Offshore Wind Energy: Technology Opportunities and Challenges

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Abstract. The global Offshore Wind Energy (OWE) industry is rapidly growing as the offshore wind resource has huge potential and is advantageous in many countries with the technology solutions becoming more cost-competitive. OWE simultaneously helps the reduction of greenhouse gas emissions, an increase in energy security and diversity, creates jobs, and promotes sustainable development. Various enterprise opportunities and jobs will be created from the development of the supply chain, surveying and assessment of resource and environment and from maritime ports and logistics. These opportunities have been themselves challenges for the OWE industry. A number of measures to overcome those challenges are discussed in this paper. Offshore wind resources, marine ecology and seabed habitats urgently need to be surveyed and assessed at nationwide scales in order to plan zones for windfarm development, ecological conservation and maritime logistics. Advanced tools including LIDAR, coupled atmosphere-ocean models, surface heat flux models among others, and the use of Marine Spatial Planning and the study of the existing frameworks in other countries are recommended. Identifying the larger contribution areas of the supply chain and their bottlenecking challenges, detail costs breakdown, and the use of integrated and coupled models for analysis and design and control measures can effectively enable cost reduction. The supply chain and projects should be designed for the different offshore environment. Operational policies and technologies and energy storage can mitigate the dispatch-down of wind energy. A multi-contracting strategy is suggested for large utilities and the EPCI contracting for the independent or less experienced developers.

Keywords: Offshore wind energy · Opportunities · Technical challenges
Supply chain · Marine Spatial Planning · Cost reduction

1 Introduction

1.1 Global Concerns in Energy Security and Climate Change

Energy security is becoming globally critical. British Petroleum (BP) recently reported that the global proved oil reserves are sufficient to meet only 50.6 years of global production at 2016 levels [1]. The proved reserves are generally taken to be those quantities that geological and engineering information indicates with reasonable

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certainty can be recovered in the future from known reservoirs under existing economic and operating conditions. The data series for total proved reserves does not necessarily meet the definitions, guidelines and practices used for determining proved oil reserves at a company level [1]. The history and distribution of global proved oil reserves [1] shows that although there are various exploration activities, the global amounts have not been considerably rising, the reserves in most of regions are decreasing whereas global oil consumption is continuously increasing.

The global proved natural gas reserves are sufficient to meet only 52.5 years of global production at 2016 levels [1]. The history and distribution of global proved gas reserves [1] shows that most of regional reserves are significantly decreasing. The world's largest reserves are in Middle East that drop from more than 400 years in 1990s to just over 120 years in 2016. The reserves in North America in 2016 are sufficient for only 15 years while the global consumption of natural gas has increased 70% from the 1991 level. Coal has been the most common fossil fuel for electricity generation and necessary for steel production and cement manufacturing. However, the proved coal reserves are sufficient for only 153 years of global production [1].

Global warming from the emissions of greenhouse gases is another major concern. Fossil-based energy is facing with not only a resource limit but also serious environmental impacts, and nuclear energy has highly-potential risks with waste disposal difficulty. Energy technology has thus been switched to renewable and clean sources such as sun, wind, biological processes, waves, tides and currents. Solar and wind are the fastest growing renewable energy generation sources [2]. Wind seems to be the most reliable and practical, with its annual increase rate of 25–30% [2]. Wind power contributes greatly to the reduction of greenhouse gases, with 0.5 Gt CO_2 reduction (9.2%) of CO_2 emissions in 2020 and 3.0 Gt CO_2 reduction (7.8%) in 2050 [3]. The CO_2 emissions of wind energy in general and offshore wind in particular is the lowest among the energy sources [4].

1.2 Development Progress of Offshore Wind in the World

Onshore wind energy is currently near the development limit in some countries due to visual and noise impact constraints that make it increasingly difficult to find appropriate sites for future growth [2]. Offshore wind energy developments have greatly reduced visual impacts, less turbulence, and lower noise constraints allowing higher turbine rotor speeds and larger turbines [2]. Moreover, offshore wind energy possess a number of properties enabling significant cost reduction such as higher full-load hours per year, longer lifetimes and higher electricity production. Offshore wind power plants can produce up to 50% more electricity than their onshore cousins, due to higher and steadier wind speeds [2]. A worldwide wind atlas based on data from about 8000 locations [5] where wind speeds were calculated at 80 m illustrates the potential of global offshore wind resources. Constructions of offshore wind turbine plants is feasible as large offshore turbines can be transported by barges or ships. Land-based wind farm capacity is limited in scale while offshore farms with more than 100 MW capacities are possible [2]. Moving offshore is said to be driving the wind energy technology development [3].

Offshore wind is becoming a global market place, with major contributions from countries such as the United Kingdom (UK), Germany, China, Denmark, The Netherlands, Belgium, Sweden, Vietnam, Japan, South Korea, and the United States (US) gaining market share as shown in Fig. 1 with data sourced from the Global Wind Energy Council [6]. Europe has been a leader in offshore wind, with circa 90% of the current global installed capacity [6]. There was a record in offshore wind in Europe in 2017 where 3.148 GW additional net was installed and grid-connected and twice as much as in 2016, 4% higher than the previous record in 2015. That contributed to a total capacity of 15.78 GW deployed in European waters, and a further 2.9 GW of capacity under development [7].

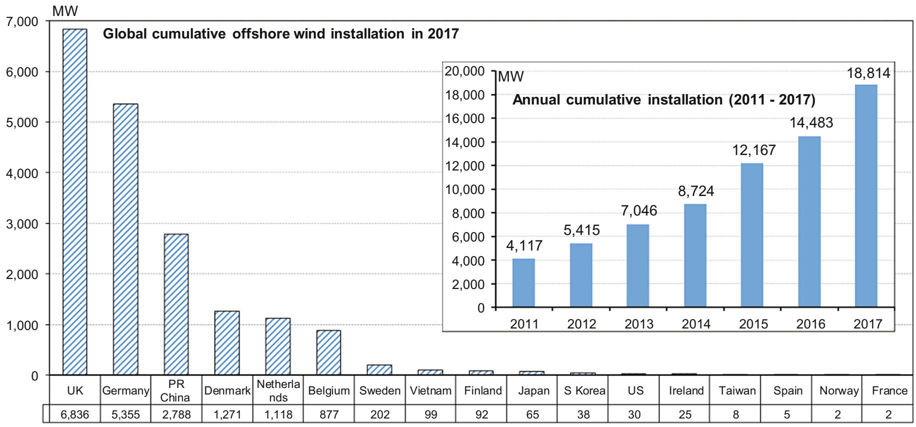

Fig. 1. Global cumulative offshore wind capacity 2017 and annual cumulative capacity (2011–2017).

1.3 Asia Pacific and Vietnam Context and Status

The history and distribution of global proved oil reserves [1] shows that the amount in the Asia Pacific region is sufficient for only 18 years. Whereas, the oil consumption in the Asia Pacific region is continuously increasing from 20% of the world total in early 1990s to 35% in 2016. Specifically, the regional oil proved reserve/production ratio in 2016 is 16.5, which is lowest in the world [1]. The region's oil proved reserve share of 2.8% in the global total in 2016 is also the lowest figure [1] whereas 60% of the world's people live in Asia [8]. The share of total oil proved reserves, oil proved reserve/production ratio, and the share of world population are respectively 13.3%, 32.3 and 6% in North America, and 9.5%, 24.9 and more than 10% in Europe and Eurasia. The figures in the Middle East are 47.7% and 69.9% and in Africa are 7.5%, 44.3, and 17% [1]. The proved natural gas reserves in Asia Pacific are sufficient for only 30 years production at 2016 levels [1] whereas the consumption on natural gas in the Asia Pacific region increases five times of the 1991 level. Coal reserves in the region have been sharply decreasing from 250 years in 1996 to less than 100 years in

2016 [1]. Those facts disclose the severity in the security of oil, natural gas and coal supply problems in the region.

The global concerns in energy security and climate change and the more serious context in the region are inevitable in Vietnam with a rapidly developing economy and large and rising population. Given the fact that the country possesses 3400 km of coastlines and more than one million km^2 of seabed in the exclusive economic zone (EEZ), the development of offshore wind energy in Vietnam potential and necessarily should be studied. This paper therefore aims at first highlighting opportunities in the development of offshore wind energy including energy security for both electricity and gas, synergy with or replacement of offshore oil and gas platforms, jobs creation and supply chain, and improvement of environment quality. The challenges to the development of offshore wind energy and their potential solution approaches are then the focuses.

2 Opportunities for the Development of Offshore Wind Energy

2.1 Advantageous Resource Allowing Potentially Lower Cost of Energy

Offshore wind speeds are relatively uniform with the lower variations and turbulence, it reduces wear of the offshore wind turbine components and consequently increases their lifetime. Moreover, due to the lower surface resistance, wind speeds over offshore sea surfaces are typically 20% higher than those over nearby lands, which is proportional to a 45–60% increase in the power captured. Thanks to steadier ocean climates, the full-load hours per year of offshore wind turbines are higher than those of the onshore ones. Also, the wake effects in offshore wind farms is smaller at higher wind speed that offers another significant benefit in allowing higher density of wind turbines [9].

Previous research has shown that onshore wind energy resources deployed at large spatial scales are limited by the energetics of the atmosphere [10]. Whereas the mean climatological surface ocean wind speeds are, on average, 70% higher than on land and highest within the mid-latitude wind belts in each hemisphere [10].

Offshore wind energy availability is timely as it is typically stronger during the day, allowing for a more stable and efficient production of energy when consumer demand is at its peak [11]. Most land-based wind resources are stronger at night when electricity demands are lower [11]. Those can be explained by the sea and land breezes resulted by the differential heating of land and water surfaces by incoming solar radiation as depicted in Fig. 2. This causes the air to rise over the land in daytime and an increase in the pressure over the land relative to that above the water at altitudes of approximately 100–200 m. At night, the temperature differences between land and water are smaller, the reverse circular flow due to land breeze has a lower speed [12].

The advantages of offshore wind mentioned above have been observed in practice. The projected capacity factor calculated for the Irish Oriel offshore wind farm is as high as 44.3% based on Siemens 6 MW turbines [14]. The capacity factor of the Hywind floating offshore wind farm in Scotland in operation since October 2017, is more than 60% leading to its over expected operation and availability as in Table 1 [13]. There

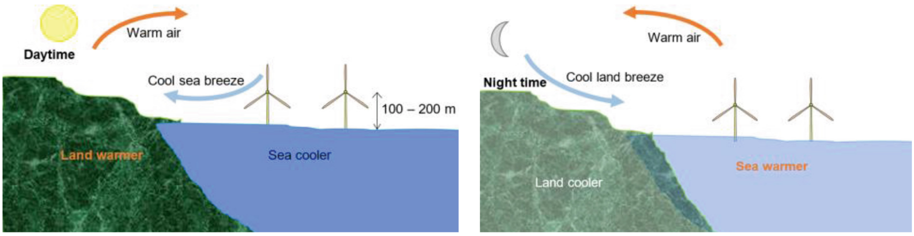

Fig. 2. Daytime sea breeze strengthening offshore wind (left) and nighttime land breeze (right).

has been no damage or instability in the Hywind turbines even in the Hurricane Ophelia with recorded gusts of 125 km/h in October 2017, and the Storm Caroline with gusts in excess of 160 km/h and waves in excess of 8 m arrived in early December 2017 [13]. This demonstrates that the wind turbine technologies and structure solutions have ensured both survival and service after extreme environment events.

Table 1. Hywind Scotland generation and availability November 2017–February 2018 [13].

Month	Generation vs. budget	Wind speed vs. expected	Availability vs. budget
11/2017	111%	117%	97%
12/2017	102%	102%	101%
01/2018	108%	97%	108%
02/2018	113%	104%	109%

2.2 Security of Sustainable Supply or Both Electricity and Gas

A concept to facilitate a large penetration of wind energy in the country, overcoming some of constraints to its deployment scale and value by integrating with hydrogen systems has been investigated [15, 16]. Furthermore, the use of wind-generated hydrogen in the transport and heat sectors will have a substantial contribution to the abatement of CO_2 and other emissions. A study to propose a pilot project for demonstrating and testing the hydrogen systems integrated with onshore wind farms in Ireland is recently reported [17]. Figure 3 shows a production concept of electricity and hydrogen from offshore wind that has been developed [18]. Also a power-to-gas (P2G) system using hydrogen to react with CO_2 increasing the methane output [19] that economically demonstrates the co-location opportunities of hydrogen production with biogas has been researched.

2.3 Synergy with or Replacement of Offshore Oil and Gas Platforms

The synergy with or replacement of offshore oil and gas platforms is another potential and cost-effective solution for offshore wind farms to ensure future energy fuel and utilise a part of the existing infrastructures, operation and maintenance services [20]. For short term scenarios such as for the North Sea [21], a pilot can be set-up to connect a wind farm to an existing platform that otherwise would be decommissioned.

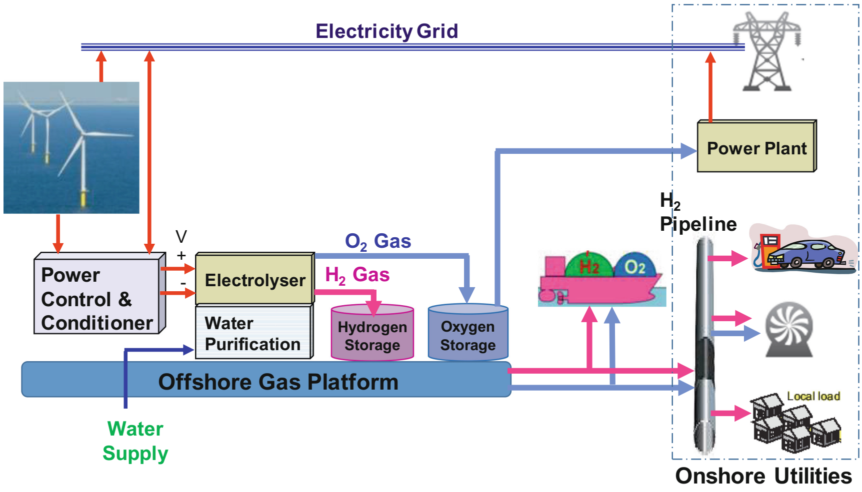

Fig. 3. Production concept of electricity and hydrogen from offshore wind.

In medium term scenarios a large offshore wind farm could be connected to a platform and synthetic natural gas (SNG) generated at the platform will be added to the natural gas grid where the CO_2 and SNG could be stored at the depleted gas field capacities [21]. In long-term scenarios, hydrogen produced at the platform as shown in Fig. 3 at a larger scale and partly transformed back to electricity via a fuel cell that turns the intermittent wind-based electricity into base load energy [21].

2.4 Jobs Creation and Supply Chain Opportunities

Economic analysis indicates three construction job years per MW of offshore wind deployed with 0.6 in ongoing operations and maintenance jobs [22]. Additionally, benefits will be derived from enterprise and employment associated with large-scale offshore wind projects and supply chain. Figure 4 depicts a typical supply chain detailed from [23]. Job creation can be referred to the total available direct and indirect full-time equivalent of 248,580 job years created by supply chain sub-elements in the low scenario (4GW) of US offshore wind [24].

The significant figures of indirect employment in broad industrial sectors related to the UK offshore wind industry are estimated by using industry input/output relationships [25]. These include:

- Extraction and utilities (agriculture, forestry and fishing, mining, and quarrying).
- Construction and manufacturing.
- Professional and business services (information and communication, finance and insurance, property, professional, scientific and technical, business administration and support services).
- Other services (motor trades, wholesale, retail, transport and storage, accommodation and food services, education, health, and public administration).

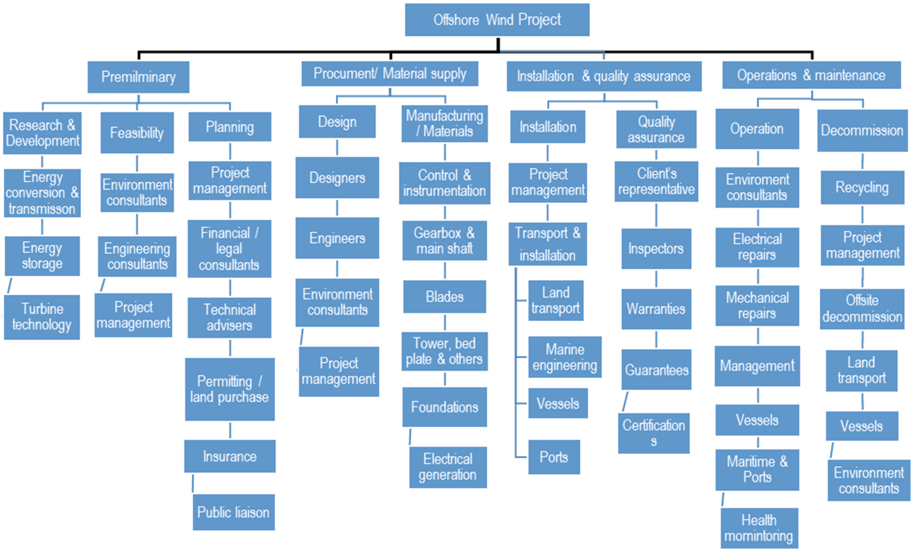

Fig. 4. Offshore wind supply chain.

Taking the sum total of direct, indirect and induced employment, total number of full-time equivalent jobs associated with the UK offshore wind industry is expected to increase from approximately 30,000 in 2017, to approximately 58,000 by 2032.

2.5 Improvement of Environment Quality

The average CO_2 emissions from offshore wind is 16 g CO_2/kWh_e compared to 75 g CO_2/kWh_e from solar photovoltaic, 28 g CO_2/kWh_e from hydropower, 33 g CO_2/kWh_e from nuclear power, 450 g CO_2/kWh_e from natural gas fired and 1050 g CO_2/kWh_e from coal fired [4]. Novel developments such as the increase of turbine size and floating plants will contribute to the exploitation of the wind resources at higher distances from shore and further reduce the greenhouse gas emissions. The slightly larger carbon footprint of present offshore wind farms compared to the onshore counterpart can be counterbalanced by better wind resource that leads to an increase in energy yield and consequently to an almost energy payback period (EPBP) [4]. The EPBP of a wind farm project expresses the period that the installation should operate to offset the amount of energy that is consumed during its lifetime operation [4]. That tendency for GHG emissions to decrease in relation to an increase in turbine size and capacity factor is confirmed by research results [26]. Offshore wind will effectively support the transition to a low carbon future.

Such environmental effectiveness will continue more profoundly as electricity and heat and transport fuel can be generated from the offshore wind sector in the future. These advantages together with the reduced visual and noise impact and increased job creation potential discussed below demonstrate the opportunities in governance and environment for offshore wind development.

3 Challenges and Potential Solution Approaches

3.1 Offshore Wind Resource Assessment and Forecast

Wind power and metocean condition assessment and forecasting plays a key role in dealing with the stochastic and intermittent nature of wind and challenges of balancing supply and demand in any electricity system, given the uncertainty associated with the wind farm power output [27]. Wind power forecasting tools enable better dispatch, scheduling and unit commitment of generators and energy storage plant and more competitive market trading [27]. The advanced methods for wind power forecasting and prediction including numeric [28], LIDAR [29] and variability assessment [30] among others should be introduced in development and operation of offshore wind plants. These will deal with barriers of poor resource characterisation and data.

As wind turbines continue to grow in size, masts for mounting cup anemometers commonly used for resource assessment of onshore wind energy, have necessarily become much taller, and much more expensive [29]. This limitation has driven the commercialization of two remote sensing (RS) tools for the wind energy industry: The LIDAR and the SODAR, Doppler effect instruments using light and sound, respectively. They can work over hundreds of meters, sufficient for the tallest turbines in, or planned for, production. Data at 100 m from both RS systems was also compared, to investigate the use of RS in determining wind speed above the height of typical (i.e., lower cost) monitoring mast height as shown in Fig. 5 [29] where the correlation coefficient was 0.962 (0.946), suggesting a good agreement between the two methods, although it is noted that both systems recorded wind, on average, lower than the cup anemometer standard.

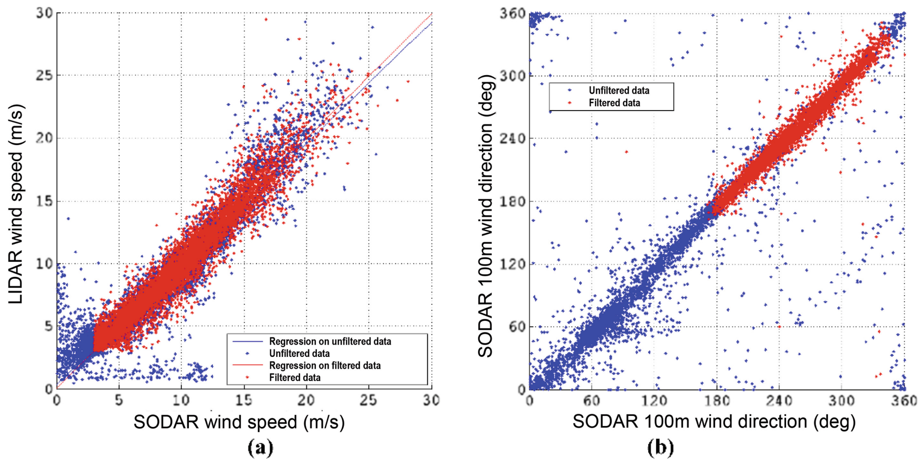

Fig. 5. Comparison of 100 m (a) wind speed and (b) wind direction, from LIDAR and SODAR

The understanding of the behaviour of sea breezes is currently limited but rapidly requires improvement due to the expansion of the offshore wind energy industry [31].

Some features including jets and calm zones are shown to influence offshore wind farm development areas up to 200 km offshore and future larger turbines will be more sensitive to sea-breeze impacts [31]. Each sea-breeze type needs separate consideration in wind power resource assessment. Coastal upwelling can produce high wind shear of $\sim$ 8 m/s across rotor blade dimensions [32] that could potentially pose engineering challenges and should be considered. While the onshore component of the sea breeze is well observed, very little is known about its unobserved offshore component. A coupled atmosphere-ocean model (Weather Research and Forecasting - Regional Ocean Modeling System, WRF-ROMS) would provide improved capabilities to diagnose coastal air-sea processes (sea breeze and coastal upwelling) for offshore wind resource assessment and to more accurately predict these processes for operational forecasting during construction and O&M phases [32].

It has been argued that the rate of electricity generation in large wind farms containing multiple wind arrays is, therefore, constrained by the rate of kinetic energy replenishment from the atmosphere above and that the rate is limited to around 1.5 W/m^2 within large wind farms [10]. However, a research shows that considerably higher power generation rates may be sustainable over some open ocean areas. In particular, that extraction rates of 6 W/m^2 and above may be sustained in the North Atlantic [10]. Furthermore, the surface heat flux from the oceans to the atmosphere may create regions where sustained high rates of downward transport of kinetic energy and thus, high rates of kinetic energy extraction may be geophysical possible [10].

3.2 Data Management, Marine Spatial Planning, Governance and Policy

Major challenges to the government and national marine authorities in planning and consenting for offshore wind projects are linked to the need to obtain sufficient and long-term data in wind resource, bathymetry, metocean data (waves, current and tides), and seabed geology and substrates. Data on human activities including civil jurisdiction boundaries, third party infrastructure, natural/cultural heritage site designations, military/aviation activities, shipping, fishing and ports or harbour restrictions are also particularly required. Other major issues are how to manage those data and integrate them effectively into other activities and strategies [18]. In this context, Marine Spatial Planning [33, 34] (MSP) is a new way of looking at how we use the marine area and planning how best to use it into the future. MSP will try to balance the different demands for using the sea including the need to protect the marine environment. It is about planning when and where human activities take place at sea, and ensuring these activities are as efficient and sustainable as possible, and involving stakeholders in a transparent way in the planning of maritime activities. MSP is being used to develop a master plan for offshore wind development in Ireland in the Eirwind project [18].

Defining governance as encompassing broader laws, regulations, policies and actions with which natural resources are managed [35], its issues are shown to be one of the main challenges of transitioning towards sustainable energy futures, with an enlarged share of marine renewable energy sources [35]. Even if laws and regulation exist, technical and engineering challenges would co-exist with governance challenges at various levels. Figure 6 highlights the theoretical understanding of governance where the governance domains and the instruments set the rules for the management of human activities. The framework for governance and policy issues in offshore wind can be referred to the studies on governance challenges of marine renewable energy developments in the US [35] and the governance barriers to sustainable energy transitions with Ireland case study of marine energy futures [36]. The various factors that influence stakeholders' behaviour and decision should be investigated [37, 38] to understand the effects, relationships and dependencies and develop support policy.

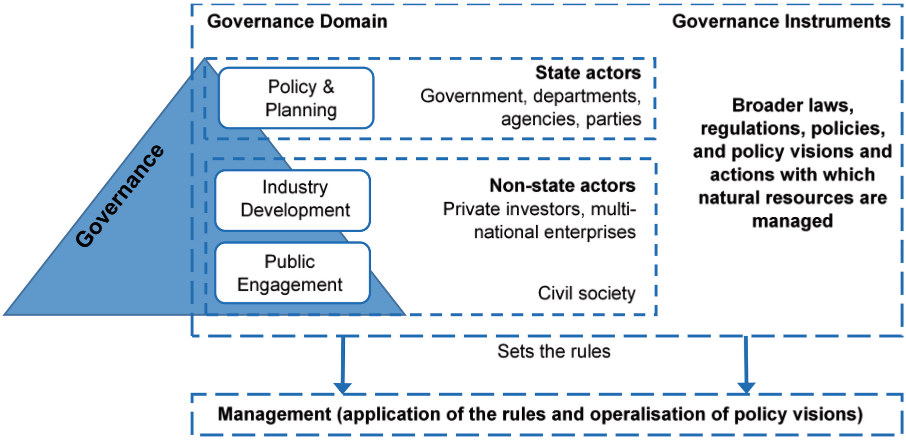

Fig. 6. Governance understanding as a basis towards setting up of rules for the management of human activities [35, 36].

3.3 Uncertainties in Cost Reduction and Estimation

An offshore wind project usually consists of five technology phases:

(i) Development and consenting
(ii) Component and turbine manufacture,
(iii) Installation,
(iv) Operation and services, and
(v) Decommissioning,

As shown in Table 2 with data source [39]. Due to the nature of the offshore marine environment, the first phase (project development, planning and consenting) can take as long time as four to five years and absorb up to 10% of CAPEX. The manufacture of turbines and components takes a shorter time of one to two years with the majority of investment, requiring 50–80% of the CAPEX. That second phase can even be shorter for the deployment of large scale or multiple wind farms. The third and fourth phases depend largely on vessels, equipment, weather windows and the reliability of facility and forecast systems which can have a high degree of uncertainty. In turn, the offshore environment significantly influences the operation expenditure (OPEX). Offshore wind farms at large scale have not been tested over a full life cycle, and their estimated life span is subjected to a number of assumptions and uncertainties.

Table 2. Offshore wind project life cycle, risks and major cost breakdowns.

Phase	Development & consenting	Component manufacture		Installation	Operations/Maintenance	Decommission
		Turbine manufacture			Support services	
Time	4–5 years	1–2 years		1.5–2.5 years	20+ years	1–2 years
Stage	CAPEX 70–80%				OPEX 20–30%	
Costs	5–10% CAPEX	Components & structure 20–30% CAPEX	Turbine 20–30% CAPEX	10–15% CAPEX	Vessel & equipment 20–30% OPEX	0–5% OPEX
Risks	Regulatory uncertainty; Costly surveys; Risk bias on developers	Multiple contracting; Lack of standardisation	Lack of risk sharing; Insufficient capacity	Constrained vessel supply & lack of bespoke vessels; Inefficient logistics; Grid connectivity bottlenecks	Heavy dependence on subsidies; Reliability	Low EOL value; Recyclability

In order to enable cost reductions, it is important to identify the larger contribution areas of the supply chain and their bottlenecking challenges [40]. A more detailed breakdown of the contribution from each area to the life-time project cost of an offshore wind farm reaching final investment decision (FID) in 2020 [41] is given in Table 3 where the turbine cost is corrected from 28% to 22% according to the data in US [24]. This cost model accounts for decommissioning costs. In a fixed-bottom wind farm with concrete foundations, the decommissioning costs may be higher than 10% and the installation costs increase due to requirement for seabed preparation such as scour protection. A floating wind farm may offer low decommissioning costs of less than 4% due to simplicity of removing mooring cables and floating the platform back to shore in comparison to fixed platforms. Nevertheless, the cost breakdown depends on a number of site-specific aspects including the type of foundation, scale of the wind farm, location, environmental condition and the availability of material and services.

Table 3. Detail breakdown of total undiscounted conventional offshore wind farm costs reaching final investment decision in 2020 (including transmission).

Main area	%	Sub area and sub %
Development & Project Management	3	Project management (**67%**), Consenting & development services (15%), Site investigations (15%), Environmental surveys (3%)
Turbine	22	Blades (18%), Drive train (19%), Power conversion (**30%**), Towers (13%), Small components (11%), Turbine assembly (4%), Large fabrications (5%)
Components & structure	19	Foundations (**40%**), Subsea cables (25%), Electrical systems (17%), Substation structures (11%), Secondary steelwork (7%)
Installation & commissioning	12	Turbine & foundation installation (**41%**), Installation equipment & support services (25%), Cable installation (20%), Onshore works (5%), Installation ports & logistics (5%), Substation installation (4%)
Operation, maintenance & service	40	Vessels and equipment (**47%**), Maintenance & inspection services (42%), O&M ports (11%)
Decommissioning	4	Marine operations (**93%**), Salvage & recycling (1%), Project management (2%), Ports and logistics (4%)

Both deployment scale and project lifetime have a significant effect on reducing offshore wind levelised costs of energy (LCOE) that are able to bring those costs in Ireland to less than €90/MWh [42]. Also, further analysis needs to be carried out to incorporate curtailment, and capacity limitations posed by the electricity transmission grid.

3.4 Modelling and Design: Coupled Analysis and Risk Allocation

Most of systems consist of a number of elements that are subjected to multiple and simultaneous actions from the environment. The response by each element depends not only on its properties and the actions on it, but also on the properties of and the actions on the other elements. The action from waves on marine structures is physically influenced by sea currents [43]. In a floating offshore wind turbine (FOWT), the vibration of the blades, nacelle, tower, and platform elements are interacted in all degrees of freedom and in all inertial, dissipative and elastic components [44]. In multiple support structures including cables and pipelines, there are differences and time-variations in both amplitudes and frequency content of the excitations and the properties of soil at each support [45]. A fixed-bottom wind turbine may be subject to earthquake excitations [46] having spatially varying amplitude and frequency content at different supports [45, 47, 48] which leads to significantly increasing responses. In practice, when each element is designed, manufactured and installed by a separate contractor, introduces an industry uncertainty relating to how system risk is allocated.

An approach to the reduction of costs of infrastructure, operation and maintenance is to minimise uncertainties in analysis and design of offshore wind turbine by using integrated and coupled models of the entire systems accounting for the physical interactions among components. Such coupled models [44, 49] can be applied to offshore wind turbines in Vietnam seas. Figure 7 shows that the maximum platform roll determined by the uncoupled model of a 5 MW spar-type FOWT is about 0.05 rad whereas the result from the coupled model is about 0.01 rad. An 80% overestimation resulted from the uncoupled model as the significant impact of the blade-nacelle-spar physical coupling was not captured.

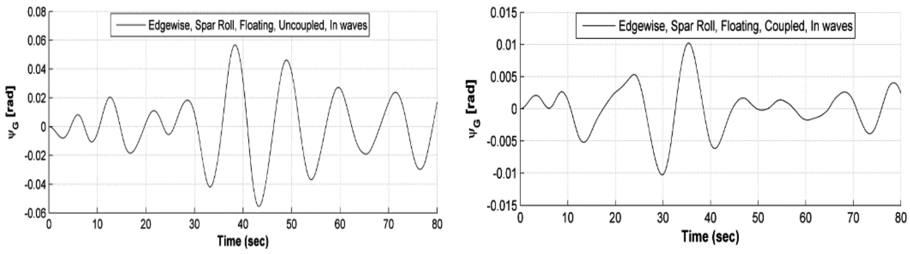

Fig. 7. Platform roll responses resulted by uncoupled model (left) and coupled model (right) of a 5 MW spar-type floating offshore wind turbine.

The relative uniformity of offshore wind profiles enables simplification of the wind turbine control systems [50, 51] that lead to other cost reduction schemes as shown in Fig. 8. Most of the tests emphasise the importance in testing at larger scales [52] and the needs for testing at more realistic environmental conditions.

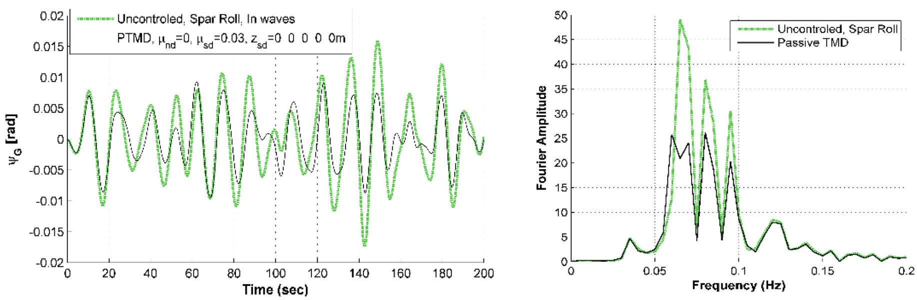

Fig. 8. Platform roll responses of uncontrolled (green curve) and passive controlled (black curve) 5 MW spar-type FOWT.

3.5 Turbine Components, Technology and Supply Chain

The global turbine supply chain will need to transform and ramp up drastically to support the development of 40 GW of offshore wind power capacity licensed by the UK Crown Estate [53], alongside similar levels of expected growth in other regions including the United States, China and continental Europe. Ensuring cost-efficient growth and guaranteeing high quality under such demand levels could pose serious challenges. The turbine supply chain is therefore a potential bottleneck. In its current state, the supply chains serving the nascent offshore wind industry possess a series of characteristics that need to evolve for mega-projects to become viable and attractive investments [39]. Many of these characteristics are a direct consequence of the absence of a strong demand-side pull that incentivises R&D spend, cost reductions, and greater competition, cooperation, integration and specialisation [39].

Much of the existing offshore turbine supply chain is set up to cater for the development of the smaller-scale, land-based wind farms. Consequently, offshore wind projects have been employing technologies, processes and business models adapted from the onshore industry, rather than designed for the very different offshore marine construction and operations environment [39]. The differences between the onshore and offshore turbine types are related to turbine size, blade materials and performance, drive train, towers and sub-structures. The development of projects increasingly further from shore means that transmission technology will very likely shift from high voltage alternate current (HVAC) to high voltage direct current (HVDC) due to the lower losses over large distances from the latter technology [39].

The level of vertical integration in the offshore wind turbine market is limited and the business models are varied. Table 4 with data source [39] shows that most of the leading turbine manufacturers focus on the manufacture of turbines, blades and towers, outsourcing the remaining components. Only Enercon, Gemesa, GE Energy and

Siemens are presently manufacturing generators, controllers and drive trains. This panorama is likely to change with the emergence of mega-projects, which could prompt more integration across the value chain and possibly further down into the substructures and grid-connection segments.

Table 4. Vertical integration of leading turbine manufacturer (*Grid connection: Infrastructure service to provide physical connection between wind farm and grid).

Company	Turbines	Rotor blades	Drive train (gearboxes/direct)	Generators	Controller	Towers	Substructures	*Grid connection
Enercon	√	√	√(Direct)	√	√	√		
Gamesa	√	√	√(Gearboxes)	√	√	√		
GE Energy	√	√	√(Gearboxes)	√	√	√		√
Nordex	√	√			√	√		√
Siemens Wind	√	√	√(Direct)		√	√		√
Suzlon	√	√		√	√	√		√
Vestas	√	√		√	√	√		

As the wind power captured is proportional to the square of rotor diameter, the use of larger turbines maximizes energy capture and enables cost reduction. The recently developed large turbines can be introduced into offshore wind such as the US NREL 5 MW [54] and the DTU 10 MW that possesses good aerodynamic performance and fairly low weight [55]. An 8 MW wind turbine has recently been developed as a part of the EU FP7 project LEANWIND that bridges the gap between the NREL 5 MW and DTU 10 MW reference turbines [56]. However, larger turbines face reliability and logistics issues, some of which can be partially offset by reducing the size and weight of some components, for example, to swap gearboxes for direct drive units.

3.6 Wind Intermittency and Grid Integration

Dispatch-down of wind energy is another infrastructure challenge. It refers to the amount of wind energy that is available but cannot be produced because of power system limitations, known as curtailments, or network limitations, known as constraints [57]. In 2016, the total wind energy generated in Ireland and Northern Ireland was 7,620 GWh, while 227 GWh of wind energy was dispatched-down representing 2.9% of the total available wind energy in the year [57]. The level of dispatch-down is affected by a number of time-varying factors including the amount of wind installed on the system and the capacity factor of the wind generation.

Several mitigation measures for wind energy dispatch-down due to constraint and curtailment in Ireland have been implemented [57] those include networks reinforcement by using new technologies and operational policies. However, the success of the programme depends on appropriate and positive engagement from all industry stakeholders. This includes conventional and renewable generators, the regulatory authorities, transmission system operators and distribution system operators [57].

An offshore windfarm is always multiples of hundreds of MW of installed power. In relation to storage, the installations required must exhibit a charging/discharging ability approximately between 1% and 3% of the total annual electricity production of the windfarm. This means that for an offshore windfarm with a nominal power of 100 MW and a capacity factor of 40%, a storage capacity of about 3,500–10,500 MWh is required. This could be provided by a large pumped storage systems or compressed air energy storage systems [58]. However the use of hydrogen storage is another option. In the long-term scenario of the synergy with or replacement of offshore oil and gas platform, hydrogen produced at the platform at a larger scale and partly transformed back to electricity via a fuel cell located at the platform that turns the intermittent wind-based electricity into base load energy [21].

It is worth noting that the vast wind resource will be further constrained by the grid. So in order to facilitate a large penetration of wind energy, overcoming some of such constraint to its deployment which lessen its value the integrating with hydrogen systems has therefore been analysed for some 15 years [15, 16]. Cost-reductions, low surplus wind electricity average value, and high hydrogen market prices may render the technology cost-effective, allowing for the installation of electrolysis units of sufficient capacity to attain the desired levelling effect and thus facilitating a larger wind penetration [15]. The use of wind-generated hydrogen in the transport and heat sectors will have a substantial contribution to the abatement of CO_2 and other emissions. A study to propose a pilot project for demonstrating and testing the hydrogen systems integrated with onshore wind farms in Ireland is recently reported [17]. A power to gas system using hydrogen (derived from surplus wind electricity) to react with CO_2 increases the methane output [19] that economically demonstrate the co-location opportunities of hydrogen production with biogas.

3.7 Project Development, Construction and Contracting

Offshore wind developers generally adopt either a multi-contracting strategy [41] as in Fig. 9 or an engineer, procure, construct and install (EPCI) strategy as in Fig. 10. Under a multi-contracting strategy, the developer typically awards about nine main contracts covering the key elements of the wind farm. Some packages can be split or combined depending on developer needs and capabilities and the value being offered by suppliers. Multi-contracting is often preferred by large utilities, particularly if the project is funded from their balance sheet [41]. In order to effectively enable cost reduction in offshore wind energy, it is important to identify the larger contribution areas of the supply chain and their bottlenecking challenges [40].

EPCI contracting usually involves three main packages [41]. The turbine package is typically kept separate as this is a critical one for the wind farm design and therefore needs to be specified before the remaining contracts can be finalised. The other two packages vary in scope according to the strengths of the bidders. The transmission assets package is treated differently depending on the jurisdiction in which the project is deployed. Independent developers and less experienced utilities prefer this approach that allows them to manage a small number of contractors and reduce its risk.

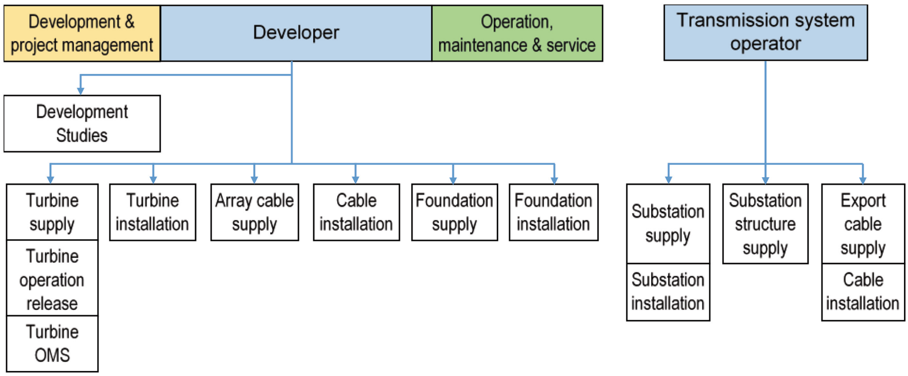

Fig. 9. Typical multi-contracting structure for offshore wind.

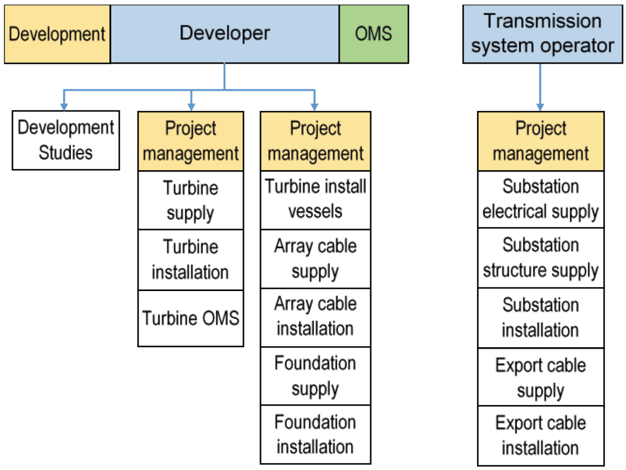

Fig. 10. Typical EPCI structure for offshore wind

4 Conclusion

Offshore wind offers a number of major opportunities and in particular this advantageous resource allows potentially a lower cost of energy. The wind speeds are relatively uniform and resulting in reduced wear on the turbine components which increases their lifetime. The higher offshore wind speeds and wake effects reduction gives a 45–60% increase in the power captured. The steadier ocean climate results in higher full-load hours per year and furthermore offshore wind is typically stronger during the daytime leading to efficient and timely production of energy. Integration with hydrogen storage, infrastructure and market systems potentially ensures security of sustainable supply for both electricity and gas. Offshore wind farms can be synergized with or substituted for oil and gas platforms. The offshore wind industry supply chain, development, construction and operation offer various direct and indirect opportunities for job creation and enterprises. More importantly, offshore wind energy effectively supports the transition to a low carbon future as its CO_2 emissions are the lowest among the energy sources with further decreases imminent due to an increases in turbine size and capacity factor.

Challenges to the development of offshore wind energy and the potential solutions have then been discussed in this paper. As the methods and tools used for onshore wind resource assessment and forecast become much more expensive and sometimes infeasible for offshore wind, new more advanced ones including LIDAR, coupled atmosphere-ocean and surface heat flux models among others should be introduced. Obtaining sufficient and long-term data in wind and metocean, bathymetry, ecology and human activities, managing those data and integrating them effectively into other activities and strategies are crucial. The use of Marine Spatial Planning and the study of the existing framework for governance and policy in other countries and the roles of the various factors influencing stakeholders' behaviour and decisions are recommended.

The difficult offshore environment adds more uncertainties to the costs related to the vessels, equipment, weather windows and the forecast systems. In order to effectively enable cost reduction, the identification of the larger contribution areas of the supply chain and their bottlenecking challenges involving detailed costs breakdown are suggested. The costs can be further reduced by minimising uncertainties using integrated and coupled models for analysis and design and control measures. Turbine supply chain including drivetrain, generators and grid connection is a potential bottleneck in offshore wind energy. The supply chain and projects should be designed for the different offshore construction and operations environment. The dispatch-down of wind energy is another serious infrastructure challenge that can be mitigated by operational policies, technologies and energy storage. Offshore wind projects are often challengingly large; a multi-contracting strategy is recommended for large utilities. Independent developers and less experienced utilities should adopt EPCI contracting that allows them to manage a small number of contractors and reduce risk.

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