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Chapter 7

Offshore wind energy developments

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Introduction

Onshore wind power is becoming increasingly competitive with conventional fossil based electricity generation. However, offshore wind power is still much more expensive than onshore wind energy. The reasons for going offshore are many fold but mostly due to higher wind resources, less environmental impact and more available space. The drawbacks are increased operation and maintenance cost and added capital expenditure mainly due to the offshore support structures but also to increased costs for cabling, transportation and installation. Since offshore wind farms lately have been moving further from shore and into deeper waters the trend in cost is increasing as seen in the *Figure 14* below.

3. http://www.gl-garradhassan.com/assets/downloads/UK_Offshore_Wind_Charting_the_Right_Course.pdf

Substantial research and development is needed, to realise the Danish MegaVind[4] vision from 2010. The focus of RTDI needs to target the most cost competitive areas. These are: Integrated design, Site conditions, Support structures, Reliability and Operation and Maintenance (O&M), Project development and planning, Business Innovation and Standards and certification.

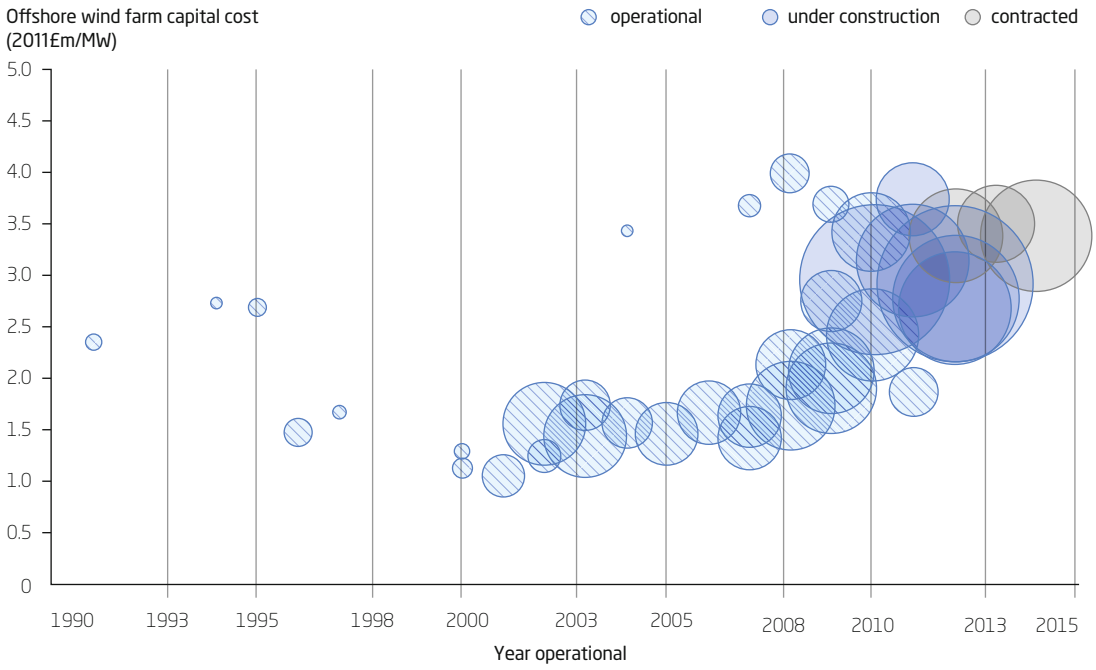
4. http://www.windpower.org/download/952/UK_megavind_report_ok.pdf

DTU has numerous research projects within the mentioned target areas. This chapter will give a brief overview of a few of the activities within offshore wind energy research, specifically 1) Support structure optimization, 2) Blade coatings for wind turbines; 3) Scour protection of foundations, 4) Offshore HVDC and 5) Offshore wind services.

Support structure optimization

Offshore wind turbines are mounted on costly bottom-fixed support structures such as monopiles and jackets. The newly funded Danish research council project – ABYSS – at DTU Wind Energy develops novel mathematical models, reliable numerical optimization techniques and software for optimal structural design of cost effective bottom-fixed offshore wind turbine support structures for all relevant water depths including deep waters in excess of 50m. Deeper water deployment expands the area for erecting wind farms at locations with superior wind conditions. The ABYSS techniques take dynamic wind and wave loads, cost, life expectancy, manufacturing, and functional requirements accurately into account. Available design tools are far from capable of performing industrial

Figure 14 – Cost trend for offshore wind farms.



Average cost in 2013 is about 3M£/MW.

Source: GL – Garrad Hassan[3]

structural optimization with this complex combination of requirements and large number of dynamic loads. The results of ABYSS will lead to a faster and more automated design process, with capabilities to design mass-producible and reliable support structures for deep waters and large wind turbines. The optimized designs have longer life expectancy and provide a decrease of cost of energy, contributing to achieving the national energy goals. The developed methods and tools are also immediately applicable to other industrial design in e.g. aerospace.

At the present stage the support structure optimization tool developed at DTU Wind Energy is able to optimize jacket and monopile support structures with static load putting constraints on fundamental eigen frequencies, displacement, and stresses. The graphical user interface for the jacket optimization tool can be seen in *Figure 15*.

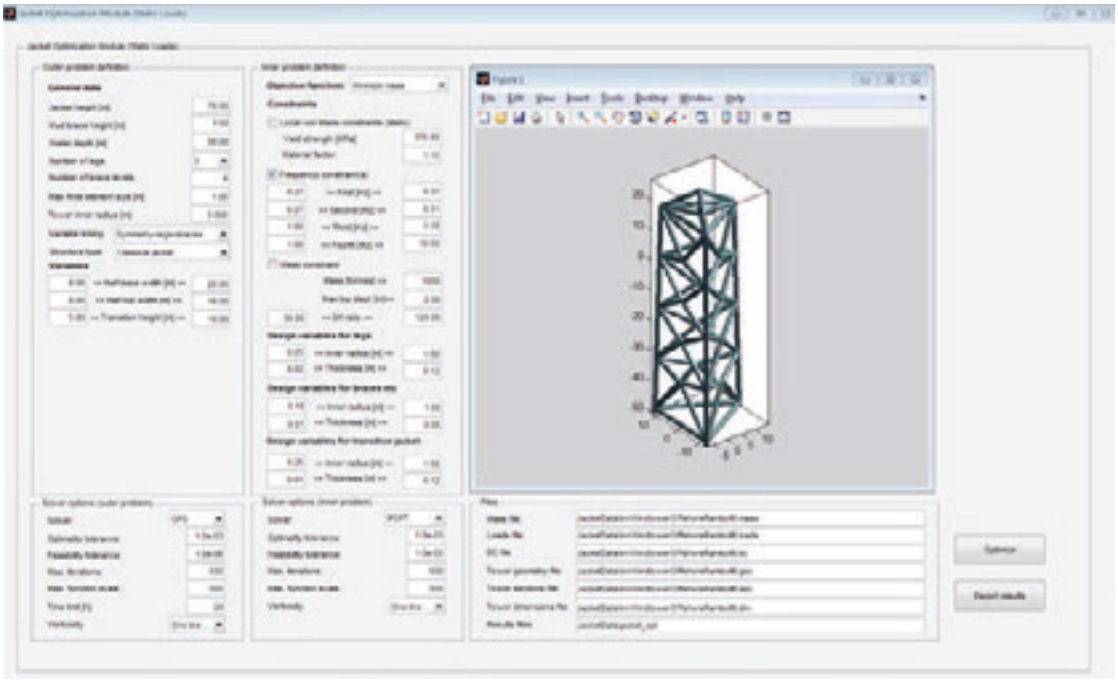
Following *Table 5*, which shows the potential CAPEX reduction for optimizing jacket support structures can be as much as 6.2%. For a future wind farm development of e.g. Kriegers Flak (which is 600 MW) and assuming a cost of 3M£/MW as previously mentioned, the potential cost reduction is $0.062 \times 600 \times 3 = 112$M£ or roughly 1 billion Danish Kroner.

Scour protection

The environments of most offshore wind farms are harsh, below as well as above sea level. To reduce costs without compromising safety it is important to have a detailed understanding of the entire structure of each wind turbine, including its foundation, with both static and dynamic loading from the integrated turbine system as well as interactions with the seabed under nominal and extreme conditions. The foundation makes up about one third of the total capital cost of a wind turbine, so it is not surprising that much research has been done to understand the interaction between the water flow, the seabed and the structure itself.

A complicating factor is the fact that the seabed usually consists of loose material – sand or silt – which moves under the influence of waves and currents. In some cases, large-scale sand waves may move across

Figure 15 – Graphical User Interface for the JacketOpt structural optimization tool.



Graphical User Interface for the JacketOpt structural optimization tool developed at DTU Wind Energy. This will include manufacturing constraints at the end of the project ABYSS.

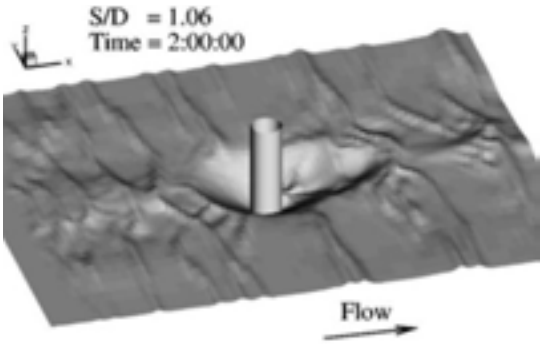
Table 5 – Potential Levelized Cost of Energy (LCoE) reduction for jacket design.

Potential Levelized Cost of Energy (LCoE) reduction for jacket design, split into CAPital Expenditure (CAPEX), Operational Expenditure (OPEX) and Annual Energy Production (AEP).

Source: BVG Associates [5]

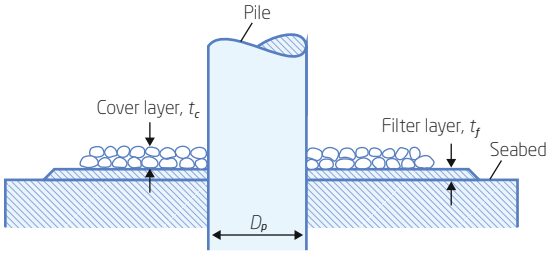
	Maximum technical potential impact				Anticipated Impact FID 2020			
Innovation	CAPEX	OPEX	AEP	LCOE	CAPEX	OPEX	AEP	LCOE
Improvements in jacket manufacturing	-4.2%	-0.6%	0.08%	-3.0%	-3.0%	-2.9%	0.05%	-2.0%
Improvements in jacket design	-1.4%	0%	0%	-09%	-0.9%	0%	0%	-0.6%
Improvements in jacket design standards	-0.6%	0%	0%	-0.4%	-0.3%	0%	0%	-0.2%
Total					-4.0%	-0.4%	0.05%	-2.8%

Figure 16 – Numerical simulation.



Numerical simulation (using a k-omega turbulence model) of a scour hole around a model monopile. In this case the scour has grown until it reaches equilibrium. [9]

Figure 17 – Scour protection around a monopile. [11]



5. http://www.bvgassociates.co.uk/Portals/0/publications/BVG%20TCE%20Technology%20work%20stream%20report%20120525.pdf

the seabed with wavelengths of the order of 10–100 m and heights of 0.5–5 m.

Foundation structures may be of four types: monopiles, tripods, jackets, and gravity bases. Monopiles are used for shallow waters (up to say 20–30 m deep), and the other types in deeper water. For all types of foundations there is a risk of heavy scour around the structure (*Figure 16*).

Scour threatens the stability of the turbine structure, so these structures are almost invariably surrounded by rocks to protect them (*Figure 17*). However, foundations without scour protection are sometimes used. [13]

Important in the design of the foundation and of the complete turbine structure are:

1. maximum mechanical load, which determines the size of the foundation and the depth to which it must extend below the seabed;
2. fatigue load, which sets the wall thickness of the foundation elements; and
3. eigenfrequencies (natural frequencies) of the complete structure, which influence the operation of the turbine itself.

On a site where scour protection is not used, or has not yet been installed, the depth of the scour hole around the foundation strongly influences these three factors. Moreover, the depth of the scour hole changes continuously as the seabed around the foundation experiences alternate scour and backfilling in an ever-changing climate of waves and currents. [12]

Where scour protection is used, the hydrodynamics describing the flow around the protection are complex, involving interactions between the water flow, the structure and the seabed. The design variables are the thickness and extent of the rock layer, the size of the rocks, and the thickness of the so-called

filter layer between the seabed and the covering layer of rocks.

Potential failure modes include sinking of the whole protection structure into the seabed, [11] and breakup of the cover layer as rocks are removed by the current, either across the top surface of the cover layer or around its edges ("edge scour"). [8] Also important are various soil processes, including sand waves and interactions between the seabed and the full depth of the foundation.

This set of problems offers great challenges to be understood through physical experiments and numerical modelling. A large-scale research programme to address these issues, Seabed Windfarm Interaction, was funded by DSF/Energy and Environment from 2008 to 2012. It was coordinated by B.M. Sumer, one of the authors of this chapter (http://sbwi.dhigroup.com).

Issues related to scour and scour protection are also on the agenda of MERMAID, a new large-scale EU project (Innovative Multi-purpose Offshore Platforms: Planning, Design and Operation; http://www.mermaidproject.eu/), which is coordinated by DTU Mechanic's Fluid Mechanics, Coastal Engineering and Maritime Engineering section. The coordinator is Professor Erik Damgaard Christensen (edch@mek.dtu.dk).

Finally, reference [10] discusses interaction between flows, structures and the seabed, including scour and scour protection, with a view to identifying the state of the art and current research challenges.

Blade coatings for wind turbines

Erosion of industrial materials by impacting water droplets is a well-known event. Already during the 1940s, with the development of the aeronautical industry, it was observed that exposure to rain was the origin of severe material damage. Likewise, blades in wind turbines are exposed to rain erosion. Research in this field is growing, driven by the fast development of the wind power industry during the last 10–15 years. The size of wind turbines has increased dramatically in recent years. Today turbines up to 8.0 MW and over 160 m rotor diameter are available, where the tip velocity of the blades can reach a linear speed close to 100 m/s.

In the case of offshore wind turbines, blade erosion is particularly problematic; the repair or the replacement of blades is very costly. Due to the presence of sea salt aerosols in the air, blade erosion rates for offshore wind turbines are approximately twice as high as the rates observed on inland wind turbines. As an example, over the past three years, more than 200 blades on 80 wind turbines have been repaired at the wind turbine park Horns Rev 1 off Blåvands Huk in Denmark [1]. The wind turbines were put into operation in 2002. Repairs have also taken place at other wind turbine parks: in Denmark at Rødsand and Middelgrunden, in Sweden at Lillgrund, in Germany at Baltic 1, in Britain at Barrow, North Hoyle, Kentish Flats, Scroby Sands, Thanet, and Robin Rigg, and in the Netherlands at OWEZ [1]. In addition to maintenance penalties, mechanical damage to the wind blades reduces the electrical efficiency of the wind turbines. Wind tunnel experiments estimate a 5% reduction of the power efficiency, depending of factors such as the type and degree of surface roughness of the blade [1].

Wind turbine blades are primarily made of fiberglass reinforced polymer composites. Skins are typically double-bias or triaxial fiberglass and the core is made of balsa or some kind of foam structure. Epoxy-based materials have been the preferred choice of binder due to their high strength, easy production and low cost. Carbon fibres are often used for local reinforcement. Blade composites are vulnerable to impact of solid particles (e.g. sand or insects) and rain droplets. Ultraviolet radiation and large temperature fluctuations can also damage the blades.

The use of high performance blade coating systems provides efficient and cost-effective protection against rain erosion. These coating systems have the ability to absorb the energy from impacting droplets. Current coating systems consist, typically, of a putty layer which is applied for filling pores in the composite substrate, a primer to secure good adhesion of the subsequent coat and a flexible topcoat, usually a polyurethane based formulationn [2].

Although there is no precise data available, a substantial fraction of the new large-blade wind turbine installations use blade coating systems. However, commercial high performance blade coating technology is relatively recent and performance data for long term exposure (>15 years) are not available.

The preferred method for evaluating rain erosion has been the so-called "whirling arm" test, developed by the Radiation Laboratory at MIT in 1946 [3]. Fundamentally, the whirling arm consists of a rotor, 2 m in diameter, rotating in an imposed artificial rainfall. Erosion data obtained in the whirling arm setup for polyurethane and neoprene coatings correlated very well with actual flight test [4,5]. In recent years, the whirling arm rig has been used to test coating systems for wind turbine blades. Tip speed of a wind turbine blade can presently be up to 100 m/s, but in the whirling arm rig up to 150 m/s rotor tip speed is used for accelerated testing [6]. Whirling arm tests last for a few hours and in most cases three samples, one on each rotor blade, can be tested simultaneously. It is not clear that in the case of wind blades the accelerated whirling arm test will provide representative data (3 hours of accelerated "heavy rainfall" versus up to 20 years natural exposure), but in absence of alternatives the whirling arm test has become a acknowledged test method for the approval of coating systems for wind blades. However, we understand that coating companies do not have whirling arm equipment available in-house and therefore must rely on external laboratories for the testing of their coating systems. Consequently, it is of utmost importance to design, construct and run simple laboratory erosion setups. The latter may be used for the initial screening experiments of blade coating systems prior to the final approval in the whirling arm rig. The setups must involve low capital and operational costs, have low footprints, be able to run many samples simultaneously and, most importantly, must be able to produce data that correlates satisfactorily with the experimental data obtained with the whirling arm test [6]. Previous attempts of erosion setups are reviewed by Zhang *et al.* [6].

In addition to novel accelerated test methods and their correlation against whirling arm or full-scale wind turbine data, blade coatings need to be improved to withstand the aggressive conditions present off-shore. This could for instance involve novel binder systems with the proper elastic properties and special additives for enhanced coating cohesion. Furthermore, proper protection of steel towers and foundations for wind turbines by anti-corrosive coatings must also be secured, but this field is more mature with barrier coating systems being the typical choice of protection [7].

High performance blade coatings can maintain optimal electrical efficiency and reduce maintenance work on off shore wind turbines significantly. Consequently, blade coatings are an important factor to take into account when planning the establishment of new wind turbine parks offshore.

Offshore HVDC

Wind farms supply power to the grid at high voltages (>72.5 kV), while the turbines within a single wind farm are interconnected by a "collection grid" at medium voltage (≤72.5 kV). So far, almost all offshore wind farms have used standard alternating current (HVAC) connections to bring their power ashore, but these are limited in length to 80–100 km, based on the active power capacity of the cable.[14] Wind farms located at greater distances offshore require high voltage direct current (HVDC) connections.

Grid connection point to wind farm platform

HVDC for point-to-point power transmission from wind farm to grid connection is beginning to be used, for example at two offshore sites in Germany: BorWin1 HVDC system (400 MW over 200 km, to the BARD Offshore 1 wind farm) and Dolwin1 HVDC system (800 MW over 165 km, to the Borkum West II wind farm, so far). The converters used to connect wind farms are of the voltage source controlled (VSC) type; in particular, modular multilevel converter (MMC) technology offers good performance. Converter technologies are available for power transmission up to 1 GW.

Wind farms connected to the grid through HVDC converters can play an important role in supporting the grid performance, even under unsymmetrical conditions, though it has to be remembered that the power required for frequency support of the

grid must come from the wind. Converters can also contribute to short-term stabilisation if they are combined with suitable energy sources. However, a change from traditional mechanical inertia – in the form of rotating mass in turbines and generators in the power system to converter-based "inertia" requires investigation of the consequences. A converter designed to compensate for missing rotating inertia from power generators requires the possibility of large units for energy storage. New technologies like supercapacitors and superconducting magnetic energy storage (SMES) may be able to meet this need, but will require considerable research effort before they can be used in practice.

Another supportive function of a VSC converter is in connection with faults. With a suitable control scheme the converter can ensure fast and robust fault ride-through (FRT). [15]

A very challenging area of offshore HVDC transmission is the need for multi-terminal HVDC systems. These would be required, for instance, to connect multiple large wind farms or to operate them as part of a grid with multiple international interconnectors. This topic requires research on converter control, protection systems and breaker technologies, plus investigation of how to implement these in different grid configurations.

HVDC collection grid

The use of HVDC for the collection grid within the wind farm seems an obvious idea, bearing in mind that DC available in all wind turbines with a converter after the generator. There are, however, many challenges to consider. [16] The main concern is the lack of DC voltages sufficiently high (30–60 kV) to minimize losses in the collection grid.

Solutions could include high-voltage generators combined with suitable series, parallel or hybrid connections between the turbines. Depending on the chosen topology, this would require either voltage source controlled (VSC) or current source controlled (CSC) converters. If the generator voltage is not sufficiently high, DC–DC step-up converters can be used to reach medium voltage level. These converters are readily available, but such a system may have no advantages compared to the conventional arrangement in which a DC–AC converter is followed by a transformer to increase the voltage. On top of these considerations, control and protection of an HVDC collection grid would pose a large number of challenges comparable to the ones in multi-terminal HVDC transmission grids.

Offshore Wind Services – perspectives from around the North Sea

For the purposes of this section Offshore Wind Services (OWS) are the services that are needed to install, operate and maintain and decommission or repower an offshore wind farm through its life cycle. In other words OWS comprises is the Balance of Plant services as well as Operations and Maintenance of the offshore wind turbines and other equipment of the farm. There is a wide industry consensus that the offshore wind industry needs to work towards lower Levelized Cost of Energy, and by extension lower life-cycle cost, to remain attractive and competitive option in the energy mix. Offshore wind is inherently costly in terms of the capital cost; up-front capital investment is up to twice that of an onshore farm [17], [18]. Over the life cycle of an offshore farm OWS comprise up to 46% of the life cycle cost of the farm including up-front investment and installation, while the actual O&M cost is estimated between 25–28% of total LCoE [18]–[20].

The difference between LCoE onshore and offshore is largely explained by environmental factors; for offshore, equipment have been specifically engineered for the marine environment, and installation as well as operations and maintenance (O&M) have to be performed on water, frequently with specialized vessels [17],[18]. Nevertheless it is expected that OWS will in its own part contribute to lowering LCoE.

In this section we discuss some of the cost drivers and challenges for OWS and opportunities to lower the cost through research, development and innovation, and lay out main areas for improvement for OWS. This section is based on data gathered within a project called European Clusters for Offshore Wind Servicing (ECOWindS, 2012–2015, see www.ecowinds.eu for more information), and

during interviews at EWEA Offshore 2013 and EWEA Annual Event 2014 (approximately 20 interviews on the exhibition floor).

We can break down the challenges for OWS to technical and organizational/business, which have some overlap. The OWS can be further divided to two main phases, installation and operation. The major technical challenges tend to revolve around lack of technical standards relating to key interfaces of components both in the installation phase and during operation. These interfaces include non-standard technical interfaces between the major componentry, but also non-standard tower access solutions, boat landings and helipads to name concrete examples. The flipside of the technical coin is technical and other standards that relate to humans interacting with the componentry. Presently, for example, O&M workers have to be trained and certified for each technical platform separately. Often also multiple overlapping if not interchangeable Occupational Health and Safety (OH&S, often related to Health, Safety, Environmental and Quality – HSEQ – policies) training and certifications are required for crews working on same equipment in different jurisdictions.

Two intertwined underlying challenges that exacerbate these issues are complexity of projects in terms engineering and delivery in complex value network and a lack of communication both horizontally and vertically in the value network between suppliers, original equipment manufacturers (OEMs), service providers, contractors, developers and operators. Complexity and poor communication in turn have their own effect to resource congestions and bottle necks in delivery, both in terms of availability of adequately specified equipment, ports and vessels as well as skilled and qualified labor.

The ECOWindS consortium is working closely with industry stakeholders on a roadmap to alleviate these challenges. The process includes an analysis of regional capabilities, setting goals and basic strategy for OWS and then populating that strategy with an action plan. The work is in progress at the time of the writing, and we present some preliminary conclusions.

The initiatives that have thus far been influenced by the ECOWindS are the Cost Reduction Platform initiated by Offshoreenergy.dk (Sommers, 2014) and the joint effort between DONG Energy and Atkins to design a standard inter-array sub-transformer station ("DONG Energy awards new contract for wind farm substation design to Atkins," 2014; Juul, 2014).[6]

The most important short to mid-term goal for the offshore wind industry is lowering the LCoE. There is a broad consensus that this is achieved through

6. Sommers, M. (2014). Knowledge-sharing is the way forward. *ON/OFF NEWS – Renewables*, 14.

DONG Energy awards new contract for wind farm substation design to Atkins. (2014, April 8). London, UK.

Table 6 - Challenges for OWS to technical and organizational/business.

Level/Phase	Installation	Operation
Technical	Depth and distance raise OWS cost and make installation more sensitive to weather windows. (Depth affects cost of foundation and installation in particular, distance affects both installation and operation)	
	Non-standard electro-mechanical interfaces	Non-standard interfaces such as boat landings and helipads Reliability of some key components (depending on mfg. OEM)
Non-technical	Planning, zoning and permitting delays; grid connections and associated project management cost overruns Dock and port availability Availability of vessels; competition with oil&gas industry over the resources	Need for overlapping but separate technical and safety training and certifications

industrialization, i.e. scaling up the volume of production and installation and leveraging the learning effects, and standardization along the value chain. Several addresses in EWEA Offshore 2013 argued that the industry is on track to achieve the targets of cost reduction by approximately 40% by 2020.

These targets are commonly shared within OWS. Within this framework, the main thrust of action is proposedly organized to two three intertwined work streams on; 1) standardization in terms of technology, interfaces as well as OH&S and qualifications, 2) setting up communication and knowledge exchange within the OWS value chain to enable streamlining operation and innovation towards cost saving solutions, and 3) securing skills and qualifications necessary to provide OWS safely, effectively and efficiently.