of a short- or medium-term project, the issues may be worked around. In the case of a long-term project, the proposal should be revisited when the requisite technologies are available.</td>
</tr>
<tr>
<td>75% - 89%</td>
<td>164-196</td>
<td>Proposal has potential for implementation, but there are some minor flaws or conflicts which may prove to be troublesome in the long-term. Implementation of this project is highly likely, but not guaranteed.</td>
</tr>
<tr>
<td>90% - 100%</td>
<td>197-220</td>
<td>Proposals falling into this category are considered to be nearly optimal projects and should be constructed as soon as is realistically feasible.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5.5 - The viability of a proposal depends on which range of values it falls under</th>
</tr>
</thead>
</table>

5.2 – Testing the model

In this section, the viability model proposed in Section 5.1 is tested on a number of real and hypothetical proposals. Justifications for the scores are based on previous assessments detailed in the Sikka L-Bajda project description (3) and in the 2009 Mott Macdonald report (6).

5.2.1 – Model testing on Is-Sikka L-Bajda

This was the premiere proposal to test the model on because the location is expected to be used for Malta’s first offshore wind farm. It is also the only offshore site in Maltese territorial waters of non-marginal capacity in waters of less than 30 metres depth:\(^{53}\) Since the wind farm is in shallow water depths, the primary foundations to consider are the gravity base and the monopile, although tripods and jackets should also be considered. In this dissertation, only the shallow depth technologies are tested.

The 2009 Mott Macdonald report considered six different permutations, using three turbines and two spacing distributions of the turbines, of how to develop an offshore wind farm at Is-Sikka L-Bajda. A brief summary of the technical and economic information relevant to the model is given in Table 5.6.

\(^{53}\) The Alpha Ventus wind farm is the deepest wind farm constructed to date in these depths and so has been taken as the maximum depth limit for current Maltese offshore wind projects.
<table>
<thead>
<tr>
<th>Turbine</th>
<th>Siemens 3.6</th>
<th>Vestas V90</th>
<th>REPower 5M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Spacing</td>
<td>9/6D 8/5D 9/6D 8/5D 9/6D 8/5D</td>
<td>9/6D 8/5D 9/6D 8/5D 9/6D 8/5D</td>
<td></td>
</tr>
<tr>
<td>Hub Height</td>
<td>80m 80m 80m 80m 90m 90m</td>
<td>80m 80m 90m 90m 126m 126m</td>
<td></td>
</tr>
<tr>
<td>Rotor Diameter</td>
<td>107m 107m 90m 90m 126m 126m</td>
<td>107m 107m 90m 90m 126m 126m</td>
<td></td>
</tr>
<tr>
<td>Space between turbines</td>
<td>963m 856m 810m 720m 1134m 1008m</td>
<td>642m 535m 540m 450m 756m 630m</td>
<td></td>
</tr>
<tr>
<td>Number of turbines</td>
<td>18 24 26 29 14 17</td>
<td>18 24 26 29 14 17</td>
<td></td>
</tr>
<tr>
<td>Total capacity</td>
<td>64.8MW 86.4MW 78MW 87MW 70MW 85MW</td>
<td>64.8MW 86.4MW 78MW 87MW 70MW 85MW</td>
<td></td>
</tr>
<tr>
<td>Expected Energy Yield</td>
<td>132-168GWh 169-216GWh 143-183GWh 157-202GWh 149-190GWh 180-227GWh</td>
<td>132-168GWh 169-216GWh 143-183GWh 157-202GWh 149-190GWh 180-227GWh</td>
<td></td>
</tr>
<tr>
<td>Net Capacity Factor Range</td>
<td>23.3%-29.5% 22.4%-28.5% 20.8%-26.8% 20.6%-26.5% 24.3%-30.9% 24.1%-30.4%</td>
<td>23.3%-29.5% 22.4%-28.5% 20.8%-26.8% 20.6%-26.5% 24.3%-30.9% 24.1%-30.4%</td>
<td></td>
</tr>
<tr>
<td>Capital Expenditures</td>
<td>€3.0-3.5 million per MW installed capacity</td>
<td>€3.0-3.5 million per MW installed capacity</td>
<td></td>
</tr>
<tr>
<td>Operation and Maintenance Costs</td>
<td>€77,000-€88,000 per MW installed capacity per annum (€1.54-1.76 million over 20 year operational life)</td>
<td>€77,000-€88,000 per MW installed capacity per annum (€1.54-1.76 million over 20 year operational life)</td>
<td></td>
</tr>
<tr>
<td>Spinning Reserves costs per annum (20 years)</td>
<td>€290,757 (€5.82 million)</td>
<td>€500,219 (€10 million)</td>
<td>€413,027 (€8.26 million)</td>
</tr>
<tr>
<td>Expected price of electricity generated</td>
<td>€0.17/kWh - €0.31/kWh</td>
<td>€0.17/kWh - €0.31/kWh</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.6 - Six turbine and spacing configurations were considered in the 2009 Mott Macdonald report. The turbines will be mounted on different foundations to allow for comparison between different foundation structures at Sikka L-Bajda. (6)

These permutations of the Sikka L-Bajda project are evaluated using the information provided in Table 5.6, information provided in earlier chapters and the April 2009 project description for Sikka L-Bajda. The results are provided in Tables 5.7 to 5.11. In order to diversify the permutations and test the model’s sensitivity with respect to the foundation structure, the Siemens turbines are mounted on concrete gravity base, the Vestas V90 on monopiles and the REPower 5M on jackets.

**Technical**

Since this is a comparison between permutations of the same development area, many of the parameters that are site-dependent are given the same score. The technical scores reveal that the Vestas V90 on monopiles and the REPower 5M on jackets are probably more suitable than the Siemens 3.6MW turbines on concrete gravity bases from a technical standpoint. The reason for this is that the Sikka L-Bajda reef is too deep for this foundation structure, and the cost for installing them in these depths would be too high.\(^{54}\)

---

\(^{54}\) There is further evidence for this in Chapter 4, where gravity base structures were used in Phase 1 of Thornton Bank in depths over 20 metres deep, but was very expensive when compared to other wind farms.
None of the six permutations scored above sixty for several reasons:

- The maximum capacity of the site is adequate, but wind farms almost 4 times larger than what is being planned have already been constructed.

- While the region is well exposed to the prevailing winds, other locations are better exposed and it is poorly exposed to other winds.

- The site is not very accessible to Malta Freeport, where servicing vessels are likely to be stationed at. Site is more accessible from the Grand Harbour or Marsamxett, provided that the facilities are adequate.

- The depth range of the area is not optimal for any of the foundations structures considered.

- There could be some difficulties in installing monopiles and particularly jackets at this site, because the rock formation is the Upper Coralline and likely Tal-Pitkal Member, which is one of the hardest rocks found in Malta. This disadvantage could be offset by the added stability of the foundation after installation, which could help reduce breakdowns and hence maintenance costs. There would also be less risks due to erosion of the scour protection.

---

**Table 5.7 - Results of the technical comparison between the six configurations.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sub-parameter</th>
<th>Siemens 3.6 (9/6D)</th>
<th>Vestas V90 (9/6D)</th>
<th>REPower 5M (9/6D)</th>
<th>Siemens 3.6 (8/5D)</th>
<th>Vestas V90 (8/5D)</th>
<th>REPower 5M (8/5D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundation</td>
<td>Gravity Base</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Monopile</td>
<td>4</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Jacket</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Maximum Capacity</td>
<td>Area of Site</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Size of Turbines</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Number of Turbines</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Expected Wind Conditions</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Exposure to NW winds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exposure to other winds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Distance to shore</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hub Height</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Distance between turbines and</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>rows</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accessibility</td>
<td>Distance to shore</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Distance to grid connection</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>point</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nearest port of access</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Depth</td>
<td>Foundation suitability</td>
<td>4</td>
<td>8</td>
<td>7</td>
<td>4</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Costs</td>
<td>2</td>
<td>6</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Geology</td>
<td>Ease of installation</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Cost of installation</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Stability of foundation</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>51</td>
<td>56</td>
<td>55</td>
<td>47</td>
<td>55</td>
<td>55</td>
</tr>
</tbody>
</table>
**Planning**

There is no reliable way to estimate the risk of collision of ships with wind turbines because of the lack of information available, which reduces the maximum available score in the planning sector to 35. However, it is anticipated that there is little risk for collision if the proper measures are taken. Moreover, the planning section of this analysis is largely independent of the turbine and foundation structure and so the same score is given throughout.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sub-parameter</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protected Areas</td>
<td>NATURA 2000 – SPA</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>NATURA 2000 – SAC</td>
<td>1</td>
</tr>
<tr>
<td>Permanent utilization of the site</td>
<td>Bunkering</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fish Farming</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Archaeological Site</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Shipwrecks</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Area of Historical Significance</td>
<td>2</td>
</tr>
<tr>
<td>Temporary utilization of the site</td>
<td>Fishing</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Boating &amp; Yachting</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Diving</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Cargo Ships</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Cruise Liners</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>2</td>
</tr>
<tr>
<td>Risk of collisions (Probability)</td>
<td>Proximity of wind farm to main shipping routes</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Average size of sea vessels</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Sea currents</td>
<td>N/A</td>
</tr>
<tr>
<td>Risk of collision (Consequence)</td>
<td>Ship types</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Foundation type</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Drift speed</td>
<td>N/A</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>23</td>
</tr>
</tbody>
</table>

*Table 5.8 - The planning scores are equivalent for all the configurations since they utilize the same development area*

There are several planning issues involved with the Sikka L-Bajda proposal, most notably the site’s proximity to Rdum il-Madonna, a NATURA 2000 SPA and SAC, the reef’s candidacy as an SAC, and the direct conflict with Bunkering Area 3. There could be some minor planning issues with fishing, boating and yachting and the nearby fish farms, but these are less of a concern.

**Environmental**

There are some major differences in the anticipated environmental impacts of the three different foundation types, particularly the impact on the *Posidonia* meadows, which is most prominent in this region according the baseline survey conducted in 2003 and referred to in Chapter 2. The gravity base structure has a very large footprint of around 1000m² and so the impact is the largest. By comparison the average jacket structure has a footprint of 290m², while the monopile is around 25m². Since these seagrass meadows are an important habitat for many marine species, this will impact fish significantly during the operation phase.

The gravity base does have an environmental edge on the other foundation types because no drilling is required, reducing the impact due to noise. However, monopile foundations were deemed to have the least overall impact, particularly in the long term.
### Table 5.9 - The results of the environmental analysis seems that monopiles have the least impact on the environment.

**Socio-Economic**

It was not possible to give scores for the ‘Public Opinion’ sector because this data is not available. Operations and maintenance costs are still uncertain in the relatively young offshore wind industry and hence were omitted from the evaluation. Spinning costs were not considered, but could have a major impact on the profitability. This reduces the maximum score of this pillar to 46.

### Table 5.10 - Results of the socio-economic analysis
Out of the three turbines, the REPower 5M turbines would generated the most electricity and at a higher capacity factor range giving it the slight edge. However, the expected energy yield is quite low when compared to similar offshore wind farms, such as Kentish Flats. The monopile foundation is the cheapest to construct at these depths and received the highest scored on a cost per MW capacity basis as well as the expected price of electricity generated, since it is less expensive to produce electricity. Once again the combination of Siemens turbines mounted on gravity base foundations has the lowest score, because of the costs incurred by installing gravity base structures in waters greater than 10 metres.

*Projections for Sikka L-Bajda*

The total score for each of the six permutations considered for the Sikka L-Bajda project is given in Table 5.11 with the percentage calculated from the maximum score of the parameters that were given a score. The results indicate that the Vestas V90 proposals on monopiles are the most viable, regardless of the spacing distribution. The poorest result was the Siemens 3.6 gravity base with only around 60% of the available points. The 9/6D spacing system received a higher overall grade despite the lower capacity in all three cases.

The differences in the result can be attributed to the different foundation structure. The gravity base is far too expensive for the depths of the site and the potential impacts on the *Posidonia* seagrass meadows are deemed to be too large. On the other hand, the site is shallow enough, so that monopiles remain technically feasible and not worth incurring extra costs by using jackets. The geology contributes to this result, since a jacket structure would require more drilling than a monopile would.

There is no conclusive evidence according to the model and mathematical figures about the optimal turbine – this is probably because of the small area of the site. More testing would be required using as many feasible combinations of turbine and foundation structure as possible.

<table>
<thead>
<tr>
<th>Pillar</th>
<th>Siemens 3.6 (9/6D)</th>
<th>Vestas V90 (9/6D)</th>
<th>REPower 5M (8/5D)</th>
<th>Siemens 3.6 (8/5D)</th>
<th>Vestas V90 (8/5D)</th>
<th>REPower 5M (8/5D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical</td>
<td>51</td>
<td>56</td>
<td>55</td>
<td>47</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>Planning</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Environmental</td>
<td>15</td>
<td>23</td>
<td>15</td>
<td>14</td>
<td>21</td>
<td>15</td>
</tr>
<tr>
<td>Socio-Economic</td>
<td>31</td>
<td>37</td>
<td>34</td>
<td>31</td>
<td>37</td>
<td>34</td>
</tr>
<tr>
<td>Total</td>
<td>120</td>
<td>139</td>
<td>127</td>
<td>115</td>
<td>136</td>
<td>127</td>
</tr>
<tr>
<td>% of Maximum</td>
<td>62.8%</td>
<td>72.8%</td>
<td>66.5%</td>
<td>60.2%</td>
<td>71.2%</td>
<td>66.5%</td>
</tr>
</tbody>
</table>

Table 5.11 - The results seem to indicate a clear favourite for the most viable configuration, although this has been mostly attributed to the foundation structure.

*5.2.2 – Testing on Benghajsa and North of Gozo sites*

Sikka L-Bajda was selected as the best site for offshore wind farm development from a total of eight candidate sites. Two of these sites, Benghajsa and North of Gozo, are revisited and re-evaluated using the same model. Since the Vestas V90 (9/6D) mounted on monopiles received the highest score, this combination is used in order to be able to distinguish between various sites. The scores are based on the analysis given in the Sikka L-Bajda project description and the results are given in Tables 5.12 to 5.15. Parameters with insufficient information to assign a score are omitted as before.

While there are no calculated figures for the costs of constructing a wind farm at either of these two locations, it is assumed that the capital costs per MW capacity would be worse than that of Sikka L-Bajda because of economies of scale. The expected energy yield is given a score based on the expected wind conditions at the site, which may be higher at North Gozo but lower at Benghajsa due to the exposure to the NW winds.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Subparameter</th>
<th>Benghajsa</th>
<th>North of Gozo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Capacity</td>
<td>Area of Site</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Size of Turbines</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Number of Turbines</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Expected Wind Conditions</td>
<td>Exposure to NW winds</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Exposure to other winds</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Distance to shore</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Hub Height</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Distance between turbines and rows</td>
<td>6 6</td>
<td>6 6</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Distance to shore</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Distance to grid connection point</td>
<td>2 0</td>
<td>0 0</td>
</tr>
<tr>
<td></td>
<td>Nearest port of access</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Depth</td>
<td>Foundation suitability</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Costs</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Geology</td>
<td>Ease of installation</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Cost of installation</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Stability of foundation</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>49</td>
<td>53</td>
</tr>
</tbody>
</table>

Table 5.12 - The technical scores for Benghajsa and Gozo are smaller than Sikka L-Bajda, but are comparable

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Subparameter</th>
<th>Benghajsa</th>
<th>North of Gozo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protected Areas</td>
<td>NATURA 2000 - SPA</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>NATURA 2000 - SAC</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Permanent utilization of the site</td>
<td>Bunkering</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Fish Farming</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Archaeological Site</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Shipwrecks</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Area of Historical Significance</td>
<td>2 2</td>
<td>2 2</td>
</tr>
<tr>
<td>Temporary utilization of the site</td>
<td>Fishing</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Boating &amp; Yachting</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Diving</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Cargo Ships</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Cruise Liners</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Risk of collisions (Probability)</td>
<td>Proximity of wind farm to main shipping routes</td>
<td>0 0</td>
<td>5 5</td>
</tr>
<tr>
<td></td>
<td>Average size of sea vessels</td>
<td>0 0</td>
<td>2 2</td>
</tr>
<tr>
<td></td>
<td>Sea currents</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Risk of collision (Consequence)</td>
<td>Ship types</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Foundation type</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Drift speed</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>26</td>
<td>37</td>
</tr>
</tbody>
</table>

Table 5.13 - Benghaja Patch suffers from significant planning issues, while Gozo probably has less planning issues than Sikka
The wind farm proposal at Benghajsa Patch received a total score of 97 out of 202, which is around 48%, meaning that the requisite recommendation, according to this system, is that the proposal should be discarded. While the proposal is comparable to that of Sikka L-Bajda from the technical pillar, there are significant planning and socio-economic issues that make wind farm development at the site undesirable.

The proposal at North Gozo fared better than that of Benghajsa, scoring 133 out of 202, or 65.8%. While the site is inferior to Sikka L-Bajda as a potential wind farm on the basis of smaller capacity, and some significant socio-economic impacts, there could be less planning issues. A major concern is the distance of the nearest grid connection point, which is 8km away at Qala. While this distance is common for most wind farms in northern Europe, whether this is viable for such a small farm is doubtful. The site at North Gozo could make a good secondary offshore wind farm, if it is constructed in a time frame as another wind farm in the Mediterranean, to reduce the cost of developing such a small area in a region where offshore wind is not yet established.
Chapter 6 – Conclusions and Recommendations

6.1 - Conclusions

Previous studies have estimated the potential of offshore wind farm development in the shallow waters of Malta, which is limited to only a handful of locations, the most notable was Sikka L-Bajda. In Chapter 2, the bathymetry of Malta was investigated and identified the northeastern part of Malta as being most favourable for transitional depths. In particular, Hurd Bank could be a relevant wind farm proposal. Since several European countries, such as Germany and the United Kingdom, are actively planning and constructing wind farms in these depths. Hurd Bank should be reconsidered for development after 2020, by then transitional technologies should become mainstream.

Extending the depth limit to up to 200 metres opens the southern coast for wind farm development using floating platforms to support the turbines. As reviewed in Chapter 3, there are a good number of concepts and prototypes currently being tested, such as the Hywind, Blue H, Sway and Poseidon. Most of these prototypes were successful for stability and work is being done to reduce costs. In the long-term, around 10-20 years, floating foundations could become commercialized.

However, there are problems with wind farm development along the southern coast. First of all the southern coast, is not well-exposed to the north westerly winds, which would reduce the efficiency of the wind farms. Southern Malta has a significantly less developed infrastructure than the north, and so grid connection costs and farm access could be an issue. While development in the south could avoid conflict with marine traffic and other marine industries, there are significant planning issues with regards to nature reserves and NATURA 2000 sites. Due to these issues, wind farm development should probably be restricted to the north and to the east.

A system for evaluating the viability of an offshore wind farm proposal was proposed. The system was subdivided into four ‘pillars’ and each were made up of several parameters and sub-parameters. Weights were assigned to every sub-parameter based on how important that parameter is judged to be to the overall viability. To test the system, it was put to the test on three proposals made in the Maltese Islands – Sikka L-Bajda, Benghajsa Patch and North of Gozo. Six different permutations of the Sikka L-Bajda proposal were tested and the best one was tested using the other two sites.

The weighted system predicted that monopiles are the most suitable foundation type for the Sikka L-Bajda project, because of the depth of the site and its low footprint, whereas gravity bases were deemed to be too costly and have too large a footprint for that location. There is no clear distinction using the permutations tested between the three turbines used, although the RePower 5M turbine would appear to be the most efficient of the three.

When this permutation was used to evaluate the Benghajsa Patch and North of Gozo, it was found that neither was superior to the Sikka L-Bajda site. Benghajsa Patch was judged to have far too many planning and socio-economic conflicts to be a viable proposal. North of Gozo may suffer from being of marginal capacity, but has the least planning issues of all the three sites.

Since the model confirms that which was concluded about these three sites, there is some validity to it. However, the model is unrefined and would be better off with pre-defined intervals for the scores of each parameter. The results are also highly prone to subjectivity because of a lack of information and the fact that the scores are given based on the opinions of the writer.

Despite these limitations, the system achieved the purpose of distinguishing between the various issues, such as Benghajsa having planning issues and the gravity base’s costs and impact on the
Posidonia seagrass meadows. Recommendations on refinement of the system are proposed in the next section.

6.2 - Recommendations

While much work has been done to try and establish a system for evaluating wind farm viability in this dissertation, in its current form it can only be utilized as guidance and the outputs are not fully reliable. The main limitation is the fact that the variables and the weights were assigned based on the judgement of a single individual, and what one considers to be important may be irrelevant to another. For example, out of the four pillars, the technical one is given much more priority than the others, particularly the environmental. There are a number of ways to improve the system, some of which are

- Reduce the subjectivity by conducting a series of consultation exercises and/or questionnaires to experts, authorities and members of the public, to find out what is considered important and what is not.
- These results can be used to redefine the variables and help to adjust the weights based on the aggregate result. The results will also help to establish a definite interval for giving a score. For example a wind farm that costs €2 million per MW capacity, operating at 23% of its generating capacity would have a predefined category under which the appropriate scores are given.
- Accurate mapping of the major shipping routes, popular cruise liner routes, fishing grounds, sea currents etc to establish a dataset from which the risk of ship-turbine collisions can be estimated.
- A major issue going forward is whether the general public will support, and pay for, offshore wind projects, as opposed to other renewables, and even fossil fuels, especially since the cost of electricity will be higher than for conventional power stations.
- Testing the system on European wind farms, which have published EIAs and which could be used to fine-tune the system and used to check whether the correct results are being produced.
- The system was designed in order to evaluate the viability of wind farms for beyond the current 2020 plan. Since there is a lack of information about transitional and deep sea sites, it was not possible to evaluate these proposals using this methodology. A couple of sample hypothetical proposals for a transitional and deepwater farm are provided in Figures 6.1 and 6.2.

A number of changes to the model described in Chapter 5 are suggested below for future iterations

- **Technical**
  - Maximum Capacity
    - Layout of site with respect to the prevailing winds
    - Distance between turbines and rows
  - Wind Conditions
    - Coastal conditions at nearest landfall (low-lying land, steep cliffs, hills)
- **Planning**
  - Risk of collision with turbines → Maritime Risks
- **Environmental**
  - Distinguish between different species of birds and fish, depending on a species importance to the Maltese ecosystem and on how sensitive the species is to anthropogenic disturbances from wind farms.
- **Socio-Economic**
  - Add a new parameter “Benefits of wind farm” with the following sub-parameters
    - CO₂ emission reduction
    - Improvement of air quality
- Energy Security
- Relocation of bunkering

Figure 6.1 - Hypothetical proposal for a transitional depth farm at Hurd Bank. With a total area of around $21\text{km}^2$, the farm would comprise of 28 5MW turbines for a maximum capacity of 140MW. The major issues about this project is the distance to shore, conflicts with Bunkering Area 3, and depth, which varies between 35-73 metres deep. A jacket structure is a likely foundation structure for this location. Since the Crown Estate’s Round 3 projects involve sites exploiting wind in these depths, this site could be a viable site in the 2020s.

<table>
<thead>
<tr>
<th>Number of Turbines</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Capacity</td>
<td>5MW</td>
</tr>
<tr>
<td>Hub Height</td>
<td>120 metres</td>
</tr>
<tr>
<td>Maximum Generating Capacity</td>
<td>140MW</td>
</tr>
<tr>
<td>Development Area</td>
<td>20.9km$^2$</td>
</tr>
<tr>
<td>Distance between Turbines</td>
<td>900 metres</td>
</tr>
<tr>
<td>Distance between Rows</td>
<td>800 metres</td>
</tr>
<tr>
<td>Distance to Shore</td>
<td>15.3km</td>
</tr>
<tr>
<td>Position relative to the Islands</td>
<td>East of Maltese Coast</td>
</tr>
<tr>
<td>Likely Geological Formation</td>
<td>Lower Globigerina Limestone</td>
</tr>
<tr>
<td>Minimum Sea Depth</td>
<td>35</td>
</tr>
<tr>
<td>Maximum Sea Depth</td>
<td>73</td>
</tr>
<tr>
<td>Exposure to Wind</td>
<td>Good from every direction</td>
</tr>
<tr>
<td>Foundation Structure</td>
<td>Jacket</td>
</tr>
</tbody>
</table>

Table 6.1 - Summary of the first hypothetical proposal
Figure 6.2 - Hypothetical proposal for an offshore wind farm in deep waters off the southern Maltese coast. The highlighted development area is around 56km$^2$ and could support a 300MW wind farm, which would probably be constructed in two equal phases. While the prospects of floating technologies becoming commercially viable are good in the long-term, this location is poorly located to exploit the prevailing NW winds and is located very close to two NATURA 2000 sites – Filfla and the cliffs. It is unlikely that this proposal would ever be viable as it is, unless it is relocated further offshore to the south or the west, or relocated completely to the north.

<table>
<thead>
<tr>
<th>Number of Turbines</th>
<th>63</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Capacity</td>
<td>5MW</td>
</tr>
<tr>
<td>Hub Height</td>
<td>130 metres</td>
</tr>
<tr>
<td>Maximum Generating Capacity</td>
<td>315MW</td>
</tr>
<tr>
<td>Development Area</td>
<td>56km$^2$</td>
</tr>
<tr>
<td>Distance between Turbines</td>
<td>900 metres</td>
</tr>
<tr>
<td>Distance between Rows</td>
<td>900 metres</td>
</tr>
<tr>
<td>Distance to Shore</td>
<td>0.5km</td>
</tr>
<tr>
<td>Position relative to the Islands</td>
<td>South of Malta and west of Filfla</td>
</tr>
<tr>
<td>Likely Geological Formation</td>
<td>Upper Coralline Limestone in the northern parts, but could</td>
</tr>
<tr>
<td>Minimum Sea Depth</td>
<td>124 metres</td>
</tr>
<tr>
<td>Maximum Sea Depth</td>
<td>184 metres</td>
</tr>
<tr>
<td>Exposure to Wind</td>
<td>Poor from the north, good from the south</td>
</tr>
<tr>
<td>Foundation Structure</td>
<td>SWAY Floater</td>
</tr>
</tbody>
</table>

Table 6.2 – Summary Description of the second hypothetical proposal
References


23. Extract from Admiralty Chart 194. 3 August 14, 2008. Scale 1:100,000.


http://www.rwe.com/web/cms/mediablob/en/311906/data/311620/50554/rwe-npower-
Marine-Sediments.


http://www.bowind.co.uk/project.shtml.

http://www.dongenergy.com/Burbo/Project/The_burbo_bank_project/Pages/The_Burbo_bank_pro-
ject.aspx.


34. C-Power. [Online] [Cited: October 21, 2010.] http://www.c-
power.be/applet_menu_en/index01_en.htm.


lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1992L0043:20070101:EN:PDF.

39. Borg, J.A. and Schembri, P.J. Alignment of marine habitat data of the Maltese Islands to conform

40. Malta Environment and Planning Authority. Threats to Habitats. [Online] [Cited: October 19,

41. Malta Maritime Authority. Malta Maritime Authority - Annual Report of Activities (1st October

42. Biehl, F. and Lehmann, E. Collisions of Ships with Offshore Wind Turbines: Calculation and Risk


60. [Online] [Cited: August 17, 2010.] http://www.ifb.uni-stuttgart.de/ifbmedia/bilder/07_Jobs/03_SD-Arbeiten/03_Windenergie/truss2.jpg.


63. ECN, MARIN, Lagerwey the Windmaster, TNO, TUD, MSC. Studie narr haalbaarheid van en randvoorwaarden voor drijvende offshore wind turbines. December 2002.


94. **DONG Energy.** NystedHavmollepark - The construction of Nysted Offshore Wind Farm. [Online] [Cited: October 21, 2010.]

95. Map of Nysted Offshore Wind Farm. [Online] [Cited: October 21, 2010.]


97. **Power Technology.** Scroby Sands Offshore Wind Farm, United Kingdom. [Online] [Cited: October 21, 2010.]

98. —. [Online] [Cited: October 21, 2010.]


112. E.ON UK. Robin Rigg Offshore Wind Farm - Project and community update from E.ON UK. Spring, 2007, 1.


127. **Vattenfall.** Thanet Offshore Wind Farm. [Online] [Cited: October 22, 2010.]


130. **Power Technology.** Rodsand II Wind Farm, Denmark. [Online] [Cited: October 22, 2010.]

131. **Scira Offshore Energy.** Sheringham Shoal. [Online] [Cited: October 22, 2010.]
http://www.scira.co.uk/about/about_the_project.html.


133. **DONG Energy.** Walney Offshore Windfarm. [Online] [Cited: October 22, 2010.]


139. **RE UK.** Ormonde Offshore Windfarm Green Light. [Online] [Cited: October 22, 2010.]


Chapter 7 - Appendices

Appendix A – Direct methods of data analysis, resource characterization, and turbine productivity

Direct Use of Data
Suppose one is given a series of \( N \) series observations, \( U_i \), each averaged over the time interval \( \Delta t \). The data can be used to calculate the following useful parameters:

1) The long-term averaged wind speed, \( \bar{U} \), over the total period of data collection is

\[
\bar{U} = \frac{1}{N} \sum_{i=1}^{N} U_i
\]

2) The standard deviation of the individual wind speed averages, \( \sigma_U \), is

\[
\sigma_U = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (U_i - \bar{U})^2} = \sqrt{\frac{1}{N-1} \left( \sum_{i=1}^{N} U_i^2 - N\bar{U}^2 \right)}
\]

3) The average wind power density, \( \frac{\bar{P}}{A} \), is the average available wind power per unit area and is given by

\[
\frac{\bar{P}}{A} = \frac{1}{2} \rho \frac{1}{N} \sum_{i=1}^{N} U_i^3
\]

Similarly, the wind energy density per unit area for a given extended time period \( N \Delta t \) long is given by

\[
\frac{\bar{E}}{A} = \frac{1}{2} \rho \sum_{i=1}^{N} U_i^3 = \frac{\bar{P}}{A} N \Delta t
\]

4) The average wind machine power, \( \bar{P}_W \), is

\[
\bar{P}_W = \frac{1}{N} \sum_{i=1}^{N} P_W(U_i)
\]

5) The energy from a wind machine, \( E_W \), is

\[
E_W = \sum_{i=1}^{N} P_W(U_i)(\Delta t)
\]
Method of bins
The method of bins provides a way to summarize wind data and to determine expected turbine productivity. The data must be separated into the wind speed intervals, or bins, in which it occurs. It is most convenient to use the same size bins. Suppose that the data are separated into $N_B$ bins of width $w_i$, with midpoints $m_i$, and with $f_i$, the number of occurrences in each bin or frequency. Then, by using Table 2.1[55],

$$N = \sum_{j=1}^{N_B} f_j = 5057$$

Then the long-term averaged wind speed, $\bar{U}$, is given by

$$\bar{U} = \frac{1}{N} \sum_{j=1}^{N_B} m_j f_j = 5.04 \text{m/s}$$

With a standard distribution of

$$\sigma_U = \sqrt{\frac{1}{N-1} \left( \sum_{j=1}^{N_B} m_j^2 f_j - N \left( \frac{1}{N} \sum_{j=1}^{N_B} m_j f_j \right)^2 \right)} = 3.20 \text{m/s}$$

The average wind power density off the coast of Malta is

$$\bar{P} = \frac{1}{A} \rho \sum_{j=1}^{N_B} m_j^3 f_j = 191.93 \text{MW/m}^2$$

The average power generated by the Vestas 90-3.0MW turbine is approximately

$$\bar{P}_W = \frac{1}{N} \sum_{j=1}^{N_B} P_W(m_j)f_j = 532.41 \text{kW}$$

And the expected generation of a single Vestas turbine off the coast of Malta in one year is

$$E_W = \sum_{j=1}^{N_B} P_W(m_j)f_j \Delta t = 4.67 \text{GWh}$$

[55] Results calculated from Table 2.1 are in bold
Appendix B – Results of studies for Sikka L-Bajda, Benghajsa Patch, and North Gozo as given in the 2009 Sikka L-Bajda Project Description

B.1 – Sikka L-Bajda

<table>
<thead>
<tr>
<th>A. Technical Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Located approximately 1.5 km away from Rdum tal-Madonna (Mellieha)</td>
</tr>
<tr>
<td>Site unconstrained (max) wind potential at sea depths up to 25 m: 95 Megawatts</td>
</tr>
<tr>
<td>Not too far from coast to make grid connection and maintenance expensive</td>
</tr>
<tr>
<td>Site is well exposed to the north westerly prevailing winds, although these are affected to a certain extent by the presence of Gozo and Comino. However the flow retardation is not expected to be as significant as in other sites for two main reasons:</td>
</tr>
<tr>
<td>(1) Site is not too close to Gozo and Comino sites. The north of Sikka l-Bajda is around 2.7 km from Comino and 5 km from Ras il-Qala in Gozo. Such distances help to re-energise the north westerly wind approaching Sikka l-Bajda</td>
</tr>
<tr>
<td>(2) Winds are known to suffer from increased turbulence levels when flowing over cliffs. The gradually sloping topography from Qala to Ras il-Qala alleviates the generation of separated (turbulent) wind flow conditions in the coastal areas in the north west of Sikka l-Bajda</td>
</tr>
<tr>
<td>Flow disturbance due to land mass is not as significant as for the other sites since it is further away from the shore</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Planning Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site is a candidate Natura 2000 Special Area of Conservation of international importance</td>
</tr>
<tr>
<td>Site is 1.5 km away from a cliff (Rdum tal-Madonna) which is designated as a Special Area of Conservation and a Special Protection Area</td>
</tr>
<tr>
<td>Used for fishing, bunkering in certain adverse weather conditions, boating and yachting</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C. Environmental Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benthic habitat is composed of <em>Posidonia oceanica</em> settled on matte</td>
</tr>
<tr>
<td>Important breeding area for fish</td>
</tr>
<tr>
<td>The cliff at Rdum tal-Madonna is an important bird area for the Cory and Yelkoun shearwater, which are protected bird species. The sea area around the cliff is a rafting zone for these sea birds.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D. Socio-economic Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site is distant from the coastal areas. Therefore visual, noise and shadow flicker impacts are less significant than for other sites.</td>
</tr>
<tr>
<td>Site is considerably distant from residential settlements and beaches. Site is 3 to 4 km away from the nearest residential settlements at Qawra (Ta’ Fra Ben).</td>
</tr>
<tr>
<td>Site is 3 to 5 km away from St. Paul’s Bay, Bugibba and Qawra which are important locations for the tourism industry.</td>
</tr>
<tr>
<td>Site is 5 km away from Ghadira beach</td>
</tr>
<tr>
<td>Unlikely to interfere with commercial marine traffic in harbour areas because the site is considerably away from the Grand Harbour and the Malta Freeport in the south of Malta</td>
</tr>
<tr>
<td>Impacts on communications, including impacts on TV receptions originating in Italy, due to the presence of turbines are insignificant</td>
</tr>
<tr>
<td>Possibly impacts on aviation can be mitigated</td>
</tr>
</tbody>
</table>
## B.2 – Benghajsa Patch

<table>
<thead>
<tr>
<th><strong>A. Technical Considerations</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Located off the coast near Freeport area in the south of Malta</td>
</tr>
<tr>
<td>Site unconstrained (max) wind potential at sea depths up to 25 m: <strong>20 Megawatts</strong></td>
</tr>
<tr>
<td>Site is just off the coast and therefore grid connection and maintenance are less expensive</td>
</tr>
<tr>
<td>Too close to the south-east coast and therefore north westerly prevailing winds are affected by the land mass.</td>
</tr>
</tbody>
</table>

### B. Planning Factors

- The coastal area at Benghajsa is a Natura 2000 Special Area of Conservation
- The offshore site is a candidate Natura 2000 Special Area of Conservation of international importance
- Used for fishing, diving, boating and yachting

### C. Environmental Factors

- Benthic habitat is mainly composed of *Posidonia oceanica* settled on sand/rock. Other parts consist of rock/coral outcrops.
- Close to an important area for avifauna
- Important breeding area for fish

### D. Socio-economic Factors

- The skyline in the vicinity already disrupted by the Malta Free Port cranes. Seascape often punctuated by the presence of large vessels as well as the occasional oil rigs
- Site is located near the entry to the Malta Freeport and is therefore likely to interfere with marine traffic at the port
- Site is known to be a popular diving site
- Significant impact on airfield operations. Site is within flight path of aircraft landing/taking off Luqa airport through runway 14/32. Site development would lead to very high risks to air traffic and ILS operations
- Site is 2.4 km away from beach at Birzebbuġa
- Impacts on communications, including impact on TV receptions originating in Italy, due to the presence of turbines are insignificant
## B.3 – North of Gozo

Located off the north coast of Gozo, between Il-Qolla l-Bajda and Nadur

### A. Technical Considerations

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site unconstrained (max) wind potential at sea depths up to 25 m.</td>
<td>25 Megawatts</td>
</tr>
<tr>
<td>Although site is just off the coast, grid connection would be more expensive</td>
<td></td>
</tr>
<tr>
<td>than for other sites as closest distribution centre is further away (at Qala).</td>
<td>This would entail considerable trenching works, up to 8 km in length</td>
</tr>
<tr>
<td>Site is easily accessible and this reduces costs for operation and</td>
<td></td>
</tr>
<tr>
<td>maintenance</td>
<td></td>
</tr>
<tr>
<td>Site is well exposed to the north-westerly prevailing winds, although</td>
<td>these are obstructed to a certain extent by the adjacent land mass.</td>
</tr>
<tr>
<td>Site is sheltered from wind blowing from some directions (west to south) by</td>
<td>the coastal terrain which extends up to around 100 m above sea level.</td>
</tr>
<tr>
<td>coastal terrain which extends up to around 100 m above sea level</td>
<td></td>
</tr>
</tbody>
</table>

### B. Planning Factors

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site is adjacent to a Natura 2000 Special Area of Conservation (Ghajn Barrani Area)</td>
<td>The offshore site is a candidate Natura 2000 Special Area of Conservation of international importance</td>
</tr>
<tr>
<td>Used for small-scale fishing, diving, boating and yachting</td>
<td></td>
</tr>
</tbody>
</table>

### C. Environmental Factors

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benthic habitat is mainly composed of <em>Posidonia oceanica</em> settled on rock.</td>
<td>There are also areas of fine sediments (predominantly clay/silt) and</td>
</tr>
<tr>
<td></td>
<td>coarse sediments (sand/pebbles)</td>
</tr>
<tr>
<td>Important breeding area for fish</td>
<td></td>
</tr>
</tbody>
</table>

### D. Socio-economic Factors

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site is too close to the coast and therefore visual and noise impacts as</td>
<td>well shadow flicker effects onshore may be considerable. Site is around</td>
</tr>
<tr>
<td>well shadow flicker effects onshore may be considerable. Site is around</td>
<td>450 – 750 m away from residential and tourist areas at Marsalforn and</td>
</tr>
<tr>
<td>450 – 750 m away from residential and tourist areas at Marsalforn and Qbajjar</td>
<td></td>
</tr>
<tr>
<td>Site is about 600 – 800 m away from Ramla Bay</td>
<td></td>
</tr>
<tr>
<td>There is a popular diving area near Qolla l-Bajda</td>
<td></td>
</tr>
<tr>
<td>Impacts on TV transmissions originating in Italy on receptor areas at</td>
<td>Marsalforn and Qbajjar may be significant</td>
</tr>
<tr>
<td>Marsalforn and Qbajjar may be significant</td>
<td></td>
</tr>
</tbody>
</table>