TKI Wind op Zee

Potential of floating offshore wind

Market study floating wind in the Netherlands

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1 Executive summary

1.1 Background

The Dutch Government and the Top consortium for Knowledge and Innovation for offshore wind (TKI-WoZ) are managing the R&D and innovation Programme for offshore wind, to achieve a 40% cost reduction and strengthen the economic activities in offshore wind in the Netherlands. The Dutch Government and TKI-WoZ are considering including floating support structures in the R&D and Innovation Programme for offshore wind.

The Dutch Government and TKI-WoZ have requested DNV GL to assist in this decision, by a study into “the status of floating support structures and expected future developments with regard to the technology, cost developments and market opportunities specifically for Dutch offshore wind companies”.

The main question posed for this study is: “Should the Dutch Government include floating foundations in its R&D and Innovation Programme?”. To address this, DNV GL has described their view on the technology development, market status and development, and the challenges and opportunities faced in the (Dutch) market for floating offshore wind turbine foundations.

1.2 Current status

Many concepts for floating support structures for offshore wind turbines have been identified; approximately 30 floating wind technologies. Only a handful have been demonstrated at MW scale. The different concepts fall into three main categories: ballast stabilised (spar buoys), buoyancy stabilised (semi-submersibles) and mooring stabilised (tension leg platforms).

Floating wind technology solutions are being developed in Europe, the USA and Japan with single MW scale device demonstrators having been installed in Norway, Portugal and Japan. Smaller scale demonstrators have also been deployed in the USA, and Italy. Small array demonstration projects are in planning for both ballast (Scotland) and buoyancy (Scotland, Portugal, USA) stabilised concepts. At present no floating wind specific incentive exists in any market beyond the small scale array demonstration phase.

The development of a market for floating wind technologies is strongly linked to the market for bottom fixed solutions. In virtually all of the regions where floating wind could be deployed there exists significant resource that can be exploited by bottom fixed technology which has already gained significant traction in some markets e.g. North-western Europe. The development of a floating wind market is dependent on demonstrating a clear route to cost reduction and so the success of the small array demonstration projects that are in planning is critical.

1.3 Challenges

For successful commercialisation, any innovation needs to develop technically, achieve deployment volume and reach cost competitiveness.

The technical challenges faced by floating wind as it moves towards technological and commercial maturity, have been identified across 6 major areas. In Table 1-1 an overview is given of the technical challenges discussed in this study.
MARKET STUDY FLOATING WIND

Table 1-1: The main technical challenges faced by floating wind foundations.

<table>
<thead>
<tr>
<th>Category</th>
<th>Technical Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>Currently available turbines are adapted from designs for use on fixed structures. There is a need to develop turbine designs specifically for use on floating structures, with particular emphasis on;</td>
</tr>
<tr>
<td></td>
<td>• Design limits for rotation and acceleration of rotor nacelle assembly</td>
</tr>
<tr>
<td></td>
<td>• Sufficient and appropriate control systems</td>
</tr>
<tr>
<td>Support Structure</td>
<td>The support structures for current demonstration projects have not been fully optimised so do not demonstrate the potential for cost reduction from floating wind.</td>
</tr>
<tr>
<td></td>
<td>The relationship between turbine rating and platform size is not fully understood leading to difficulty in determining the optimum turbine and structure combination.</td>
</tr>
<tr>
<td></td>
<td>Fatigue design of structure and components is poorly understood due to lack of operational experience leading to conservatism in designs.</td>
</tr>
<tr>
<td></td>
<td>Yards with manufacturing capability are not equipped for serial production leading to uncertain cost reduction potential in manufacturing.</td>
</tr>
<tr>
<td>Moorings and Anchors</td>
<td>Poor understanding of the dynamic behaviour of moorings, particularly for shallow water (40 – 60m) leading to suboptimal mooring design.</td>
</tr>
<tr>
<td></td>
<td>Cost of anchors and their installation is high.</td>
</tr>
<tr>
<td></td>
<td>Large footprint for spread mooring systems creates potential for conflict with other operators in vicinity of installation.</td>
</tr>
<tr>
<td></td>
<td>TLP anchor performance is sensitive to soil conditions so increases risk and cost of installation.</td>
</tr>
<tr>
<td>Electrical Infrastructure</td>
<td>Lack of experience with dynamic power cables leading to conservative design.</td>
</tr>
<tr>
<td></td>
<td>Lack of experience with substations on floating structures.</td>
</tr>
<tr>
<td>Transport and Installation</td>
<td>Lack of consensus on best approach to installation, e.g. use of special purpose or multi-purpose vessels.</td>
</tr>
<tr>
<td>Operation and Maintenance</td>
<td>Distance from shore and harsh environmental conditions limit availability for inspection and maintenance.</td>
</tr>
<tr>
<td></td>
<td>Methods for inspection and maintenance are unproven.</td>
</tr>
<tr>
<td>Design Standards and Tools</td>
<td>Lack of installation and operational experience means that design drivers are poorly understood so designs may be conservative.</td>
</tr>
<tr>
<td></td>
<td>Target safety levels (probability of failure) in design standards are not reflective of risk profile of floating wind, potentially leading to conservative design.</td>
</tr>
<tr>
<td></td>
<td>Software tools that simulate the whole system behaviour are not fully developed or validated.</td>
</tr>
</tbody>
</table>

Apart from these technical challenges, one of the key challenges for the development of offshore wind remains its economic viability. Using the DNV GL cost model, applied to hypothetical bottom fixed and floating 800MW wind farms, the current cost level of floating wind solutions is estimated to be approximately 60% higher than bottom fixed solutions. The rate of convergence between the costs of fixed and floating is dependent on a number of factors but if floating is to become competitive it must demonstrate significant cost reduction especially in the support structure, installation, moorings and anchors. A stated above, the success of the small array demonstration projects that are in planning is a critical next step as a positive outcome will help define a clear route to cost reduction.

These cost reductions are required if a market for offshore floating wind is to develop. Floating wind is in direct competition with fixed offshore wind (and other RES options). Fixed offshore wind, as the
incumbent technology, has yet to reach levels of deployment that make it necessary to consider other (floating) solutions. As a result a compelling case has yet to be made for the politically driven financial support that will be required to commercialise floating wind technology in any one market.

In light of this, the further development of floating wind technology is dependent on:

- The (technical) success of the small array demonstration projects,
- Realised or expected cost reductions for floating wind, and
- Further public support targeted at creating a long term market for the technology.

1.4 Opportunities

Given the relatively shallow depths of Dutch territorial waters a significant home market for floating wind technologies is considered unlikely.

However, given the position of the Dutch companies in related offshore sectors (including fixed wind and Oil & Gas) there are good opportunities for Dutch industry to both support and supply to floating markets that may develop elsewhere. DNV GL has made an initial assessment of the capabilities of the parties that are or could be involved in floating wind from an office located in the Netherlands. This initial assessment can be found in Fout! Verwijzingsbron niet gevonden., the findings can be summarised as follows.

In R&D there is a strong presence of capabilities related to the floating support structure. Work in this field is strongly dependent on cooperation with the technology developers, and none of the major concepts (Hywind spar, WindFloat, Sway) that we see today are from Dutch companies. International cooperation for a global market is therefore key. Several companies are already actively involved in this field.

In detailed design there is strong Dutch capability, again dependent on international cooperation in a global market.

In fabrication there are several companies that are capable of fabricating the floating support structure. So far all floating structures in operation have been built as a one-off in a shipyard. For commercial deployment the structures need to be serially produced to reduce costs. The possibilities for this are dependent on the concept, as the main part of a spar buoy can be more easily serially produced by fabrication companies of tubulars, while the semi-sub and TLP concepts fabrication at shipyards will have to be streamlined. This field is strongly related to markets in the vicinity.

In Transport & Installation there is a strong presence of Dutch market parties. This field is more dependent on markets in the vicinity.

In Operation & Maintenance there are companies that could be involved on a strategic level and in execution of actual operation & maintenance, the latter being more dependent on the markets in the vicinity.
2 Introduction

2.1 Background

The Dutch Government and the Top consortium for Knowledge and Innovation for offshore wind (TKI-WoZ) are managing the R&D and innovation Programme for offshore wind, to achieve a 40% cost reduction and strengthen the economic activities in offshore wind in the Netherlands.

As stated by TKI-WoZ in their request, the focus of their first programme has been on fixed foundations due to the relatively shallow nature of Dutch territorial waters which make floating foundations less feasible and less competitive than fixed foundations. TKI-WoZ states that due to recent developments in floating foundations for possible cost saving potential, and the possibilities for economic activities of Dutch companies, the Dutch Government and TKI-WoZ are considering including floating support structures in the R&D and Innovation Programme for offshore wind.

The Dutch Government and TKI-WoZ have requested DNV GL to assist in this decision, by a study into “the status of floating support structures and expected future developments with regard to the technology, cost developments and market opportunities specifically for Dutch offshore wind companies”.

2.2 Aim and approach

The main question posed for this study is: “Should the Dutch Government include floating foundations in its R&D and Innovation Programme?” To address this, ten research questions have been formulated by TKI-WoZ, defined as follows:

1. What floating foundation technology options are available or under development?

2. What is the current state of the offshore wind floating foundation market (differentiated per geographic region)?

3. How is this market expected to develop over the coming 5 to 15 years?

4. What is the current cost level and how is this expected to develop for various technologies?

5. What is the position of Dutch companies in this market (Engineering, Manufacturing, Transport and Installation)?

6. What is the opportunity looking forward? Specifically regarding the water depths where floating foundations can be applied and for the Dutch industry.

7. What are the key problems to be addressed in the development of new floating foundation technology?

8. What role can R&D Programme’s such as the TKI Wind op Zee play in the innovation process?

9. What instruments are required to support R&D and Innovation?

10. What is the required R&D roadmap for the coming years that can be implemented by in the Dutch governmental policy?

In this report, the first seven research questions are addressed: the status of the technology is summarised by describing the main concepts and their Technology Readiness (see below), the
Current market status is also summarised and the expected future developments especially concerning the Netherlands are discussed, finally the challenges faced by floating wind technologies are described and the opportunities these challenges offer to Dutch companies are highlighted.

In a separate report, possibilities for the R&D and Innovation Programme are suggested, answering the remaining three research questions for this study (questions 8-10).

For this report, all concepts will be discussed in the context of two frameworks that describe the status of the technology for this concept:

- Technology Readiness Levels (TRL)
- Commercial Readiness Index (CRI)

The challenges and opportunities are addressed by looking at all key parts or critical technical elements of a floating wind turbine and its support structure e.g. hull and mooring lines.

In the remainder of this chapter, the TRL and CRI terms are explained.

### 2.2.1 Technology Readiness levels

The TRL is a measure of the maturity of a technology, as it develops from blue sky research to system demonstration over the full range of expected conditions. A technology is said to be in a certain TRL if the status as described in that TRL has been achieved. Subtly different definitions of TRLs are used in different contexts; for the purposes of this study we have adopted the description as defined in a report on floating wind published by the Crown Estate, reproduced here as Table 2.1.

The terminology supports a common understanding of the status of a technology. It should be noted that the TRL as status description of a technology is context-specific, as a technology may be more mature in a certain system than in another system, dependent on the fit of the technology in the system itself and in its operational environment.

The first three levels, TRL 1-3, described the start of scientific research and feasibility research on a component level, with the discovery of practical applications and proof of concept. Active research begins at TRL 3. At TRL 4-6, the technology is further developed on component or subsystem level. At TRL 7-8, the technology is validated, demonstrated and qualified on a system level. TRL 9 represents the full technical maturity of the technology operating at full-scale within the actual system.

As a technology moves from TRL 1 to 9 targeted investments are required to push forward three equally significant parameters: technical development, deployment volume and cost competitiveness. For example, it would not be appropriate to try to demonstrate a cost reduction through volume for a technical solution that is sub-optimal or to demonstrate a technical solution that provides short term cost reduction for a one-off that would not scale with volume.

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<table>
<thead>
<tr>
<th>TRL</th>
<th>Technology status</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Proof of concept in the lab</td>
<td>Basic principles observed and reported. Scientific research begins to be translated into applied research and development. Examples include paper studies of basic characteristics.</td>
</tr>
<tr>
<td>2</td>
<td>Technology concept and/or application formulated</td>
<td>Practical applications of basic key principles can be ‘invented’ or identified. The application is still speculative and experimental proof or detailed analysis to support the proposal could be missing. Examples are limited to analytical studies.</td>
</tr>
<tr>
<td>3</td>
<td>Analytical and experimental critical function and/or characteristic proof of concept</td>
<td>Active research and development is initiated. Analytical studies to set the technology into the appropriate context, and laboratory-based work to physically validate that the analytical predictions are correct. These should constitute the ‘proof of concept’ validation.</td>
</tr>
<tr>
<td>4</td>
<td>Concept development and scale testing</td>
<td>Component or experimental model validation in a laboratory environment. Basic technological components are integrated to establish that the ‘pieces’ will work together. The validation is relatively small-scale compared to the eventual technology; it could be composed of ad hoc discrete components in a laboratory.</td>
</tr>
<tr>
<td>5</td>
<td>Component or experimental model validation in a relevant environment</td>
<td>At this level, the reliability/scale of the component being tested has to increase significantly. The basic technological components must be integrated with reasonably realistic supporting elements so that the total applications can be tested in a ‘simulated’ environment.</td>
</tr>
<tr>
<td>6</td>
<td>Technology model or prototype demonstration in a relevant environment</td>
<td>A major step in the reliability/scale of the technology demonstration follows the completion of TRL 5. At TRL 6, a prototype going well beyond ad-hoc or discrete components is tested in the working environment.</td>
</tr>
<tr>
<td>7</td>
<td>Prototype demonstration</td>
<td>Full-scale technology demonstration in operational environment. The prototype is near or at the scale of the planned operational system. TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in the working environment.</td>
</tr>
<tr>
<td>8</td>
<td>Actual system completed and qualified through test and demonstration</td>
<td>Represents the stage at which the technology is tried and tested in its actual form and expected circumstances. In almost all cases, this level is the end of true ‘system development’ for most technology elements.</td>
</tr>
<tr>
<td>9</td>
<td>Commercial demonstration and system development</td>
<td>Actual system proven by successful operation. Technology deployment in its actual form and operational conditions.</td>
</tr>
</tbody>
</table>

Table 2.1 Technology Readiness Levels

### 2.2.2 Commercial Readiness Index

As a technology progresses to TRL 9, the majority of technical risk can be removed. The final stage, TRL 9, represents the point at which the technology is proven. However, at this stage the technology is not necessarily commercially viable in either a free or supported market. In the demonstration and deployment phase significant commercial uncertainty and risk may remain. Typically, a new technology enters a market where it faces competition from the proven technology of incumbents.

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and barriers for receiving finance from risk-adverse capital lenders. This is particularly relevant for renewable energies, as access to capital is a key barrier to accelerating the development.

To assess the commercialisation of a technology and the associated uncertainties and risks of this later phase in technology development and deployment, the Australian Renewable Energy Agency (ARENA) has developed the Commercial Readiness Index (CRI) as a tool that can be used to measure the commercial readiness of emerging renewable energy solutions. The relationship between the TRL and CRI frameworks is illustrated in Figure 2.1.

As a technology moves towards the highest TRL it must bridge the gap between the technology development phase and move into the commercialisation phase. At this stage, CRI2, the technology will be at the small scale, commercial trial stage. Further, increasingly significant investment is required to move the technology through the CRI until its commercial status reaches CRI6: a ‘bankable’ asset with known standards and performance expectations.

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3  FLOATING wind technology

3.1  Introduction

Most floating wind substructures are based on well-known technologies used in the oil & gas sector. However, as with fixed foundations, the application is new with specific requirements, e.g. it needs to be serially produced for a cost-effective wind farm. There are three basic stability philosophies by which floating support structures can be classified:

- Buoyancy: stability is achieved through distributed buoyancy. The semi-submersible concepts are mainly based on this.
- Mooring: stability is achieved by tensioned mooring lines. An example is the Tension Leg Platform (TLP).
- Ballast: stability of the platform is achieved by ballast weights underneath a central buoyancy tank, creating a righting motion and high inertial resistance to pitch and roll. Spar buoys utilise this type of stability.

In Figure 3-1 the main concepts regarded in this study, the semi-submersible, TLP and Spar buoy concepts, are placed in a triangle based on their stability concept. Several examples of floating foundation concepts are placed in the triangle to show the reliance on each stability philosophy per concept.

![Figure 3-1: Stability triangle. Several concepts are placed in the stability triangle to represent their reliance on the three main stability philosophies. The concepts are categorised into the three main concept categories: TLP, Semi-Submersible and Spar buoy.](image)

3.2  Leading concepts

In the following sections these three main concepts for floating foundations are explained. Next the existing concepts are presented. Other, more radical innovations, such as a floating foundation with multiple wind turbines or vertical axis wind turbines are considered outside of the scope. For each of the leading concepts a general description is given, followed by an example for a floating foundation being developed using this concept.

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### 3.2.1 Semi-submersible

#### Technical description

**Structural design**
Typically low draft where the linked columns provide floating- and stability-support. Adding heave plates to the structure helps reducing its heave response. The structure should be designed to reduce or avoid response with heave, roll or pitch eigenperiods to reduce extreme loads.

Mooring, anchoring and seabed footprint
Mooring lines are typically taut or catenary. Anchors are chosen based on the soil conditions. Drag embedment anchors are versatile and often used, as is suction anchors. Large seabed footprint, horizontal distance between anchor and fairlead is normally 4-6 times the water depth, but can potentially be considerably larger (10-20 times indicated).

**Fabrication and installation**
A welded structure that is constructed or assembled on-shore or in a dry dock. Transport to site is done by using conventional tugs. Fully equipped platforms can float with drafts lower than 10 meters during transport. Towing to field can typically be done in relatively high wave heights.

Because of the low draft and stability, transport can be done in shallow water. However, in order to pre-assemble when is shallow waters inshore, dry-dock or onshore assembly is required.

**Operation and maintenance**
Major maintenance can be done by towing the structure to shore. Most concepts can be reached from all columns in case of in-situ maintenance and service. Due to the size of the structure access is relatively easy. Some concepts plan to build helidecks on the substructure. Regular inspection of welded connection, both above and below sea-level is necessary in order to identify and mitigate fatigue cracks, corrosion, etc.

**Application**
Semi-submersible has typically the lowest draft of the the philosophies and can be seen as an alternative to jacket structures in certain places. Transport can be done in 10 m draft allowing assembly and transport in shallow and sheltered areas.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Strengths / Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural design</td>
<td>+ The most flexible design with regard to water depth with a typically low draft</td>
</tr>
<tr>
<td></td>
<td>- Might have larger wave-induced motions that may impact the rotor, tower and blades</td>
</tr>
<tr>
<td>Fabrication &amp;</td>
<td>+ Possibility to construct and assemble the structure on-shore or in a dry dock</td>
</tr>
<tr>
<td>Installation</td>
<td>- Complex structure to manufacture: larger amount of welds and connections</td>
</tr>
<tr>
<td></td>
<td>- between structural elements than other philosophies</td>
</tr>
<tr>
<td>Decommissioning</td>
<td>+ Easy decommissioning is expected, towing to shore/dry dock.</td>
</tr>
<tr>
<td>Operation &amp;</td>
<td>+ The stability and low draft enables semi-submersibles to be easily towed back to</td>
</tr>
<tr>
<td>Maintenance</td>
<td>- shore in case of major repairs</td>
</tr>
<tr>
<td></td>
<td>- Might be more subject to corrosion and ice-loads since much of the structure is close</td>
</tr>
<tr>
<td></td>
<td>to the water surface</td>
</tr>
</tbody>
</table>

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**Schematic**

Because of the low draft and stability, transport can be done in shallow water. However, in order to pre-assemble when is shallow waters inshore, dry-dock or onshore assembly is required.
3.2.2 Semi-submersible example: WindFloat

WindFloat is a semi-submersible floater developed by Principle Power Inc. It has three columns with a single turbine on one of the columns. The hull has a shallow draft and a displacement of about 5,500 t. It has an asymmetric mooring system with four catenary lines, with two mooring lines connected to the column carrying the turbine and one on each of the other columns. The substructure has an active ballast system that transfers water between the columns to keep the platform upright as the wind direction changes.

The structure (including turbine) can be fully assembled on shore in a suitable dry dock or slipway, using a large crane. The shallow draft of the structure allows for tow-out of the fully assembled unit by regular tugs. No special vessels are required. The anchors will be pre-laid and ready for mooring of the platform upon arrival to site. Maintenance could be done in a dry dock or at a quay side.

In 2011, a 2MW prototype was installed in Aguçadoura, 5km off the Portuguese coast in 40-50 m water depth. This was the first ever full-scale semi-submersible to be deployed, and it went from lab scale to full-scale prototype in 30 months. The concept has therefore achieved TRL 8.

Currently, Principle Power is planning for two pilot parks: one 30 MW off the coast of Coos Bay, Oregon, US, supported by the US Department of Energy, and a 27 MW wind farm in Portugal, in partnership with EDP, Repsol and A. Silva Matos. In May 2014 the USDOE announced that the demonstration project had been selected to receive up to $47m in match grant funding under the Advanced Offshore Wind Programme\(^6\). The concept has also been selected for the Kincardine development in Scotland.

For the 2 MW prototype, a Vestas V80 commercial turbine was used. The only modifications made to the turbine compared to a standard onshore deployment were the use of a wind class 1 tower (stronger) and modified control software. According to Principle Power, the size of the platform is primarily driven by the met-ocean conditions, and not the turbine size. The pre-commercial prototypes are likely to use WTGs in the 3-7 MW range. For the planned demonstration project off the coast of Oregon, Principle Power intends to use 6 MW direct-drive Siemens turbines.

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\(^7\) Pictures taken from [http://www.mhivestasoffshore.com/windfloat](http://www.mhivestasoffshore.com/windfloat) and [https://www.facebook.com/principlepower/](https://www.facebook.com/principlepower/)
3.2.3 Tension Leg Platform (TLP)

Technical description

**Structural design**
TLPs are high stability platforms. Typically soft in surge and sway but stiff in the rotational modes.

**Mooring, anchoring and seabed footprint**
Vertical tendons connect the floating turbine to the anchors on the seabed. The anchors could typically be of gravity based, suction or pile driven type. The tendons are pre-tensioned and provides stability.

Small seabed footprint. Typically only directly below the floating structure.

Fabrication and installation

A TLP can be assembled onshore or in a dry dock. When the structure has been completed it can be transported to site either with special purpose vessels, like for the PelaStar concept, or with more traditional solutions (towed to site) as has been indicated for the Gicon TLP. Various solutions are under development and remains to be proven in practice.

![Schematic](image)

Shallow and deep waters inshore:

1) Dry-dock assembly  2) Towing (or support) to turbine  3) Hook-up

*Because of the low draft and stability, transport can be done in shallow water. Some concepts might require additional stability support during transport and hook-up.*

Operation and maintenance

Component replacement would typically be done in- or onshore, as long as an easy hook-off system is in place. The hook-off procedure will have to deal with transitional phase of going from a TLP to a free-floating platform. This can be done by adding stability elements to the structure.

Application

TLP has low draft; several concepts mention technical feasibility for shallower waters up to 20 metres deep although economic feasibility is mentioned at 50 metres. The concept should be applicable also in sites with high tidal ranges based on the possibility to adjust the draft of the substructure. For example, the draft of the PelaStar concept is 22m during operation.

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<table>
<thead>
<tr>
<th>Parameters</th>
<th>Strengths/Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural design</td>
<td>+ Lower fatigue loads in tower and blades than semi-submersibles, and lower fatigue</td>
</tr>
<tr>
<td></td>
<td>loads in the tower base than spar buoys</td>
</tr>
<tr>
<td></td>
<td>- Less technological experience from offshore wind application than for spars and semi-</td>
</tr>
<tr>
<td></td>
<td>submersibles</td>
</tr>
<tr>
<td>Fabrication &amp; installation</td>
<td>+ Can be fully assembled in a dry-dock</td>
</tr>
<tr>
<td></td>
<td>- Tendon tensioning and transitioning from a free-floating phase to a TLP phase could be challenging</td>
</tr>
<tr>
<td>Decommissioning</td>
<td>+ Relatively easy decommissioning is expected. Special purpose vessels may be used for transport to shore.</td>
</tr>
<tr>
<td>Operation &amp; maintenance</td>
<td>+ Simple structure to inspect. Few active systems and components. Low amount of welds that will require inspection</td>
</tr>
<tr>
<td></td>
<td>- Can be challenging to disconnect for tow-to-shore in case of major repairs. Tendon termination points (and possibly active tensioning system) needs attention.</td>
</tr>
</tbody>
</table>
1.1.1 TLP example: GICON-SOF

The GICON SOF is a Tension Leg Platform (TLP) being developed by the German company GICON. SOF stands for ‘Schwimmendes Offshore-Fundament’. The four-legged hull provides the buoyancy to ensure constant rope tension in the mooring lines anchored to the ocean floor\(^8\). The manner of anchoring is flexible and can be adjusted to the soil type on site; piles, micro piles or gravity anchoring can be used\(^9\). The current prototype has a gravity-based anchor of a weight high enough to stabilise the structure.

GICON states that the TLP can be installed in water depths of 17 to 500 metres, and that one shipyard could produce two TLPs per week. The substructure and turbine can be pre-assembled at a wharf or port and then towed out to the site for installation using fairly simple tugs. According to GICON, the SOF can be transported at a towing speed of up to 5 knots in 2.5 metres swells.

In June 2013 combined wind and wave tests have been performed with a 1:37 scaled model of a 2MW TLP at MARIN. GICON states that the accelerations in the nacelle are lower than for a monopile\(^10\). In March 2015, GICON received consent to install a 2MW prototype in the Baltic Sea. A permit has also been received for the grid connection of the prototype at the Baltic 1 offshore wind farm. The 2MW prototype substructure weighs around 742 tonnes without tower and turbine and has a displacement of 2070 m\(^3\). The width of the structure is 32 metres. It is currently being fabricated in Germany and installation is planned for spring 2016. The total costs are stated by GICON to be around 18 million euro, of which 5 million euro is provided as a state grant by the state of Mecklenburg-Vorpommern.

GICON plans to pre-assemble the anchor to the structure as well. At the site, the structure is then installed by lowering the anchor to the seabed. This method will not be used for the upcoming 2MW prototype in the Baltic Sea.

GICON is also planning to install a 5-6MW prototype in the North Sea. This should have a displacement of around 3500 m\(^3\) and the substructure weighs around 1200 tonnes, at a structure’s width of 42 metres.

\(^8\) http://www.gicon-sof.de/en/technical-solution.html
\(^9\) https://www.sintef.no/globalassets/project/deepwind2014/presentations/e/adam-f_gicon.pdf
3.2.4 Spar buoy

**Technical description**

**Structural design**
Stable structure with high inertial resistance to pitch and roll motions. Relatively stiff in surge and sway, but more flexible in rotational modes.

**Mooring, anchoring and seabed footprint**
Mooring lines, typically taut or catenary. Large seabed footprint. Horizontal distance between anchor and fairlead is normally 4-6 times the water depth, but can potentially be considerably larger (10-20 times indicated).

**Fabrication and installation**
Due to large draft, the spar may require towing to a deep-water site in horizontal position, where it is upended, stabilized and the turbine is mounted by a crane barge. In case of deep water fabrication sites, the full assembly can be done in-shore, followed by tow-out using conventional tugs. Development of specialized vessels and/or customized turbines may enable horizontal towing. Concrete can be used instead of steel as manufacturing material.

**Operation and maintenance**
Component replacement would typically be done offshore. In case of deep water transport routes and maintenance site, hook-off and towing to shore could be possible. Most concepts have limited room for resting.

**Application**
The spar concepts have usually the largest depth requirements. This limits the areas suitable for this concept.

**Parameters**
- **Structural design**
  - Inherently high stability structure
  - Fatigue load in tower base might be higher for spar buoys than for TLP
- **Fabrication & Installation**
  - Relatively simple structure to manufacture, minimum amount of welds, and there is a possibility to use concrete instead of steel.
  - The large draft may limit the possibility for in-shore assembly which would add several offshore operations
- ** Decommissioning**
  - Relatively easy decommissioning is expected. Special purpose vessels may be used for transport to shore.
- **Operation & Maintenance**
  - Few active systems or complicated components
  - The large draft may limit the possibility for tow-back to shore in case major maintenance is required

**Strengths /Weaknesses**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural design</td>
<td>+ Inherently high stability structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Fatigue load in tower base might be higher for spar buoys than for TLP</td>
<td></td>
</tr>
<tr>
<td>Fabrication &amp; Installation</td>
<td>+ Relatively simple structure to manufacture, minimum amount of welds, and there is a possibility to use concrete instead of steel.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- The large draft may limit the possibility for in-shore assembly which would add several offshore operations</td>
<td></td>
</tr>
<tr>
<td>Decommissioning</td>
<td>+ Relatively easy decommissioning is expected. Special purpose vessels may be used for transport to shore.</td>
<td></td>
</tr>
<tr>
<td>Operation &amp; Maintenance</td>
<td>+ Few active systems or complicated components</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- The large draft may limit the possibility for tow-back to shore in case major maintenance is required</td>
<td></td>
</tr>
</tbody>
</table>
3.2.5 Example Spar-buoy: Hywind

Hywind is a spar buoy concept developed by Statoil; they started development in 2001. The spar buoy is a long cylindrical pile ballasted in the bottom, giving it high inertial resistance to pitch and roll motions and it is relatively stiff in surge and sway.

Although an inherently stable and relatively simple structure, the large draft may limit construction inshore in many markets. Tow-in and tow-out of the upended structure will require deep waters. Maintenance is planned to be performed offshore, although if required the structure can be released from the anchoring lines and towed to shore for the necessary repair. This tow-back in the upended (vertical) position again requires deep waters and a deep water maintenance area (at least around 80m).

In 2009 a 2MW prototype was installed 10 km off the Norwegian west coast. The unit is still up and running as of September 2015, and had a capacity factor of 50% in 2011. This prototype demonstrates that the concept is at TRL 8.

Statoil is planning a Hywind pilot wind farm at Buchan Deep, approximately 25 km off the east coast of Scotland in waters of 95 to 120 m deep\(^\text{11}\). The pilot park will consist of five Hywind units with a total maximum capacity of 30MW. Draught of the units is between 70 and 85 m and the rotor will have a diameter of 154 m. A three point mooring and anchoring system will be applied with a radius of 600 to 1200 m.

![Figure 3-4: Hywind transport to installation site, offshore assembly, and transport to site\(^\text{12}\).](image)

3.3 Other concepts

A study published by the Offshore Renewable Energy Catapult\(^\text{13}\) identified a large number of floating wind concepts that have been proposed and many of which are being actively developed. In Figure 3-5, the number of concepts at or exceeding the stated TRLs are summarised.

Whilst an earlier stage concept may prove to be more cost-effective in the longer term, the challenge of moving from TRL 1 to TRL 9 is a major technical and financial undertaking, usually taking a number of years to complete. On the other hand, when considering investments in R&D it is important to recognise that the diversity of concepts could delay progress towards maturity if funding is spread widely in order to avoid ‘picking a winner’ at an early stage. For floating wind support structures, the

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\(^{12}\) Source Statoil website, [http://www.statoil.com](http://www.statoil.com)

market leaders are quite far ahead of other concepts, leaving the less developed concepts facing a real challenge to ‘catch up’.

Two concepts have been proposed by (partly) Dutch companies: The Blue H TLP developed by Blue H Engineering and the Tri-Floater proposed by Gusto MSC. The Blue H TLP (see Figure 3-6) is a buoyant body connected to a counterweight that is lowered to the seabed. A small scale prototype with an 80 kW turbine has been placed at a water depth of 113 m in the Adriatic Sea in late 2007, making it the first installed floating wind turbine. Since this prototype, the design has changed considerably. The Gusto MSC Tri-Floater is a semi-submersible floating foundation\textsuperscript{14}, see Figure 3-8. It consists of a hull with three slender, braceless columns, moored by three catenary mooring lines. Gusto MSC started its development in 2002 and in 2013 a test campaign was performed with a scale model at Marin.

\[ \text{Figure 3-5: The histogram shows the number of concepts exceeding the stated TRL.} \]

\[ \text{Figure 3-6: Blue H TLP prototype installed in 2007.} \textsuperscript{16} \]

\[ \text{Figure 3-7: Blue H TLP.} \]

\[ \text{Figure 3-8: Gusto MSC Tri-Floater} \textsuperscript{17} \]

\textsuperscript{14} http://www.gustomsc.com

\textsuperscript{15} Catapult Floating wind technology assessment.

\textsuperscript{16} François Huber et al, ‘The first floating wind turbines’, 2\textsuperscript{nd} International Conference on Ocean Energy 15-17 October 2008, Brest, France.

\textsuperscript{17} http://www.blueengineering.com/technology.html
4 Current Market status and development

4.1 Introduction
The development of floating wind technology is global with most technology developers seeking to access opportunities both within and beyond their ‘home’ markets. The most significant developments in Japan, the US and Europe are described in the following sub-sections.

4.2 Market status
4.2.1 Japan
The combination of national R&D programmes and the water depth of much of the continental shelf surrounding Japan it is viewed as one of the leaders in the deployment of floating wind technology. The largest project in Japan is the Fukushima FORWARD project, initiated following the Great East Japan earthquake in 2011.18 It aims at increasing the understanding of design, deployment and operation of floating offshore wind farms, to contribute to the development of what could become a major export industry for Japan. The Fukushima FORWARD project is also aimed at promoting Fukushima as a centre for this new industry and creating new sources of employment as the region recovers from the impact of the earthquake. In Figure 4-1 the ambitious project and its timescale is depicted.

Figure 4-1: The Fukushima FORWARD project.

18 http://www.fukushima-forward.jp/english/
Apart from the Fukushima FORWARD project, a number of other R&D projects and feasibility studies have been, or are being, carried out in Japan, the main ones to mention are:

- **GOTO FOWT**\(^\text{19}\): A 2MW Hitachi turbine was installed on a spar buoy near Kabashima Island in 2012. This was the first grid connected floating wind turbine to be installed in Japan.

- **HYWIND-HITACHI collaboration**\(^\text{20}\): In 2013 Statoil and Hitachi Zosen announced that they were working together to explore the feasibility of using Hywind technology off the coast of Japan.

In March 2014 an offshore wind feed-in-tariff of 36 Japanese Yen/kWh (~270€/MWh) was introduced. The level of the FIT was set following a market hearing which involved developers of bottom-fixed wind. According to the Ministry of Environment, Transport and Infrastructure (METI), the FIT should be sufficient to support the development of offshore wind in Japan and enable easier project financing. A number of offshore wind projects have been announced\(^\text{21}\) since the introduction of the FIT. In March 2015 METI confirmed that the offshore wind FIT would remain at 36 Yen/kWh\(^\text{22}\).

The Offshore wind industry in Japan was the subject of a detailed appraisal performed by the Carbon Trust\(^\text{23}\). The appraisal which was published in October 2014 looks at the potential for both fixed and floating offshore wind. Quoting the Japan Wind Power Association (JWPA), the study reports that the realistically exploitable offshore wind potential in Japanese waters is approximately 600GW of which 10-15% could be developed using fixed turbines, with the remainder suitable for floating.

Despite the significant potential for both fixed and floating wind in Japan, DNV GL understands that current discussions within the Japanese government suggest that only limited deployment will occur before 2030. Table 4-1 shows the likely breakdown of electricity production from different sources in 2030. The 1.7% share from wind corresponds to an installed capacity of 10GW. Current installed capacity stands at 2.7GW with an additional 5.2GW already planned. The remaining 2.1GW is likely to be fulfilled from onshore or shallow water offshore developments. Whilst this is subject to change, particularly if the experience gained from demonstration projects in Japan, and elsewhere proves positive, it does, along with the lack of a floating specific feed-in-tariff, suggest that it is unlikely that Japan will drive floating wind towards a real commercial prospect in the next decade.

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Contribution percentage total energy production [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewables</td>
<td>22-24% (wind 1.7%)</td>
</tr>
<tr>
<td>Nuclear</td>
<td>20-22%</td>
</tr>
<tr>
<td>LNG</td>
<td>27%</td>
</tr>
<tr>
<td>Coal</td>
<td>26%</td>
</tr>
<tr>
<td>Oil</td>
<td>3%</td>
</tr>
</tbody>
</table>

*Table 4-1: Likely breakdown of electricity production from different sources in 2030 for Japan.*

\(^{19}\)http://goto-fowt.go.jp/english/

\(^{20}\)http://www.windpowermonthly.com/article/1173416/statoil-hitachi-consider-hywind-japan

\(^{21}\)http://www.offshorewind.biz/2015/02/09/another-offshore-wind-farm-planned-for-japan/

\(^{22}\)http://www.meti.go.jp/english/press/2015/0319_01.html

A number of floating technology demonstration projects are being pursued in the US:

- The first grid connected offshore wind turbine in the US was installed on a floating foundation in 2013 at 1:8 scale. The VolturnUS 1:8 was developed by the University of Maine (UoM) which has since been awarded $3m from the US DOE to carry out the design of a full scale (6MW) prototype to be installed in a demonstration project in a water depth of 95m.

- In addition to their activities in Europe, Principle Power, using funds from the US DOE’s Offshore Wind Advanced Technology Demonstration program, are planning the WindFloat Pacific Project (WFP) which will see five 6MW turbines installed on floating foundations off the coast of Coos Bay, Oregon.

- In May of 2015 the Danish developer Alpha Wind Energy (AWE) announced that it intends to develop a large (several-hundred-megawatt) floating wind project off the Hawaiian island of Oahu24. The turbines to be used for the proposed project have yet to be chosen but AWE has indicated that it intends to use the WindFloat technology developed by Principle Power for the floating foundations. In announcing the project AWE has indicated that a significant commercial driver is the relatively high retail price of electricity in Hawaii.

The offshore wind resource potential along the US coastline and the Great lakes is estimated to exceed 4,000 GW with at least 60% located in water depths greater than 60 m. Given that the vast majority (~80%) of US electricity demand originates in coastal states, the US Department of Energy has recognised that offshore wind is a resource that should make a significant contribution towards the country’s clean energy mix. The National Offshore Wind Strategy25 states a target of 54GW of offshore wind capacity to be deployed by 2030 with a target cost of energy of $0.07/kWh.

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Demonstration\textsuperscript{26}, for the final design and construction of demonstration projects. In total, the three projects are eligible for funding up to $46.7 million. The other two projects are fixed offshore wind projects. A further $3 million was awarded to smaller projects that are at an earlier stage of development.

4.2.3 Europe

Europe is the leading market for offshore wind, with more than 91% of the world’s capacity installed in the North, Baltic and Irish Seas and the English Channel\textsuperscript{27}. Europe has also provided a home for floating wind pioneers for the following prototype projects that are still in operation:

- Statoil’s Hywind being the first full scale floating wind technology to be deployed in 2009.
- Principle Power’s WindFloat demonstration project in Portugal installed in 2011\textsuperscript{28}.
- The small scale prototype of the Sway spar installed in 2011.

Further activities at the development and planning stage in European waters include:

- **The Hywind Scotland Pilot Park** \textsuperscript{29}: Statoil plans to build the first floating wind farm off the Scottish coast. The park will be located near Buchan Deep, approx. 25-30 km off the coast of Peterhead in Aberdeenshire. The primary objective of the Pilot Park is to demonstrate cost efficient and low risk solutions for commercial scale parks.

- The second phase of Principle Power’s three phase commercial floating offshore wind farm in Portugal, **the WindFloat Atlantic Project (WFA)**. The first phase was the WindFloat 2MW prototype that is currently in operation. The second phase of the WFA aims to build upon learnings from the first phase and prove the commercial efficacy of the WindFloat technology. Total capacity for the second (pre-commercial) phase of the project is planned to be 24 to 28 MW\textsuperscript{30}, employing next generation multi-megawatt offshore wind turbines\textsuperscript{31}.

- GICON has received consent from the German government for a **prototype of their GICON-SOF** (Schwimmendes Offshore Fundament) to be placed in the Baltic Sea in a water depth of 18.5 m\textsuperscript{32}. It is currently under construction and is planned for installation in the spring of 2016\textsuperscript{33,34}. It is a TLP floating foundation and a 2.3MW Siemens wind turbine will be installed on the GICON-SOF. GICON is also a developing a 5-6MW prototype for installation in the North Sea as a model for serial production.

- The placement of the **Vertiwind prototype at the Mistral test site** has been consented in France. This is a vertical axis turbine placed on a floating foundation. An onshore prototype

\textsuperscript{26} http://energy.gov/eere/wind/offshore-wind-advanced-technology-demonstration-projects \\
\textsuperscript{27} http://www.gwec.net/global-figures/global-offshore/ \\
\textsuperscript{28} SWAY also installed a 1:6 scale prototype in sheltered conditions in 2011 http://sway.no/?page=206\&news=761\&title=Sway successfully deployed prototype. \textsuperscript{29}http://www.statoil.com/en/TechnologyInnovation/NewEnergy/RenewablePowerProduction/Offshore/HywindScotland/Pages/default.aspx?redirectShortUrl=http%3a%2f%2fwww.statoil.com%2fHywindScotland \\
\textsuperscript{31} http://www.principlepowerinc.com/news/press_PPI_NER300.html \\
\textsuperscript{32} http://www.rechargenews.com/wind/1396770/gicon-cleared-for-baltic-pilot-of-sof-floating-wind-turbine \\
\textsuperscript{33} http://www.gicon-sof.de/en/sof-chronik.html \\
\textsuperscript{34} https://www.sintef.no/globalassets/project/deepwind2014/presentations/e/adam-f_gicon.pdf
has been in operation since May 2014, consisting of only first level of planned three levels of blades.

Figure 4-3: Onshore Vertiwind prototype, a vertical axis wind turbine.

The offshore 2 MW prototype at Mistral test site is planned for 2016, and the next step is a pilot farm ‘Provence Grand Large’ consisting of 13 turbines (34 MW) planned after 2017.

- **The FLOATGEN project**, led by IDEOL, will see the deployment of a 2 MW floating turbine in the Atlantic Ocean, at SEM-REV test site located 12 nautical miles from the city of Le Croisic on the French Atlantic coast. The objective of the FLOATGEN project is to demonstrate the technical and economic feasibility of floating-wind turbine, in order to expand the development potential of offshore wind farms into more windy and deeper waters that are not currently commercially viable and demonstrate potential in decrease of costs for electricity generation.

- In 2013 the Energy Technologies Institute (ETI) selected The Glosten Associates as the company to design an offshore wind floating platform system demonstrator. The ‘Pelastar’ demonstrator was to be installed at the Wave Hub site off the north coast of Cornwall in the UK but difficulties with planning permission have resulted on the project being put on hold as the resulting delay pushed the project beyond a date when it could be funded by the ETI which is being wound up at the end of 2017.

A number of concepts have undergone model tests with full scale demonstration projects at the planning stage, e.g. the Trifloater in the Netherlands and a TLP concept being pursued by Iberdrola in collaboration with Strathclyde University.

Floating wind technology developments are being supported through a number of different initiatives in Europe, from the provision of testing and demonstration sites to funding for R&D and demonstration from the Seventh Framework Programme (FP7), the New Entrants Reserve (NER300) and Horizon 2020 (H2020). National programmes are also providing funds e.g. the Grand Emprunt in

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France has provided loans to WINFLO and Vertiwind in addition to the support that the Environment and Energy Management Agency has provided to IDEOL’s FLOATGEN project.

The French government has made 150 million euro funding and feed-in tariffs available for a floating wind tender posted by the French environmental agency ADEME in August 2015\(^{40}\). One third of the funding is investment subsidies and the remaining 100 million euro is a loan. Feed-in tariffs are expected to vary between 150 and 275 €/MWh. The tender asks to submit proposals for arrays of three to six floating turbines of at least 5 MW individual capacity for four sites in the Mediterranean and off Southern Brittany.

At present, no floating specific market incentives are in place aimed at utility scale projects. Most activities are technology developer-led, with the noted exceptions of Statoil and Iberdrola who are actively involved in the development of floating offshore wind projects.

4.3 Market developments

4.3.1 Floating wind project pipeline

As demonstrated in Section 4.2, floating wind is being pursued at the prototype and demonstration phase in a number of markets. A recent study published by the Carbon Trust on behalf of Scottish Government\(^{42}\) lists the floating wind projects that have been built or announced. The timing and locations of the projects are summarised in Figure 4-4, the tables listing all the projects can be found in 0.

![Figure 4-4: Completed and planned annual and cumulative installed capacity of floating wind projects](image)

Whilst there is considerable uncertainty surrounding many of the developments the following observations can be made:

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\(^{40}\) [http://www.reuters.com/article/2015/08/05/us-france-windpower-floating-idUSKCN0QA26E20150805](http://www.reuters.com/article/2015/08/05/us-france-windpower-floating-idUSKCN0QA26E20150805)


• The initial deployments of prototypes in Norwegian and Japanese waters have yet to be followed by larger scale deployments.

• The first larger scale deployment planned for Portugal will build on the experience gained from prototype deployment at the same site.

• The larger scale deployments planned in Scotland, and the USA will build on experience gained from prototype deployments elsewhere (e.g. Norway and Portugal).

• Plans for prototype deployment of Vertiwind technology in France in 2016 are paving the way for larger scale deployments in 2018

• All of the mentioned demonstration deployments will benefit from some form of public support be it enhanced revenue, capital grant, or provision of critical infrastructure.

4.3.2 Outlook deployment 2015 - 2030

Whilst the previous sections demonstrate activity in a number of countries there is no clear commitment to the development of a market specifically for floating wind. In a market consultation undertaken for this study, none of the consultees expected floating wind to be taking off before 2020.

Whilst (bottom fixed) offshore wind is now an established, and growing, part of the energy mix in parts of northern Europe, the extent of deployment has not met the expectations set in the early years of this decade. This means that the need to exploit the deeper water sites that might make floating technology more competitive is yet to create any real market pull. The outlook for deployment over the next 5 to 10 years is therefore dependent on floating wind becoming competitive with bottom fixed technologies in relatively shallow waters for markets such as the UK and Japan.

Several small-scale projects of up to 30MW are now planned. For a market to arise for floating after 2020 towards utility scale wind farms in markets with mainly deeper waters, much depends on the success of these demonstration projects and the cost reduction achieved especially in installation, design and O&M.
4.4 The cost reduction challenge

4.4.1 Comparison to fixed offshore wind

Using the DNV GL cost model we have estimated CAPEX, OPEX and LCoE for two reference 800MW wind farms at 25 km from shore, one fixed and one floating, if they were built today with no learning assumed.

For this comparison, it has been assumed that the same wind turbine technology has been used for both the fixed and floating wind farm and therefore the cost per MW for the turbines is the same for both options. The assumed water depth for the floating foundation wind farm is 100 metres, while it is 30 metres for the fixed foundation. The assumed water depth differs for two reasons:

- The costs for the floating foundation are relatively insensitive to water depth, and some concepts (e.g. the Spar buoy) is not viable in shallower waters, while other concepts (TLP, semi-sub) become more expensive in shallower waters as for instance more stiffeners have to be added.
- If floating is to compete with fixed foundation wind farms in the short to medium term (the next 5 to 10 years), the costs have to reduce to the level of fixed projects in relatively shallower waters.

The ratio of floating to fixed costs is presented in Table 4-2. The relative cost comparison of the CAPEX costs are depicted in Figure 4-5. In this figure the component costs have been normalized to the total costs of the fixed foundation to illustrate the relative magnitude of the costs for each technology option. In Figure 4-6 the cost breakdown of the CAPEX for the floating and fixed wind farms are compared.

<table>
<thead>
<tr>
<th>Category</th>
<th>Ratio (Floating/Fixed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAPEX</td>
<td>160%</td>
</tr>
<tr>
<td>OPEX</td>
<td>200%</td>
</tr>
<tr>
<td>LCoE</td>
<td>167%</td>
</tr>
</tbody>
</table>

Table 4-2: Cost comparison of floating to fixed foundations for an offshore wind farm of 800 MW installed capacity if it was built in 2015 with no learning assumed.
When comparing the floating with the equivalent fixed wind farm it is found that the initial capital expenditure increases by 60% and the operating costs are doubled. These two factors combined result in the LCoE for the floating wind farm being 67% higher. The capital expenditure for floating wind is higher than for bottom fixed mostly due to the following cost components:
- Installation of the wind turbine and sub-structure (50% higher for floating). It should be noted that this is based on the current status. Significant reduction of the installation time is expected as one moves from prototypes to commercial deployment. Although simpler tugs are used for installation, the installation time is longer and therefore more susceptible to weather delays\textsuperscript{43}.

- Offshore electrical infrastructure (70% higher for floating)

- The installation of the electrical infrastructure (180% higher than fixed, although the floating cost is based on the costs for a much smaller demo park and so is probably on the high side)

- Substructure, mooring and anchoring (which, when compared with the equivalent substructure cost for fixed, is more than 200% higher)

The ratio of fixed to floating costs can be used to identify where it is necessary to focus efforts to reduce the cost of floating wind and therefore make it competitive with fixed either through technical improvements or via the ‘learning by doing’ that will be generated by further deployments.

For the OPEX, the main challenge is to perform heavy maintenance and repair works in deep waters, when Jackup vessels can no longer be used. One solution is to disconnect the substructure of its mooring lines and tow it to port and perform the necessary heavy work from shore, but this method is so far unproven.

From this high level analysis it is clear that if floating wind is to become competitive with fixed, technology developers must focus on the design and installation of the floating support structure (including moorings) and the electrical infrastructure, as well as reducing the O&M costs. This high level analysis therefore indicates the R&D priorities that can map across to the Dutch supply chain. A more detailed analysis of the technical challenges faced by floating wind and how they map across to the Dutch supply chain is presented in Section 5.

Most studies into floating wind show that floating wind can become cost competitive to fixed offshore wind from water depths starting at around 50 metres. From around waters of 50 metres or more, the cost for the conventional fixed foundation increases due to the rise in required steel, while the required material for floating stays almost independent from water depth.

### 4.4.2 Cost reduction potential

The Carbon Trust\textsuperscript{44} conducted a comparative analysis of the LCoE estimations for semi-submersible, spar and TLP concepts. The report states that projected values are under 100/\text{MWh} in commercial deployment from 2020, whereas the leading concepts expect 85-95\text{£}/\text{MWh} (around 116-137\text{€}/\text{MWh}). The Carbon Trust states that this does however require considerable cost reductions and technical barriers to overcome to achieve these cost reductions.

### 4.5 When will floating wind achieve commercialisation?

For a successful commercialisation, any innovation needs to develop technically, achieve deployment volume and reach cost competitiveness. In light of this, the further development of floating wind projects is dependent on:

- The (technical) success of the small array demonstration projects,

\textsuperscript{43} Carbon trust ‘Floating offshore wind market and technology review, 2015

\textsuperscript{44} Carbon trust ‘Floating offshore wind market and technology review, 2015
Further public support targeted at creating a long term market for the technology, and

Realised or expected cost reductions for floating wind.

Whilst the potential exploitable resource for floating wind is considerable in a number of markets that are actively investigating floating wind (UK, Japan and USA in particular, and more recently France), the commercialisation of floating is dependent on fixed offshore wind for two primary reasons:

- The rate of deployment of offshore wind (whether fixed or floating) is driven by energy policy concerning the targets and level of financial support (e.g. capital grants, revenue support) that are set by governments within the markets identified.

- In all of the markets there exists significant resource potential that could be exploited with fixed offshore technology.

When considered together these two reasons will result in a situation where, unless floating wind can demonstrate significant cost benefits when compared with the cost of exploiting fixed offshore resource in relatively shallow water, fixed is likely to continue to be the technology of choice for those developing offshore wind projects in the coming decade. Continued focus on fixed offshore technology may exacerbate the challenges faced by floating as fixed technology will be further improved and its costs further reduced.
5 Challenges and opportunities

In Section 4.4 the key areas where cost reduction is required for floating wind technologies were identified. Some of the cost reduction could be achieved through learning by doing that will deliver stepwise improvements if the number of projects that are rolled out increases but some direct technological improvements must be made in parallel if costs are to reduce rapidly.

5.1 Challenges

5.1.1 Technical challenges

The Offshore Renewable Energy (ORE) Catapult recently issued a Floating Wind Technology Assessment\(^45\) which presents interim findings based on research performed by DNV GL on behalf of the Crown Estate and ORE Catapult.

<table>
<thead>
<tr>
<th>Category</th>
<th>Technical Challenge</th>
<th>Mitigation</th>
<th>Technology Readiness Level (Research, Development or Demonstration)</th>
<th>Involved parties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>Currently available turbines are adapted from designs for use on fixed structures. There is a need to develop turbine designs specifically for use on floating structures, with particular emphasis on; • Design limits for rotation and acceleration of rotor nacelle assembly. • Sufficient and appropriate control systems</td>
<td>Challenge current design limits through engagement with turbine and component designers and manufacturers. Better understanding of cost-benefit of improvements, taking in to account complete system (turbine and support structure). Encourage collaboration between wind turbine designers and floating support structure designers to ensure optimisation.</td>
<td>At TRL 9+ Development and Demonstration of modifications/enhancements to mature technology used by fixed offshore developments</td>
<td>Turbine manufacturers (outside NL)</td>
</tr>
<tr>
<td>Support Structure</td>
<td>The support structures for current demonstration projects have not been fully optimised so do not demonstrate the potential for cost reduction from floating wind. The relationship between turbine rating and platform size is not fully understood leading to difficulty in determining the optimum turbine and structure combination. Fatigue design of structure and components is poorly understood due to lack of operational experience leading to conservatism in designs. Yards with manufacturing capability are not equipped for serial production leading to uncertain cost reduction potential in manufacturing. Moorings and Anchors are poor understood of the dynamic behaviour of moorings, particularly for shallow water (40 – 60m) leading to suboptimal mooring</td>
<td>Future demonstration projects should demonstrate the potential for cost reduction through optimisation, using learning from early projects to improve next generation designs. Develop understanding of relationship between turbine size and support structure through optimisation of designs and learning from demonstration projects. Improvements to design tools/methodologies and learning from monitoring and measurement of demonstration projects. Investigate how streamlined manufacturing can reduce costs Desk based and experimental testing and research in to the behaviour of mooring systems, with a focus on shallow water depths (40 – 60m).</td>
<td>TRL 7-8 Development and Demonstration of optimised technology solutions TRL 7-8 Research and Development of optimised technology solutions TRL 7+ Development of enhanced design tools based on full scale demonstration TRL8+ Development of commercial scale manufacturing facility TRL 4+ Research leading to improved understanding and design</td>
<td>Support structure designers, fabricators and turbine manufacturers Academia Turbine manufacturers and support structure designers to do development Universities, Research Institutes, Design Tool Developers Support structure designers in combination with fabrication facilities Research Institutes, Mooring suppliers</td>
</tr>
</tbody>
</table>

\(^{45}\) https://ore.catapult.org.uk/documents/10619/110659/Floating+wind+technology+assessment+June+2015/cb73c3f1-6331-4197-98c9-b10ba3d45d2f
<table>
<thead>
<tr>
<th>Design.</th>
<th>Engagement with oil and gas industry to understand how existing techniques can be adapted and lessons implemented.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of anchors and their installation is high</td>
<td>Investigation into innovative anchor systems/ shared anchor points</td>
</tr>
<tr>
<td>TRL 4+</td>
<td>Research leading to improved understanding and design</td>
</tr>
<tr>
<td>Large footprint for spread mooring systems creates potential for conflict with other operators in vicinity of installation</td>
<td>Engagement with relevant stakeholders to fully understand risks and mitigations to minimise risk to floating wind components and impact on other marine activities.</td>
</tr>
<tr>
<td>TRL 6+</td>
<td>Development of robust anchoring systems and installation techniques. Development of understanding of geotechnical investigation requirements.</td>
</tr>
<tr>
<td>TLP anchor performance is sensitive to soil conditions so increases risk and cost of installation</td>
<td>Development of a robust application of a specific solution</td>
</tr>
<tr>
<td>Research Institutes, Anchor suppliers and installation companies</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-1 and Table 5-2 summarise the technical challenges and possibilities for mitigation from the ORE Catapult document. The technical challenges faced by floating wind as it moves towards technological and commercial maturity, are identified across the following 6 major areas:

- Turbine developments,
- Support structure development,
- Mooring systems: moorings and anchors,
- Electrical infrastructure,
- Transport and installation,
- Operations and maintenance.

Added to the tables is an indication of the current TRL in each of the key issues to address in these areas, the type of projects relevant for its further development and the relevant parties that could address these technical challenges.
## MARKET STUDY FLOATING WIND

<table>
<thead>
<tr>
<th>Category</th>
<th>Technical Challenge</th>
<th>Mitigation</th>
<th>Technology Readiness Level (Research, Development or Demonstration)</th>
<th>Involved parties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>Currently available turbines are adapted from designs for use on fixed structures. There is a need to develop turbine designs specifically for use on floating structures, with particular emphasis on; • Design limits for rotation and acceleration of rotor nacelle assembly. • Sufficient and appropriate control systems</td>
<td>Challenge current design limits through engagement with turbine and component designers and manufacturers. Better understanding of cost-benefit of improvements, taking in to account complete system (turbine and support structure). Encourage collaboration between wind turbine designers and floating support structure designers to ensure optimisation.</td>
<td>At TRL 9+ Development and Demonstration of modifications/enhancements to mature technology used by fixed offshore developments</td>
<td>Turbine manufacturers (outside NL)</td>
</tr>
<tr>
<td>Support Structure</td>
<td>The support structures for current demonstration projects have not been fully optimised so do not demonstrate the potential for cost reduction from floating wind.</td>
<td>Future demonstration projects should demonstrate the potential for cost reduction through optimisation, using learning from early projects to improve next generation designs.</td>
<td>TRL 7-8 Development and Demonstration of optimised technology solutions</td>
<td>Support structure designers, fabricators and turbine manufacturers</td>
</tr>
<tr>
<td></td>
<td>The relationship between turbine rating and platform size is not fully understood leading to difficulty in determining the optimum turbine and structure combination.</td>
<td>Develop understanding of relationship between turbine size and support structure through optimisation of designs and learning from demonstration projects.</td>
<td>TRL 7-8 Research and Development of optimised technology solutions</td>
<td>Academia Turbine manufacturers and support structure designers to do development</td>
</tr>
<tr>
<td></td>
<td>Fatigue design of structure and components is poorly understood due to lack of operational experience leading to conservatism in designs.</td>
<td>Improvements to design tools/methodologies and learning from monitoring and measurement of demonstration projects.</td>
<td>TRL 7+ Development of enhanced design tools based on full scale demonstration</td>
<td>Universities, Research Institutes, Design Tool Developers</td>
</tr>
<tr>
<td></td>
<td>Yards with manufacturing capability are not equipped for serial production leading to uncertain cost reduction potential in manufacturing.</td>
<td>Investigate how streamlined manufacturing can reduce costs</td>
<td>TRL8+ Development of commercial scale manufacturing facility</td>
<td>Support structure designers in combination with fabrication facilities</td>
</tr>
<tr>
<td>Moorings and Anchors</td>
<td>Poor understanding of the dynamic behaviour of moorings, particularly for shallow water (40 – 60m) leading to suboptimal mooring design.</td>
<td>Desk based and experimental testing and research in to the behaviour of mooring systems, with a focus on shallow water depths (40 – 60m). Engagement with oil and gas industry to understand how existing techniques can be adapted and lessons implemented.</td>
<td>TRL 4+ Research leading to improved understanding and design</td>
<td>Research Institutes, Mooring suppliers</td>
</tr>
<tr>
<td></td>
<td>Cost of anchors and their installation is high</td>
<td>Investigation in to innovative anchor systems/ shared anchor points</td>
<td>TRL 4+ Research leading to improved understanding and design</td>
<td>Research Institutes, Anchor suppliers and installation companies</td>
</tr>
<tr>
<td></td>
<td>Large footprint for spread mooring systems creates potential for conflict with other operators in vicinity of installation</td>
<td>Engagement with relevant stakeholders to fully understand risks and mitigations to minimise risk to floating wind components and impact on other marine activities.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TLP anchor performance is sensitive to soil conditions so increases risk and cost of installation</td>
<td>Development of robust anchoring systems and installation techniques. Development of understanding of geotechnical investigation requirements.</td>
<td>TRL 6+ Development of a robust application specific solution</td>
<td>Research Institutes, Anchor suppliers and installers</td>
</tr>
</tbody>
</table>

Table 5-1: Technical challenges. The TRLs depend on the specific concept, this table represents a general view.
<table>
<thead>
<tr>
<th>Category</th>
<th>Technical Challenge</th>
<th>Mitigation</th>
<th>Technology Readiness Level (Research, Development or Demonstration)</th>
<th>Involved parties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Infrastructure</td>
<td>Lack of experience with dynamic power cables leading to conservative design</td>
<td>Research in to, and testing of, power cables subject to dynamic loading</td>
<td>TRL 4+ Research and Development of application specific solutions</td>
<td>Research Institutes, Cable suppliers</td>
</tr>
<tr>
<td></td>
<td>Lack of experience with substations on floating structures</td>
<td>Qualification of electrical components for use on floating structures, in particular for the inclinations and accelerations that they would be subject to.</td>
<td>TRL 7+ Full scale Demonstration</td>
<td>Substation suppliers in combination with support structure designers and fabricators</td>
</tr>
<tr>
<td>Transport and Installation</td>
<td>Lack of consensus on best approach to installation, e.g. use of special purpose or multi-purpose vessels.</td>
<td>Innovation focused on installation systems. Research in to the design of turbines and support structures for installation.</td>
<td>TRL 6+ Research leading to improved understanding and design</td>
<td>Research Institutes, Installation Contractors</td>
</tr>
<tr>
<td>Operation and Maintenance</td>
<td>Distance from shore and harsh environmental conditions limit availability for inspection and maintenance.</td>
<td>Investigate and develop remote inspection and maintenance systems.</td>
<td>TRL5+ Research and Development leading to improved or new solutions</td>
<td>Universities, Research Institutes, Operation and Maintenance Contractors</td>
</tr>
<tr>
<td></td>
<td>Methods for inspection and Maintenance are unproven</td>
<td>Prove the feasibility of methods for O&amp;M strategies concerning access to the floating substructures and major replacement, such as hook-off and tow-into harbour.</td>
<td>TRL5+ Research and Development leading to improved or new solutions</td>
<td>Operation and Maintenance Contractors, Installation contractors, Research institutes</td>
</tr>
<tr>
<td>Design Standards and Tools</td>
<td>Lack of installation and operational experience means that design drivers are poorly understood so designs may be conservative</td>
<td>Focus on better understanding of design drivers in demonstration projects, including analysis of observed behaviour and feedback to design</td>
<td>TRL 7+ Development of enhanced design tools based on full scale demonstration</td>
<td>Universities, Research Institutes, Design Tool Developers</td>
</tr>
<tr>
<td></td>
<td>Target safety levels (probability of failure) in design standards are not reflective of risk profile of floating wind, potentially leading to conservative design</td>
<td>Review of target safety levels in design standards to reflect risk profile of floating offshore wind, in particular with respect to quantity of hydrocarbons and unmanned status of structures.</td>
<td>TRL 7+ Research based on (limited) operational experience to determine appropriate safety levels</td>
<td>Universities, Research Institutes, Classification Agencies</td>
</tr>
<tr>
<td></td>
<td>Software tools that simulate the whole system behaviour are not fully developed or validated.</td>
<td>Demonstration projects and scale tests should be required to deliver high quality measurements for validation of design tools.</td>
<td>TRL 7+ Development of enhanced design tools based on full scale demonstration</td>
<td>Universities, Research Institutes, Design Tool Developers</td>
</tr>
</tbody>
</table>

Table 5-2: Technical challenges (continued). The TRLs depend on the specific concept, this table represents a general view.
5.1.2 Market barriers

In the recent study by the Carbon Trust\textsuperscript{46} market barriers affecting the development of floating wind were identified, these are presented in Table 5-3.

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perception that fixed-bottom offshore wind sites need to be exhausted</td>
<td>Demonstrate that LCOE for floating wind in deep water can be lower than</td>
</tr>
<tr>
<td>before industry moves to deeper floating wind</td>
<td>fixed-bottom foundations</td>
</tr>
<tr>
<td>Lack of long-term political support</td>
<td>Long-term political commitment, including tariff support for floating</td>
</tr>
<tr>
<td>Lack of awareness in industry of the technology options and LCOE potential</td>
<td>Public support for full-scale prototypes of the most promising</td>
</tr>
<tr>
<td>floating wind</td>
<td>concepts to demonstrate cost reduction potential.</td>
</tr>
<tr>
<td>Identification of the lowest cost concepts – more mature concepts may not</td>
<td>Independent cost comparison of the leading floating wind concepts,</td>
</tr>
<tr>
<td>be the most cost-effective</td>
<td>with demonstrations to validate cost potential</td>
</tr>
<tr>
<td>High cost for first prototypes/projects</td>
<td>Funding support from national governments</td>
</tr>
<tr>
<td>Financial risk of new technology (bankability)</td>
<td>Multi-megawatt scale offshore demonstrations</td>
</tr>
<tr>
<td></td>
<td>Engagement with banks on pilot and pre-commercial projects</td>
</tr>
<tr>
<td></td>
<td>Securement of insurance from reputable brokers/underwriters in offshore</td>
</tr>
<tr>
<td></td>
<td>wind industry and maintenance of unscathed track record</td>
</tr>
<tr>
<td>Lack of industry partners for innovators – developers and OEMs</td>
<td>Public support to validate the cost competitiveness of floating wind</td>
</tr>
<tr>
<td></td>
<td>concepts</td>
</tr>
<tr>
<td></td>
<td>Engage with turbine manufacturers through open and continuous dialogue</td>
</tr>
<tr>
<td></td>
<td>with floating wind community.</td>
</tr>
<tr>
<td>Lack of access to high quality simulation facilities at an affordable cost</td>
<td>Investment in test facilities</td>
</tr>
<tr>
<td>Availability of offshore test sites</td>
<td>Publically funded test facilities available to industry at reduced cost</td>
</tr>
<tr>
<td>Obtaining consent / grid connection</td>
<td>Early engagement with stakeholder and consent authorities to better define</td>
</tr>
<tr>
<td></td>
<td>differences between floating and fixed structures as well as similarities</td>
</tr>
<tr>
<td></td>
<td>and advantages</td>
</tr>
</tbody>
</table>

Table 5-3: Key market barriers identified by Carbon Trust in \textsuperscript{47}.

During the consultation for this study, many of the listed market barriers were mentioned also by the consultees. The high costs for prototypes or projects have been mentioned and connected to whether the current most mature concepts are the most cost-effective. The access to scale testing facilities is limited, as test at the basin are generally booked around 1.5 years in advance.

The overriding themes that can be drawn from the Carbon Trust report and the consultation exercise undertaken for this study are:

- Fixed offshore wind, as the incumbent technology, has yet to reach levels of deployment that make it necessary to consider other (riskier) solutions,


MARKET STUDY FLOATING WIND

- Proponents of floating wind i.e. technology developers, have yet to fully engage with either turbine OEMs or offshore wind project developers,
- As a result a compelling case has yet to be made for the long term politically driven financial support that will be required to commercialise floating wind technology in any one market.

5.2 Opportunities

5.2.1 A Dutch home market

In the Energy Agreement (Energieakkoord), market parties and the Dutch government agreed to the installation of 3500 MW extra installed capacity at a 40% cost reduction to be achieved in the period between 2014 and 2024. In 2015 the Route-map how to achieve this extra installed capacity has been announced: 5 tenders will be announced of 700 MW each, to be divided over two wind farms in each tender. One can see that for the announced tenders, water depths do not go beyond 40 m: up to 2023, the expected construction year for the last tendered wind farms, offshore wind turbines will not be placed in deeper waters.

<table>
<thead>
<tr>
<th>Tender Year</th>
<th>Windfarm zone</th>
<th>Water depth [m]</th>
<th>Distance to Coast [km]</th>
<th>Distance to port [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Borssele 1</td>
<td>17-37</td>
<td>30</td>
<td>65</td>
</tr>
<tr>
<td>2016</td>
<td>Borssele 2</td>
<td>17-37</td>
<td>38</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>South Holland coast 1</td>
<td>18-22</td>
<td>26</td>
<td>35</td>
</tr>
<tr>
<td>2017</td>
<td>South Holland coast 2</td>
<td>18-22</td>
<td>26</td>
<td>35</td>
</tr>
<tr>
<td>2018</td>
<td>North Holland coast</td>
<td>19-24</td>
<td>25</td>
<td>30</td>
</tr>
</tbody>
</table>

Over the entire Dutch EEZ the water depth does not go beyond 50 metres in depth. This limits the application of floating support structures, especially those concepts that need a considerable draft for their stability: the application for Spar buoy and Semi-sub concepts are usually mentioned to start at 50 metres water depth. The deeper waters are in the Northern corner of the Dutch EEZ

48 http://www.noordzeeloket.nl/
water where depths of around 45 metres are reached and application of Semi-sub floating support structures (requiring the least draught) are possible. However, the likely areas for deployment after 2023 are depicted in yellow in Figure 5-1: these areas will likely not exceed 40 metres, see Figure 5-2.

Some concepts boost technical feasibility for application to shallower waters, perhaps making application in Dutch waters possible. This concerns the TLP concepts. For instance the GICON-SOF TLP states technical feasibility for application in water depths from 17 to 500 metres. The 6MW prototype under development has a minimum draft of 25 metres\(^{49}\) and an estimated substructure weight of 1200t\(^{50}\). A comparable monopile will likely be lighter and is easier to serially produce; so even though application of a floating substructure in the Dutch EEZ is technically feasible, at the likely water depths for the Netherlands cost competitiveness to fixed wind is an issue.

To conclude, it is unlikely that the Dutch waters will offer a viable home market for the commercial application of floating wind technology and therefore floating related R&D or supply chain activity in the Netherlands should address the needs of markets elsewhere. Nearby markets are the waters in the North-North Sea and near the West coast of France and Portugal, as there the deep waters allow the application of floating offshore wind, see Figure 5-3.

This also has an impact on addressing the market barrier of offshore test sites as mentioned in the previous section. Several consultees mentioned that offshore test sites should have a representative water depth for testing the dynamic behaviour of a prototype, meaning test sites should offer water depths of at least 50 metres deep. The Dutch waters are therefore less suitable for offshore test sites.

Figure 5-2: Water depths in the Dutch EEZ (LLWS)\(^{51}\)

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\(^{49}\) https://www.sintef.no/globalassets/project/deepwind2014/presentations/e/adam-f_gicon.pdf

\(^{50}\) http://www.gicon-sof.de/en/technical-solution.html

\(^{51}\) http://www.noordzeeatlas.nl, last visit July 2015.
5.2.2 The Dutch supply chain

To assess the opportunities for the Dutch supply chain, the capabilities of the Dutch supply chain need to be compared to the technical challenges already discussed in section 5.1.1. Because the conclusion was drawn that a Dutch home market is unlikely, the focus lies on the challenges in the markets that are accessible to the Dutch companies, see Figure 5-4 for a graphical representation. This accessibility depends on the type of challenge: challenges in fabrication are dependent on markets in the vicinity, while design and engineering type of work depends on the openness of the potential market.

Figure 5-4: Mapping of the capabilities of the Dutch industry and the challenges in markets accessible for them.

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52 Source Acciona, 1Tech, DNV GL
DNV GL has made an initial assessment of the capabilities of the parties that are or could be involved in floating wind from an office located in the Netherlands, meaning that floating wind could provide value for economic activities in the Netherlands and therefore fits with TKI’s target of supporting a Dutch industry. This initial assessment can be found in Fout! Verwijzingbron niet gevonden. In this table the turbine is not included, as there are no major turbine manufacturers in the Netherlands. Instead the parts examined are the anchors, moorings, hull or structure, and electrical infrastructure. The table starts from basic R&D to detailed design, fabrication, installation and ending with the operation & maintenance. From this table one can see and note the following:

- In **R&D** there is a strong presence of capabilities related to the structure. Work in this field is strongly dependent on cooperation with the technology developers, and none of the major concepts (Hywind spar, WindFloat, Sway) that we see today are from Dutch companies. International cooperation for a global market is therefore key. Several companies are already actively involved in this field.

- In detailed design there is a strong presence within the Dutch capabilities, again dependent on international cooperation in a global market.

- In fabrication there are several companies that are capable of fabricating the hull. So far all floating structures in operation have been built as a one-off in a shipyard. For commercial deployment the structures need to be serially produced to reduce costs. The possibilities for this are dependent on the concept, as the main part of a spar buoy can be more easily serially produced by fabrication companies of tubulars, while the semi-sub and TLP concepts fabrication at shipyards will have to be streamlined. This field is strongly related to markets in the vicinity.

- In Transport & Installation there is a strong presence of Dutch market parties. This field is more dependent on markets in the vicinity.

- In Operation & Maintenance there are companies that could be involved on a strategic level and in execution of actual operation & maintenance, the latter being more dependent on the markets in the vicinity.
6 Conclusions

6.1 Introduction

Floating wind offers the potential for the offshore wind sector to become truly global, bringing previously inaccessible regions within reach and allowing site selection on the basis of optimum wind speed rather than depth of water. The technology has developed rapidly yet is still young, with major risks to be tackled before it can be considered technically mature enough to be commercialised. If floating wind becomes cost competitive with fixed offshore wind, there is potential to deploy floating technology in a range of markets. Dutch companies enjoy significant market share in the fabrication, installation and marine operations market for fixed offshore wind. If floating wind takes off then it will be important for these companies to build on this strong position.

This study set out to answer a number of research questions posed by TKI, conclusions are drawn in the context of each of the questions below.

6.2 Current status

1. What floating foundation technology options are available or under development?

Approximately 30 floating wind technologies have been identified although only a handful have been demonstrated at MW scale. The different technologies fall into three categories: ballast stabilised (spar buoys), buoyancy stabilised (semi-submersibles) and mooring stabilised (tension leg platforms). Small array demonstration projects are in planning for both ballast and buoyancy stabilised concepts.

2. What is the current state of the offshore wind floating foundation market (differentiated per geographic region)?

Floating wind technology solutions are being developed in Europe, the USA and Japan with single MW scale device demonstrators having been installed in Norway, Portugal and Japan. Smaller scale demonstrators have also been deployed in the USA, and Italy. At present no floating wind specific incentive exists in any market beyond the small scale array demonstration phase.

3. How is this market expected to develop over the coming 5 to 15 years?

The development of a market for floating wind technologies is strongly linked to the market for bottom fixed solutions. In virtually all of the regions where floating wind could be deployed there exists significant resource that can be exploited by bottom fixed technology which has already gained significant traction in some markets e.g. North-western Europe. The development of a floating wind market is dependent on demonstrating a clear route to cost reduction and so the success of the small array demonstration projects that are in planning is critical.

4. What is the current cost level and how is this expected to develop for various technologies?

Using the DNV GL cost model, applied to hypothetical bottom fixed and floating 800MW wind farms, the current cost level of floating wind solutions is estimated to be approximately 60% higher than bottom fixed solutions. The rate of convergence between the costs of fixed and floating is dependent on a number of factors but if floating is to become competitive it must demonstrate significant cost reduction in support structure, installation, moorings and anchors. A stated above, the success of the small array demonstration projects that are in planning is a critical next step as a positive outcome would define a clear route to cost reduction.
5. What is the position of Dutch companies in this market (Engineering, Manufacturing, Transport and Installation)?

DNV GL has made an initial assessment of the capabilities of the parties that are or could be involved in floating wind from an office located in the Netherlands. This initial assessment can be found in Fout! Verwijzingsbron niet gevonden., the findings can be summarised as follows.

In R&D there is a strong presence of capabilities related to the structure. Work in this field is strongly dependent on cooperation with the technology developers, and none of the major concepts (Hywind spar, Wind Float, Sway) that we see today are from Dutch companies. International cooperation for a global market is therefore key. Several companies are already actively involved in this field.

In detailed design there is a strong presence within the Dutch capabilities, again dependent on international cooperation in a global market.

In fabrication there are several companies that are capable of fabricating the hull. So far all floating structures in operation have been built as a one-off in a shipyard. For commercial deployment the structures need to be serially produced to reduce costs. The possibilities for this are dependent on the concept, as the main part of a spar buoy can be more easily serially produced by fabrication companies of tubulars, while the semi-sub and TLP concepts fabrication at shipyards will have to be streamlined. This field is strongly related to markets in the vicinity.

In Transport & Installation there is a strong presence of Dutch market parties. This field is more dependent on markets in the vicinity.

In Operation & Maintenance there are companies that could be involved on a strategic level and in execution of actual operation & maintenance, the latter being more dependent on the markets in the vicinity.

6.3 Challenges and Opportunities

6. What is the opportunity looking forward? Specifically regarding the water depths where floating foundations can be applied and for the Dutch industry.

Given the relatively shallow depths of Dutch territorial waters a significant home market for floating wind technologies is considered very unlikely.

However, as described above, given the position of the Dutch companies in this market there are good opportunities for Dutch industry to both support and supply to floating markets that may develop elsewhere.

7. What are the key problems to be addressed in the development of new floating foundation technology?

The technical challenges faced by floating wind as it moves towards technological and commercial maturity, have been identified across 6 major areas. In Table 6-1 an overview is given of the technical challenges discussed in this study.

Apart from these technical challenges, one of the key challenges for the development of offshore wind remains its economic viability; cost reductions are required if a market for offshore floating wind is to develop, especially for the support structure, installation, moorings and anchors.

The approach that a Dutch R&D programme could take to addressing the technical challenges is considered in the R&D Road Map that has been developed as part of this study.
Currently available turbines are adapted from designs for use on fixed structures. There is a need to develop turbine designs specifically for use on floating structures, with particular emphasis on:

- Design limits for rotation and acceleration of rotor nacelle assembly.
- Sufficient and appropriate control systems.

The support structures for current demonstration projects have not been fully optimised so do not demonstrate the potential for cost reduction from floating wind.

- The relationship between turbine rating and platform size is not fully understood leading to difficulty in determining the optimum turbine and structure combination.
- Fatigue design of structure and components is poorly understood due to lack of operational experience leading to conservatism in designs.
- Yards with manufacturing capability are not equipped for serial production leading to uncertain cost reduction potential in manufacturing.

Poor understanding of the dynamic behaviour of moorings, particularly for shallow water (40 – 60m) leading to suboptimal mooring design.

- Cost of anchors and their installation is high.
- Large footprint for spread mooring systems creates potential for conflict with other operators in vicinity of installation.
- TLP anchor performance is sensitive to soil conditions so increases risk and cost of installation.

Lack of experience with dynamic power cables leading to conservative design.

Lack of experience with substations on floating structures.

Lack of consensus on best approach to installation, e.g. use of special purpose or multi-purpose vessels.

Distance from shore and harsh environmental conditions limit availability for inspection and maintenance.

Methods for inspection and Maintenance are unproven.

Lack of installation and operational experience means that design drivers are poorly understood so designs may be conservative.

Target safety levels (probability of failure) in design standards are not reflective of risk profile of floating wind, potentially leading to conservative design.

Software tools that simulate the whole system behaviour are not fully developed or validated.

Table 6-1: Technical challenges identified and discussed in this study.
## APPENDIX A FLOATING FOUNDATION CONCEPTS

### A1 LIST

The Technology Readiness Levels (TRL) of the concepts were assessed by DNV GL in 2012 and 2014.

<table>
<thead>
<tr>
<th>Name</th>
<th>Approximate TRL level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Spar</td>
<td>TRL2</td>
</tr>
<tr>
<td>Aerogenerator X</td>
<td>TRL0-1</td>
</tr>
<tr>
<td>Blue H</td>
<td>TRL1</td>
</tr>
<tr>
<td>Concrete Star</td>
<td>TRL1</td>
</tr>
<tr>
<td>Deepwind</td>
<td>TRL1</td>
</tr>
<tr>
<td>DIWET</td>
<td>TRL1</td>
</tr>
<tr>
<td>Floating Hallade</td>
<td>TRL1-2</td>
</tr>
<tr>
<td>Gicon TLP</td>
<td>TRL4</td>
</tr>
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Name: Glosten Floating TLP Pelastar
Approximate TRL level: TRL4

Name: Hexicon Energy design
Approximate TRL level: TRL1-2

Name: Hitachi
Approximate TRL level: TRL0

Name: Iberdrola
Approximate TRL level: TRL1-2

Name: Goto FOWT
Approximate TRL level: TRL6

Name: HiPRWIND
Approximate TRL level: TRL1

Name: Hywind
Approximate TRL level: TRL8

Name: Ideol
Approximate TRL level: TRL1-2
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<tr>
<th>Name</th>
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<tr>
<td>Mitsui</td>
<td>TRL6</td>
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<tr>
<td>Mitsui Engineering&amp; shipbuilding</td>
<td>TRL1</td>
</tr>
<tr>
<td>Nautilus</td>
<td>TRL0-1</td>
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<tr>
<td>Ocean Breeze</td>
<td>TRL0</td>
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<tr>
<td>Mitsubishi</td>
<td>TRL2-3</td>
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<tr>
<td>Nautica AFT</td>
<td>TRL0-1</td>
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<td>NREL</td>
<td>TRL1</td>
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<td>Olav Olsen Stee / Floatgen</td>
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Name: Sway  
Approximate TRL level: TRL4

Name: TriFloater  
Approximate TRL level: TRL2

Name: Vertiwind  
Approximate TRL level: TRL1

Name: WindFlo  
Approximate TRL level: TRL2

Name: WindFloat  
Approximate TRL level: TRL8

Name: Windsea  
Approximate TRL level: TRL2

Name: 3Sphere TLP  
Approximate TRL level: TRL0
## APPENDIX B FLOATING PROJECTS

### B.1 List

<table>
<thead>
<tr>
<th>Status</th>
<th>Commissioning</th>
<th>Country</th>
<th>Project</th>
<th>Project capacity</th>
<th>Concept</th>
<th>Typology</th>
<th>Manufacturer</th>
<th>Developer</th>
<th>Turbine manufacturer</th>
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</thead>
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<tr>
<td>Operational</td>
<td>2009</td>
<td>Norway</td>
<td>Hywind demonstrator</td>
<td>1x 2.3MW</td>
<td>Hywind</td>
<td>Spar</td>
<td>Statoil</td>
<td>Statoil</td>
<td>Siemens</td>
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<tr>
<td>Operational</td>
<td>2011</td>
<td>Portugal</td>
<td>WindFloat-Phase1</td>
<td>1x 2MW</td>
<td>WindFloat</td>
<td>Semi-Sub</td>
<td>Principle Power</td>
<td>EDPR/Repsol</td>
<td>Vestas</td>
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<td>Sway</td>
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<td>Spar</td>
<td>Sway A/5</td>
<td>Sway A/5</td>
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<td>Kabashima (Goto Islands)</td>
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<td>VolturnUS 1:8 Prototype</td>
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<td>Semi-Sub</td>
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<td>Deep C Wind Consortium</td>
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<tr>
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<td>Japan</td>
<td>Fukushima FORWARD-Phase1</td>
<td>1x 2MW</td>
<td>Compact semi-sub</td>
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<td>Mitsui</td>
<td>Marubeni Corporation</td>
<td>Hitachi</td>
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<td>Under Construction</td>
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<td>Japan</td>
<td>Fukushima FORWARD-Phase2</td>
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<td>V-shape semisub</td>
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<td>MHI</td>
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Table 6-2: Floating wind projects in operation\(^{53}\).

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<tr>
<th>Status</th>
<th>Commissioning</th>
<th>Country</th>
<th>Project</th>
<th>Project capacity</th>
<th>Concept</th>
<th>Typology</th>
<th>Manufacturer</th>
<th>Developer</th>
<th>Turbine manufacturer</th>
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<tr>
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<td>2015-2016</td>
<td>Japan</td>
<td>Fukushima FORWARD-Phase2</td>
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<td>Under Construction</td>
<td>2015</td>
<td>Germany</td>
<td>GICON-SOF Pilot</td>
<td>2.3MW</td>
<td>GICON-SOF</td>
<td>TLP</td>
<td>GICON</td>
<td>GICON</td>
<td>Siemens</td>
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<tr>
<td>Consented</td>
<td>2015</td>
<td>France</td>
<td>FLOATGEN</td>
<td>2MW</td>
<td>Ideol</td>
<td>Semi-Sub</td>
<td>Ideol</td>
<td>FLOATGEN</td>
<td>Gamesa</td>
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<td>Consented</td>
<td>2015</td>
<td>Japan</td>
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<td>0.5MW</td>
<td>SKWID</td>
<td>Hybrid wind/wave</td>
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<td>France</td>
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<td>Semi-Sub</td>
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<td>EDF Energy</td>
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<td>Planned</td>
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<td>Portugal</td>
<td>WindFloat-Phase 2</td>
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<td>Principle Power</td>
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<td>Hywind Pilot Park</td>
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<td>Statoil</td>
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<td>USA</td>
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<td>Kincardine</td>
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<td>Dounreay</td>
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<td>TBC</td>
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<tr>
<td>Planned</td>
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<td>France</td>
<td>SEAREED (Groix)</td>
<td>6MW</td>
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Table 6-3: Planned floating wind turbine projects\(^{54}\).

\(^{54}\)http://www.carbontrust.com/about-us/press/2015/06/scotland-opportunity-to-lead-floating-wind
Please be aware that this is an initial assessment and it does not represent an exhaustive list of the market parties that could be involved in floating wind from a Dutch location. Not all parties have been contacted to list the capabilities.

**Legend**

- **Green**: Is already active in floating wind
- **Blue**: Could be actively involved in R&D and commercial projects
- **Black**: Could be actively involved in commercial projects

**Legend**

- **A**: Anchors
- **M**: Moorings
- **H**: Hull / substructure
- **E**: Electrical infrastructure
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