Fei Duan

Wind Energy Cost Analysis

CoE for offshore Wind and LCOE financial modeling

Helsinki Metropolia University of Applied Sciences

Bachelor

Environmental Engeering

Thesis

August 23, 2017

Author(s) Title Number of Pages Date	Fei Duan Wind Energy Cost Analysis CoE for offshore Wind and LCOE financial modeling 75 pages 23 August 2017
Degree	Bachelor
Degree Programme	Environmental Engineering
Specialisation option	Renewable Energy
Instructor(s)	Christian Leegaard Thomsen, Senior Specialist Antti Tohka, Principal Lecturer

The thesis mainly discusses the cost level of offshore wind energy. As one of the most vital renewable energy resource, offshore wind energy has developed gradually worldwide. Nevertheless, relative high cost is considered as a major barrier for offshore wind industry development. This thesis introduces the cost component for offshore wind energy, analyzed the cost level and relative influence factor for different markets. Furthermore, in order to better understanding levelized cost of wind energy, a LCOE financial modeling was developed. By using two reference offshore wind projects, computational principle of financial modeling was interpreted, and LCOE calculation process was demonstrated as well.

Keywords	Offshore wind, CoE, LCOE

Acknowledgments

This Bachelor's thesis was mainly supported by Christian Leegaard Thomsen, Senior Specialist Wind & Site Offshore, K2 Management. I would like to thank him and my colleagues Kwang-Woon Jung, Ulrik Møller Thomsen, and Francesco Durante Schiavone for providing insight and expertise that greatly assisted the research. I extend my thanks to Michael Andersen for assistance with the building and final review of LCOE financial modeling.

Special thanks to Lin Li, Jinghua Wang for sharing their pearls of wisdom with me during the course of this thesis writing.

Finally, I would also like to show my gratitude to my family and friends for their support and encouragement throughout my life.

August 23, 2017
Helsinki, Finland
Fei Duan

Contents

Abbreviations

LCOE	Levelized Cost of Energy
O&M	Operation and Maintenance
SCBS	System cost breakdown structure
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
BOP	Balance of Plant
NREL	National Renewable Energy Laboratory
OWF	Offshore Wind Farm
NPV	Net Present Value
IRR	Internal Rate Return
K2M	K2 Management
WACC	Weighted Average Costs of Capital
PV	Present Value
DF	Discount Factor
AEP	Annual Energy Production
PtD	Periods to Discount
CF	Capacity Factor
CO	Capacity Operational
EWEA	European Wind Energy Association
BWFZ	Borssele Wind Farm Zone
FID	Final Investment Decision
OEM	Original Equipment Manufacturer
RO	Renewable Obligations
CfD	Contract for Difference
LCCC	Low Carbon Contracts Company
LECs	Levy Exemption Certificates
WTG	Wind Turbine Generator
CoE	Cost of Energy
SOE	State-Owned Enterprise
NEA	National Energy Administration
SOA	State Oceanic Administration
NDRC	National Development and Reform Commission
FIT	Feed-in Tariff

EIT	Enterprise Income Tax
VAT	Value Added Tax
RPS	Renewable Portfolio Standard
REC	Renewable Energy Certificate
OSS	Offshore Substations
JWPA	Japan Wind Power Association
METI	Japanese Ministry of Economy, Trade and Industry
EIA	Environmental Impact Assessment

1 Introduction

Wind, free and non-exhaustive, has huge potential on power generation worldwide, especially offshore wind. Like any other renewable energy resources, such as solar, hydro, especially in Europe, wind power plays an increasingly significant role in current and future energy industry. For instance, in 2016, 37.6% of Denmark's electricity consumption was covered by wind energy; what is more, the future plan is to reach 50% of its electricity consumption from wind by 2020 [1] .

With growing concern of climate issues, governments, investors, international organizations have attached the importance to wind energy due to its zero carbon emission. Until the end of 2015, the global cumulative wind capacity was 32.9GW, and 63 GW of wind power capacity were installed in 2015, which represents 17% of wind market growth [2].

Unlike onshore wind, offshore wind is relatively immature. Global new installed offshore wind capacity in 2015 was 3,398MW, and cumulative capacity until the end of 2015 was 12,107MW which accounts for merely 2.8% of total cumulative wind capacity (Table 1, Figure 1 and Figure 2).

Table 1 Global Installed Capacity of Wind Power [3] Unit: GW

	New Installed Capacity in 2015	Cumulative Capacity Until 2015
Onshore Wind	60.069	420.793
Offshore Wind	3.398	12.107
Total	63.467	432.9

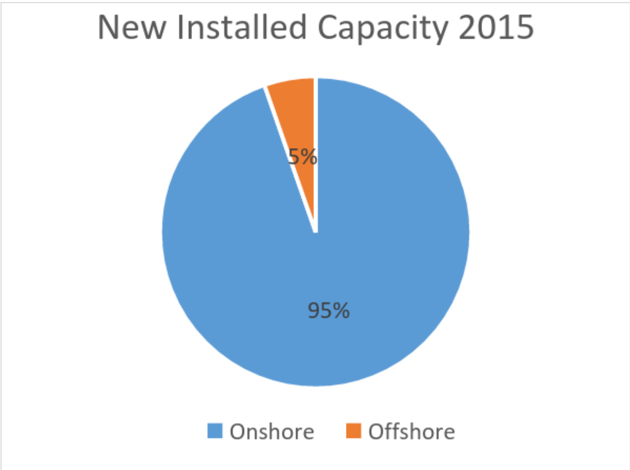

Figure 1 New Installed Capacity of Wind Energy 2015

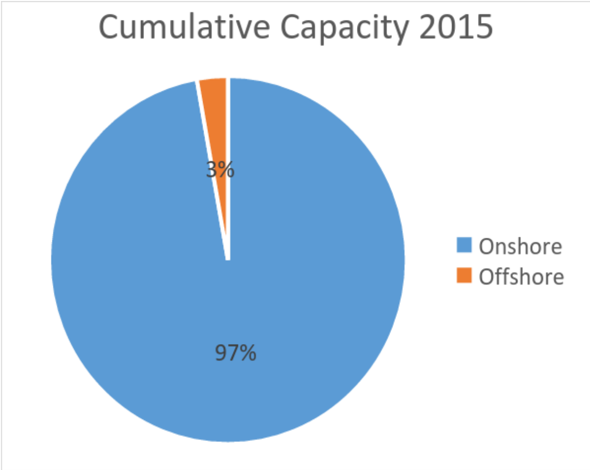

Figure 2 Cumulative Capacity of Wind Energy 2015

Generally speaking, high cost and technical obstacles are the major barriers to offshore wind in worldwide development. Figure 3 shows the levelized cost of energy (LCOE) estimation of major power technologies in Europe 2015. It is shown that LCOE of offshore power ranges between €105/MWh and €155/MWh whose cost is highest compare to the rest, and it is worth stressing that carbon emission cost and governmental subsidies are not considered in this case. Nevertheless, LCOE of onshore wind ranges from €52/MWh to €100/MWh, even cheaper than that of natural gas.

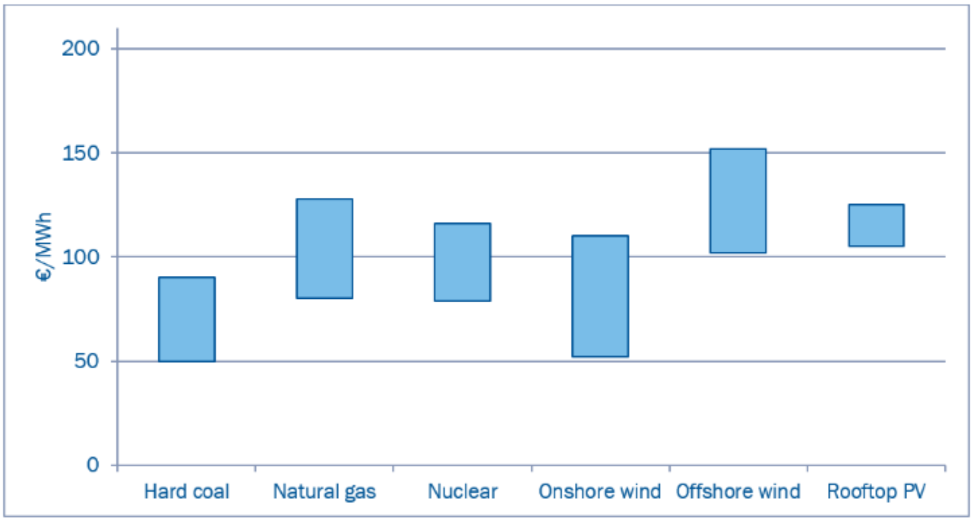

Figure 3 LCOE of major power generation technologies in Europe [4]

Europe has a leading position in offshore wind market and advanced offshore technologies. Until the end of 2015, over 10 GW offshore capacities had been installed in Europe [3]. It is expected that LCOE of offshore will be decreased to €100/MWh by 2020 and €85 to €79/MWh by 2025.

In the US, according to the report from U.S. Energy Information Administration published on August 2016, for the offshore wind power plants to start operating in 2022, LCOE is estimated to range from €122/MWh to €190/MWh($137.1/MWh – $213.9/MWh). See Figure 4 for a comparison of the LCOEs of different new generation resources. Compare to the European market, the offshore wind market in the US is still in the very beginning stage, even though the potential of offshore wind development is quite promising. Until the end of 2015, the cumulative offshore wind capacity in the US was merely 0.02MW [4].

	Range for Total System Levelized Costs (2015 $/MWh)				Range for Total System Levelized Costs with Tax Credits[1] (2015 $/MWh)			
Plant Type	**Minimum**	**Non-weighted average**	**Capacity-weighted[2] average**	**Maximum**	**Minimum**	**Non-weighted average**	**Capacity-weighted average**	**Maximum**
Dispatchable Technologies								
Advanced Coal with CCS[3]	129.9	139.5	N/B	162.3	129.9	139.5	N/B	162.3
Natural Gas-fired								
Conventional Combined Cycle	53.4	58.1	56.4	67.4	53.4	58.1	56.4	67.4
Advanced Combined Cycle	52.4	57.2	55.8	65.5	52.4	57.2	55.8	65.5
Advanced CC with CCS	78.0	84.8	N/B	93.9	78.0	84.8	N/B	93.9
Conventional Combustion Turbine	103.5	110.8	105.4	122.8	103.5	110.8	105.4	122.8
Advanced Combustion Turbine	87.7	94.7	93.6	105.8	87.7	94.7	93.6	105.8
Advanced Nuclear	99.5	102.8	99.7	108.3	99.5	102.8	99.7	108.3
Geothermal	41.1	45.0	42.3	51.8	38.4	41.9	39.5	47.8
Biomass	81.5	96.1	N/B	115.6	81.5	96.1	N/B	115.6
Non-Dispatchable Technologies								
Wind	43.0	64.5	58.5	78.5	35.4	56.9	50.9	70.9
Wind – Offshore	137.1	158.1	N/B	213.9	125.7	146.7	N/B	202.5
Solar PV[4]	65.6	84.7	74.2	126.2	51.6	66.3	58.2	97.7
Solar Thermal	172.3	235.9	N/B	363.4	131.3	179.9	N/B	277.3
Hydroelectric[5]	59.6	67.8	63.7	78.1	59.6	67.8	63.7	78.1

Figure 4 Variation in LCOE for New Generation Resources in the US [7]

Technology and energy policy and regulations are two essential considerations for the cost of offshore wind energy. Larger turbines can be adopted for an offshore wind farm with larger capacity; however, the cost is increasing correspondingly, as are also risk challenges.

The capital investment of offshore wind is 27% higher, on average, as compared to that of onshore wind (Figure 3), since the harsh sea environment requires higher standards for the turbine and the foundation. Besides, cost for transportation and assembling also lead to higher capital cost due to insufficient installation vessels and accessibility issues of construction sites. Similarly, grid connection, operation and maintenance (O&M) are other concerns for investors.

This thesis project investigated the cost of offshore wind energy from three different angles:

- Cost component and cost structure
- LCOE of offshore wind energy and LCOE financial modeling in different regions
- Cost of offshore wind energy in different countries

Each angle is elaborated on the following chapters.

2 Cost of Energy for Offshore Wind

In this chapter, the cost of energy for offshore wind is briefly discussed in Chapter 2.1. Furthermore, offshore wind project cost breakdown is specified and illustrated by hierarchy diagram and charts in Chapter 2.2. System cost breakdown structure (SCBS) developed by NREL is used in order to interpret the component costs for an offshore wind project.

Due to distinctive policies and regulations for each different country, the cost components for offshore wind project are slightly different from region to region. However, this chapter only discusses the cost breakdown in a general way.

2.1 Offshore wind CoE description

The full lifetime cost of a wind power plant is divided into two main parts, capital expenditure and operational expenditure (later referred to as CAPEX and OPEX). Unlike the traditional power plant, which consumes fossil fuels such as coal, oil and natural gas to generate electricity, a wind power plant requires no fuel cost, which is one of the fundamental motivations for wind energy investment. Nevertheless, even without the fuel cost during the operational phase, the cost of electricity produced from offshore wind farm is still extremely high.

The cost of power plant is typically divided to CAPEX and OPEX, yet, the actual price also depends on subsidies, taxes, fuel price. For example in Finland, the carbon price is low, but taxes for fossil fuels are high and subsidies for renewable energy are also high.

According to the report, Energy for the future or relic of the past written by Richard Anderson, the cost of energy produced by offshore wind in 2015 was around 185$/MWh, which is over 4 times higher than that of energy produced by gas(closed cycle), less than 40$/MWh. On the other hand, the cost of an offshore wind farm is much higher than that of an onshore farm; however, with the improved technology, the cost differential constantly narrows down. Figure 5 illustrates the comparison of cost breakdown between onshore wind and offshore wind. It is seen that the electrical infrastructure and foundations for an offshore wind farm accounted for about 45 % of the costs, which is over three times the corresponding costs for an onshore wind farm.

Based on the current situation of offshore wind energy, it is doubtless to say that offshore wind is indeed a capital-intensive investment, which is critical challenge for wind industry. Nevertheless, according to global costs analysis [8], 2016 is the first year when the installation cost of offshore wind farm starts to decline, which is discussed in detail in Chapter 4.

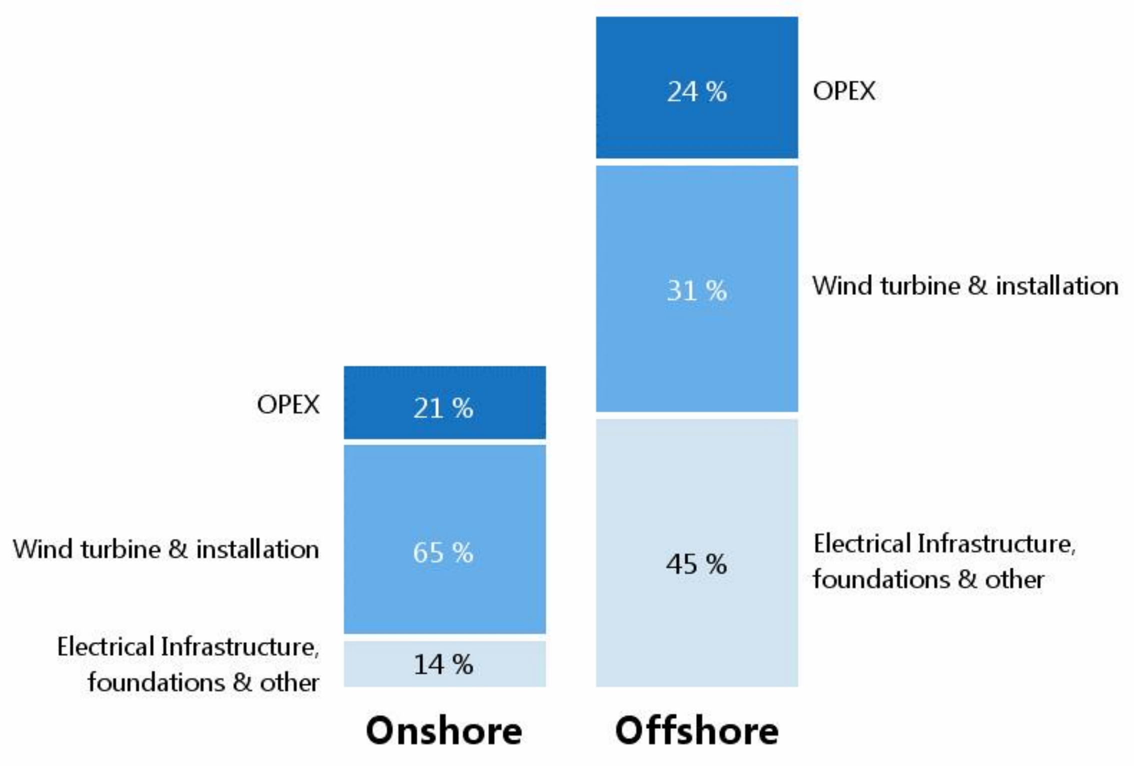

Figure 5 Cost Comparison between Onshore and Offshore Wind Projects

2.2 Offshore wind farm cost breakdown

As mentioned above, capital expenditure (CAPEX) and operational expenditure (OPEX) are the two fundamental costs for an offshore wind farm. Each of them can be further divided into several more detailed cost branches. For example, CAPEX can be deconstructed into wind turbine, balance of plant (BOP), and financial costs. Likewise, OPEX cost breakdown includes operation costs and maintenance costs. See Figure 6. It should be noted that in practice, there are minor differences of cost component depending on the market and that the cost breakdown of offshore wind discussed in this thesis applies to the most general scenario.

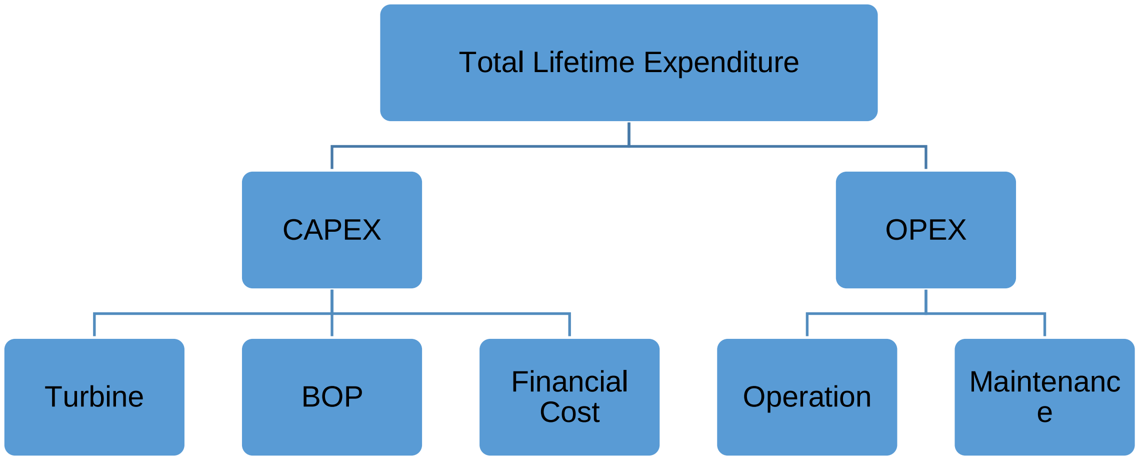

Figure 6 Wind Project Cost Breakdown [8]

2.2.1 System Cost Breakdown Structure (SCBS) Description

For the purpose of systematic management, National Renewable Energy Laboratory (NREL) developed a system cost breakdown structure (SCBS), which can be both applied for onshore and offshore wind projects. SCBS identifies an offshore wind project at a component level, providing a deeper view of project cost breakdown. All the cost components are arranged in a hierarchy system, and by employing the system, users can have a clear overview of relationships among each individual component and how they are grouped together into system cost breakdown structure, and further manage and analyze cost data in a more efficient way.

In this structure, total lifetime costs are divided into six levels from top to down. The lower the level is, the more specific the cost component is. SCBS defines CAPEX and OPEX as Level 1. Turbine, BOP and financial cost are three component costs of CAPEX; operation and maintenance are two component costs of OPEX; therefore, logically, they are identified as Level 2. Similarly, each of the remaining four levels are identified (Figure 7).

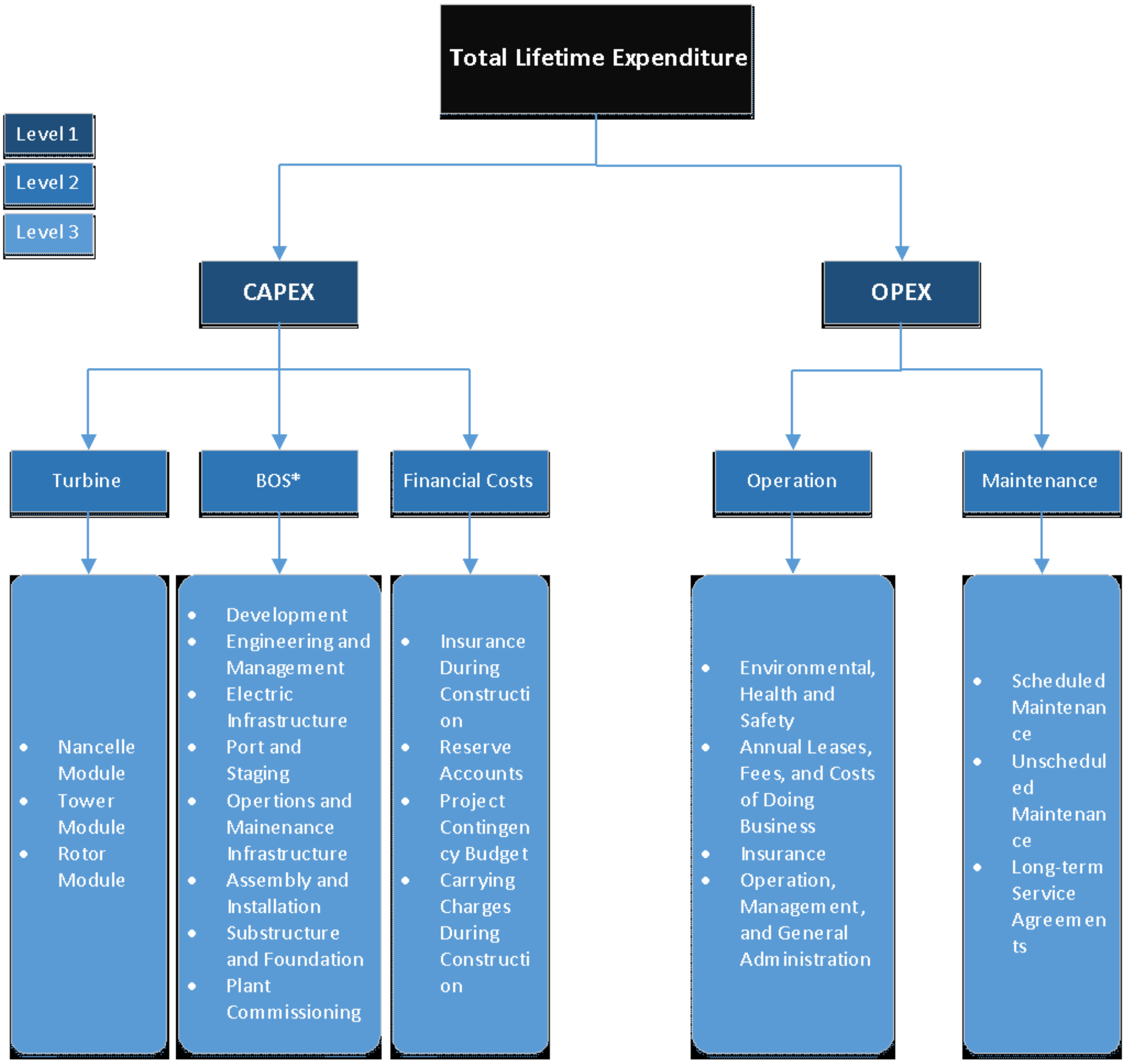

Figure 7 Level 1, 2 and 3 of SCBS [8]

NOTE: BOS refers to BOP (Balance of Plant)

With the descending level cost structure, the number of cost components increases (e.g. 5 cost components for Level 2; 22 cost components for Level 3), which is shown hierarchical information in SCBS. In total, over 300 cost components are included.

2.2.2 Benefits and limitations

SCBS is a standardized approach which defines a wind project expenditure specifically at the component cost level. The hierarchical system describes both the position of each cost (e.g. tower module cost is in Level 3) and the relationship between each cost (e.g. Tower module cost is under Turbine category and is parallel with Nacelle module cost). SBBS has three benefits:

- Government, investor, or project developer can manage and manipulate cost data issues in an efficient way.
- As there are clearly defined expenditure categories, the chance of double counting decreases as well
- It is easier to make cost comparison across different data sources, and it is more precise due to the simplified structure.

Nevertheless, even though SCBS is able to represent the general wind project characteristics, there are still some limitations for SCBS adoption. Entities may use a different approach to collect and analyze cost data; therefore, it may be unable to compare the expenditure from project to project due to different standards for subcomponents. Furthermore, owing to various technical specifications, projects may have different cost components (e.g. a direct-drive wind turbine does not have a gearbox). Therefore, it is necessary to mention that SCBS cannot perfectly be utilized for every practical projects.

3 Levelized Cost of Energy for Offshore Wind

Levelized cost of energy (LCOE) is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime [5]. It is an essential and fundamental consideration for the cost of electricity generated from power plant during its whole lifetime. In this chapter, LCOE of two OWFs is elaborated on by employing the developed financial modeling. The chapter consists of introduction of developed financial modeling, explanation of each key performance indicator, and LCOE calculation of reference projects by using financial modeling.

3.1 Financial modeling

Financial modeling is an important tool for project evaluation and decision. It illustrates project payment and cash flow, delivering annual revenue, net present value (NPV), and internal rate of return (IRR) for the investor. Normally, the economic feasibility of wind power projects are highly determined by financial modeling.

3.1.1 Overview

In this thesis, a financial modeling for LCOE calculation of wind projects was developed. The financial model is based on Excel spreadsheet calculations and aims to analyze and compare different scenarios for certain wind projects so as to evaluate the effect of each financial assumption and make the corresponding adjustments.

Theoretical basis for the LCOE model is formed by K2M[1]; however, it is important to note that in this thesis, the developed mathematical tool is a simple version of financial modeling, and it is only for LCOE calculation. Cash flow, relevant payment, NPV, IRR are not considered and calculated in this mathematical tool.

The financial model consists of 5 worksheets, and the function of each sheet is shown in Table 2 below. The main worksheets, Input, Modeling, and Output are defined in following chapters.

Table 2 LCOE Financial Modeling Structure

Worksheet	Function
INSTRUCTION	• Provides an overview of the financial modeling and explains functions of each worksheet
INPUT	• Populates general information and assumptions of wind project
MODELING	• Calculates the associated key performance indicators of multiple model runs. • Key performance indicators include annual AEP, CAPEX, and OPEX
OUTPUT	• Delivers the results and chosen project scenario and evaluates the LCOE of chosen wind farm project
REFERENCE DATA	• A supportive sheet for data validation of INPUT worksheet

[1] In this thesis, K2M is the short for K2 Management, http://www.k2management.com/.

3.1.2 Input

The Input worksheet is considered as an interface to apply wind farm basic information and financial assumptions. It builds the foundation of calculation and defines the parameters used for calculation in the Modeling worksheet. The worksheet consists of five items: wind farm information, valuation assumption, power production assumption, CAPEX assumption and OPEX assumption. Each item includes few indicators to be specified. The construction of Input worksheet is illustrated in Figure 8.

Wind farm information

- Country
- Onshore/Offshore
- Turbine Type
- Rated capacity
- Number of turbines
- Installed capacity

Valuation assumption

- Currency
- Unit
- Entry-year for valuation
- Valuation data
- Pricing year
- WACC

Power production assption

- Operational lifetime
- First power
- Last power
- Capacity factor
- Power price inflaton multiple

CAPEX assumption

- CAPEX/MW
- Total CAPEX
- CAPEX share (first power year) -3
- CAPEX share (first power year) -2
- CPAEX share (first power year) -1
- CPAEX share (first power year)

OPEX assumption

- OPEX driver
- OPEX multiple (per unit production cost)

Figure 8 Financial Modeling Input Worksheet Structure[2]

In the Input worksheet, a maximum of three scenarios can be applied so as to compare the LCOE of different scenarios. Initially, each indicator is required to be inserted, then the number of applied scenario is input in single cell. LCOE is calculated automatically in the modeling worksheet, and the result is delivered in the Output worksheet. By changing the number of applied scenario, LCOE can be further compared.

It is important to note that the quality of LCOE calculation highly depends on the quality of Input data, including technical parameters, for example, capacity factor and financial assumption such as *CAPEX/MW*, *OPEX Multiple, inflation multiple* and *discount factor*[3]. In this modeling, the input of CAPEX/MW, OPEX Multiple are defined as the Level 1 cost of SCBS (described in 2.2.1); thus, the cost component of CAPEX and OPEX (Level 2, Level 3…) cannot be described in the modeling. In addition, LCOE calculation is highly sensitive to the underlying data and assumptions used for project key parameters; therefore, it is crucial to apply data within the range of reasonable estimation.

3.1.3 Modeling

Modeling functions as calculation worksheet. LCOE of a wind project is calculated over the full lifetime of the plant, including development, construction, and operation[4]. Development and construction duration is set to be 3 years; operation duration is set to be 25 years; based on generic case, yet, the duration of each phase can be adjusted based on project circumstance.

In Modeling worksheet, electricity production, CAPEX and OPEX are calculated on an annual basis based on input data. In addition, by applying power price inflation multiple in Input worksheet, the annual inflation rate is calculated, and the annual operational expenditure is further determined.

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[2] CAPEX share(first power year) - 3 is to count backwards of 3 years from the first power year, for instance, if the first power year is 2017, then CAPEX share(first power year) - 3 is 2014.
[3] Discount factor is typically reflected by weighted average costs of capital (WACC).

[4] Due to the complexity and various executed standards of decommissioning, the decommissioning of wind power plant is not considered in the modeling.

It is necessary to point out that, in practice, in order to provide investor with useful IRR/NPV, the type of subsidy should be seriously considered in financial model. However, as the current version of modeling cannot deliver IRR and NPV, the type of subsidy is not considered as one of the key parameters of the modeling.

The LCOE model outline is constructed based on the following formula and major calculation parameters are presented in the Table 3.

$$LCOE = \frac{PV(CAPEX)^{\star} + PV(OPEX)^{\star\star}}{PV(Production)^{\star\star\star}}$$

$$\star \quad PV(CAPEX) = \sum_{k=1}^{n} AnnualCAPEX_K \times DF_K$$

$$\star\star \quad PV(OPEX) = \sum_{k=1}^{n} AnnualOPEX_K \times DF_K$$

$$\star\star\star \quad PV(Production) = \sum_{k=1}^{n} AEP_K \times DF_K$$

$$DF = (1 + WACC)^{PtD}$$

$$AnnualCAPEX = CAPEX/MW \times InstalledCapacity$$

$$AnnualOPEX = OPEXmultiple \times (1+i)^n$$

$$AEP = InstalledCapacity \times CF \times CO \times 8760$$

Table 3 Major Calculation Parameters for LCOE

Notation	Definition
PV	Present value
n	Full lifetime of wind power plant (yr)
DF	Discount factor (%)
AEP	Annual energy production (MWh)
WACC	Weighted average costs of capital (%)
PtD	Periods to discount (yr)
i	Inflation rate (%)
CF	Capacity factor (%)
CO	Capacity operational (%)

3.1.4 Output

The Output worksheet provides a project summary statement based on the calculations. The Output outline is presented in Table 4.

Table 4 Output Indicators and Interpretations

Output	Interpretation
Full lifetime of wind farm	• Development and construction phase: 3 years • Operational phase: 25 years
Capital expenditure	Annual CAPEX (normally the first 4 years during the lifetime of wind farm)
Operational expenditure	Annual OPEX (normally starts from the 4th year)
AEP	Annual production (normally starts from the 4th year)
WACC	Financial assumption
Valuation date	The precise date that the data and assumption of wind power plant are applied
Discount factor	Discount factor for each year during the life time of wind farm plant
PV (CAPEX)/PV (OPEX)/PV (Production)/LCOE	Key results indicators

As a key result indicator, LCOE of the chosen wind project is delivered, and it is a fundamental consideration for project feasibility study. Moreover, the calculated results are also visible in header information.

3.2 Input parameters

3.2.1 Capital Expenditure

Capital expenditure (CAPEX), is also known as fixed cost (a cost that does not change with an increase of decrease in the amount of goods or services produced or sold) [6]. According to SCBS, the CAPEX of an offshore wind project consists of three parts, namely, turbine, BOP, and financial cost, covering project development, deployment, commissioning, which are shown in Figure 9.

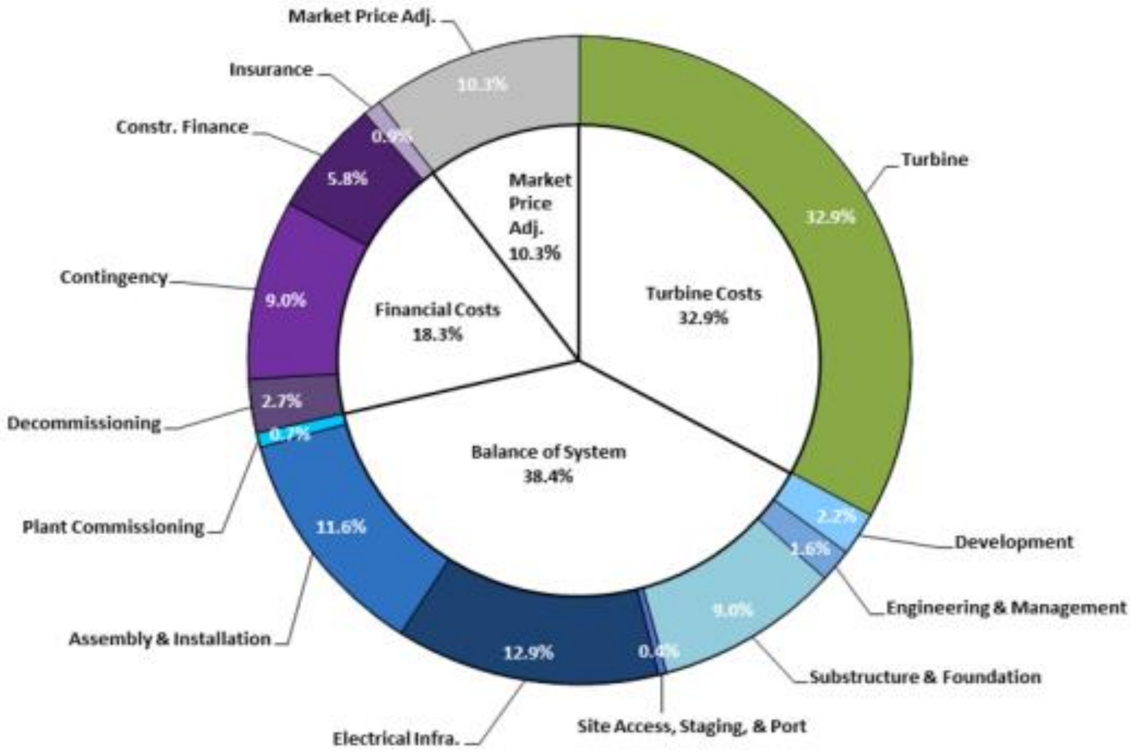


Figure 9 Capital Expenditures for the Offshore Reference Wind Plant Project [8][5]

3.2.2 Operational Expenditure

Operational expenditure covers all the costs paid after the windfarm take over point including operation costs and maintenance costs, which are required to maintain plant availability. OPEX is normally annualized cost with the unit €/MWh (kWh). As a percentage of LCOE, OPEX makes up a considerably higher portion for offshore project than onshore.

Operation cost covers all the non-equipment costs of operations for a windfarm,

- Environmental, health, and safety monitoring
- Annual leases, fees, and other costs of doing business
- Insurance
- Operation, management, and general administration

[5] The market price adjustment is the difference between the modeled cost and the average market price paid for the typical project in 2014.

Maintenance cost covers the following vessel, labor and equipment costs of operations for the windfarm:

- Long-term service agreement
- Scheduled maintenance
- Unscheduled maintenance

3.2.3 Annual Energy Production

In this thesis, AEP refers to the annual energy production of a wind power plant, normally stated as kWh or MWh. Due to the inconstant wind speed, the actual wind power production can never reach theoretical maximum production. AEP is one of the key factors that affect the level of LCOE. The more electricity generated from the wind power plant, the lower LCOE.
As stated above, AEP is calculated based on installed capacity of wind farm, capacity factor, and capacity operational, and capacity factor plays the most important role among them.

$$AEP = InstalledCapacity \times CF \times CO \times 8760$$

The capacity factor is determined by several parameters, including, for example, rrepresentative wind resource, rotor diameter, hub height, generator technology. Normally, the capacity factor ranges from 15% - 50%, typically speaking, due to better wind resource in the sea area, the capacity factor of offshore wind farm is higher than that of onshore wind farm. According to the statistics of European Wind Energy Association (EWEA), in Europe, the average capacity factors for onshore and offshore are respectively 24% and 41% [7].
With the improved generator technology and optimized design of wind turbine blade, the capacity factor increases continuously, thus to raise energy yield accordingly.

3.3 Reference project introduction

In this thesis, the Vesterhav Nord and Syd wind farm and the Borssele 1 and 2 wind farm are selected as reference projects. Both of them are considered as the latest representatives of nearshore and offshore wind projects due to large installed capacity and great site condition.
Offshore wind farm descriptions of Vesterhav Nord and Syd and Borssele 1 and 2 project are summarized in Table 5 below:

Table 5 Summary Description of Reference Projects

		Nearshore	Offshore
LOCATION & NAME	Project Name	**Vesterhav Nord and Syd**	**Borssele 1 and 2**
	Location	Denmark	Netherlands
WTG & CAPAC-ITY	Installed Capacity	350MW	750MW
	Turbine Model	Siemens SWT-8.0-154 [6]	Siemens SWT-8.0-154
	Turbine Capacity	8MW	8MW
	Number of Turbines	44 WTGs	94 WTGs
FOUNDATION & SITE COND.	Foundation Type	Monopile	Monopile
	Water Depth(average)	20 m	28 m
	Distance From Shore	6 km	22 km
ARRAY/EXPORT CABLES	Offshore Substations	0	2
	Nominal Export Voltage	NA	220 kV
	Array Voltage	NA	66kV

Note: the turbine model for Vesterhav wind farm is assumed as Siemens SWT-8.0-154 so as to be comparable for two projects

SOURCE: K2M

3.3.1 Vesterhav Nord & Syd

Vesterhav Nord & Syd nearshore wind farms are located in the offshore area outside Hvide Sande and Thyborøn on the west coast of Jutland in Denmark. The location of Vesterhav Nord & Syd is shown in Figure 10 and Figure 11.

[6] The turbine model chosen for Vesterhav Nord and Syd is an assumption for comparison.

Figure 10 Location of Vesterhav Nord and Syd Nearshore Wind Farm [12]

Figure 11 Location of Vesterhav Nord and Syd [13]

The total wind farm capacity is 350MW, dividing into 170MW for Vesterhav Nord and 180MW for Vesterhav Syd. The Vesterhav wind farm covers an area of 116km^2 in total (Vesterhav Nord: 59km^2; Vesterhav Syd: 57km^2), located around 6km from the west coast of Jutland. The water depth of that area ranges from 15m to 25m, and the annual average wind speed is 10.19m/s[7] [5].

[7] The wind speed is 10-year mean wind speed with the height 100 meters.

Siemens SWT154, 8.0 MW is assumed as the wind turbine model for Vesterhav wind farm. The same turbine is chosen for the Borssele 1 and 2 wind farm in order to reach comparability.

3.3.2 Borssele 1 and 2

With the advantage of great offshore wind potential, the Netherlands government has developed the Borssele wind farm zone (BWFZ), which is located in the southern part of the North Sea. With the total capacity of 1400MW, BWFZ will be the largest wind farm in the EU. BWFZ covers approximately 344km2, and it includes four zones: Borssele 1, Borssele 2, Borssele 3 and Borssele 4. In this thesis, only Borssele 1 and 2 are discussed. The location and layout of Borssele 1 and 2 are shown as Figure 12 and Figure 13.

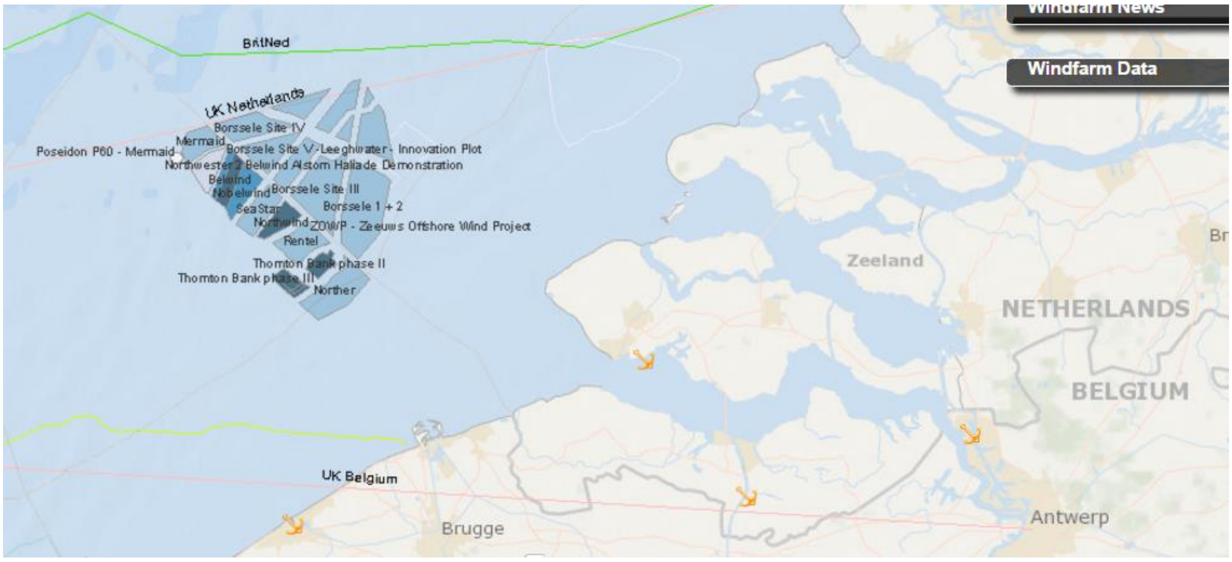


Figure 12 Location of Borssele 1 and 2 [13]

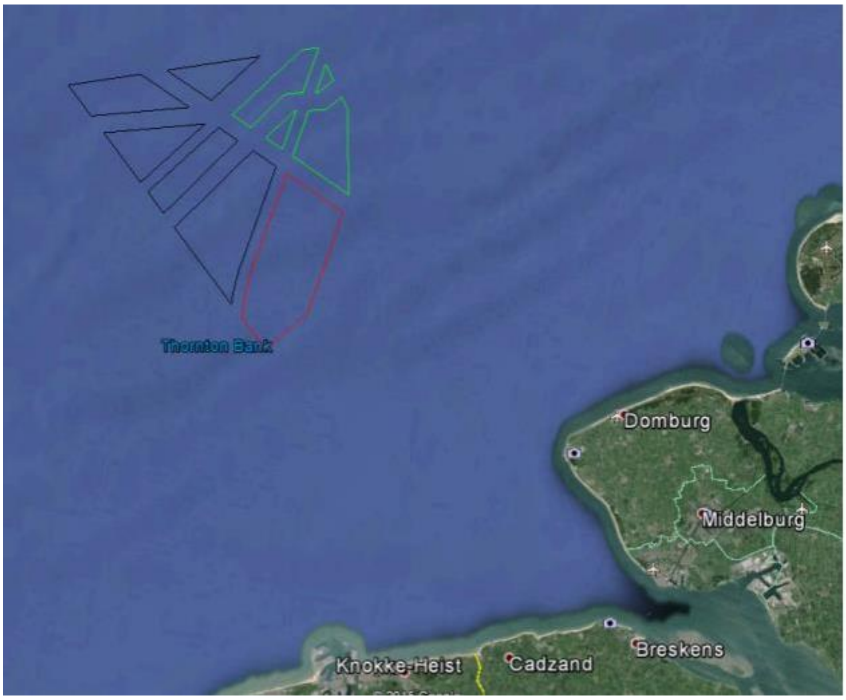


Figure 13 Borssele 1 (green) and Borssele 2 (red) SOURCE: K2M

The total wind farm capacity is 700MW, dividing into 350MW (Zone1) and 350MW (Zone2). The two zones cover an area of 112.6 km^2 in total (Borssele 1: 49.1km^2; Borssele 2: 63.5km^2), located around 22km from the coast of the Dutch province of Zeeland. Water depth of that area ranges from 14m to 38m and annual average wind speed is 10.21m/s[8] [5]. Siemens SWT154, 8.0 MW is selected as a wind turbine for Borssele 1 and 2.

3.4 LCOE calculation of reference projects

3.4.1 Input Parameters and Assumptions

A reference project overview for Vesterhav Nord and Syd and Borssele 1 and 2 wind farms is descried in Chapter 3.3. Major input parameters and assumptions of the reference projects applied in the financial modeling are summarized in Table 6.

[8] The wind speed is 10-year mean wind speed with the height 100 meters.

Table 6 Input Assumptions for Vesterhav Nord and Syd and Borssele 1 and 2

	Vesterhav Nord and Syd	Borssele 1 and 2
WACC	5%	5%
Operational lifetime	25 years	25 years
Capacity factor	39%	42%
Power price inflation multiple	2%	2%
CAPEX/MW	2.5m€	2.69m€
CAPEX share (first power year)-3	1%	1%
CAPEX share (first power year)-2	1%	1%
CAPEX share (first power year)-1	33%	33%
CAPEX share (first power year)	65%	65%
OPEX Multiple	19.06€/MWh	26.68€/MWh

It is necessary to emphasize that all the input assumptions in Table 6 are made by K2M; they may differ from the real data. Input interface of financial modeling is shown in Figure 14.

Wind Farm Information	Applied assumption	Applied scenario	Scenario 1	Scenario 2	Scenario 3
Project Name	**Vesterhav Nord&Syd**	**1**	**Vesterhav Nord&Syd**	**Borssele 1&2**	**Metropolia C**
Country	Denmark	1	Denmark	Nethelands	
Onshore/Offshore	Nearshore	1	Nearshore	Offshore	
Turbine type	SWT-8.0-154	1	SWT-8.0-154	SWT-8.0-154	
Rated capacity	8.0 MW	1	8.0 MW	8.0 MW	
Number of turbines	44 WTGs	1	44 WTGs	94 WTGs	
Installed capacity	352.0 MW	1	352.0 MW	752.0 MW	
Valuation Assumptions					
Currency	EUR	1	EUR	EUR	
Unit	m	1	m	m	
Entry-year for valuation	2016	1	2016	2016	
Valuation date	2017/7/1	1	01.07.2017	01.07.2017	
Mid-year adjustment	Yes	1	Yes	Yes	
Pricing year	2017 real	1	2017 real	2017 real	
WACC	5%	1	5%	5%	
Power production assumptions					
Operational lifetime	25 years	1	25 years	25 years	
First Power	1/1/2019	1	1/Jan/2019	1/Jan/2019	
Last Power	1/1/2044	1	1/Jan/2044	1/Jan/2044	
Capacity factor	39%	1	39%	42%	
Power price inflation multiple	2%	1	2%	2%	
CAPEX Assumption			CAPEX Mutiple	CAPEX Mutiple	CAPEX Mutiple
CAPEX/MW	2.5	1	2.5	2.69	
Total CAPEX	880	1	880	2022.88	
CAPEX share (first power year)-3	1%	1	1%	1%	
CAPEX share (first power year)-2	1%	1	1%	1%	
CAPEX share (first power year)-1	33%	1	33%	33%	
CAPEX share (first power year)	65%	1	65%	65%	
OPEX Assumption			OPEX Mutiple	OPEX Mutiple	OPEX Mutiple
OPEX driver	MWh	1	MWh	MWh	
OPEX Multiple	19.06	1	19.06	26.68	

Figure 14 Input Interface of Financial Modeling by Applying Reference Projects

It is seen that both CAPEX and OPEX of Borssele 1 and 2 offshore wind farm are higher than those of the Vesterhav Nord and Syd nearshore wind farm. Due to the farther distance from the shore, the capital cost and O&M cost for the offshore wind farm are higher than those of the nearshore/onshore wind farm, for instance, the capital cost for Vesterhav Nord and Syd and Borssele 1 and 2 are 2.5m€/MW and 2.69m€/MW, respectively, and the O&M for these farms are 19.06€/MWh and 26.68€/MWh, respectively.

As the distance and water depth both increases, the cost for foundation, BOP and installation increases, as well as O&M cost during the operational phase. However, as a result of better and stable wind resources, normally, the capacity factor of offshore wind farm is higher (Vesterhav Nord and Syd: 39%; Borssele 1 and 2: 42%), thereby producing more electricity annually.

3.4.2 Calculation results

By changing the number of the applied scenario (Vesterhav Nord and Syd: 1, Borssele 1 and 2: 2), LCOE of the two reference projects are computed automatically using LCOE financial modeling, as shown in Table 7.

Table 7 LCOE of Vesterhav Nord and Syd and Borssele 1 and 2 wind farm

	Vesterhav Nord and Syd	Borssele 1 and 2
PV(CAPEX)	862.52 m€	1918.81 m€
PV(OPEX)	384.87 m€	1244.90 m€
PV(Production)	16,232,032 MWh	37,508,341 MWh
LCOE	**77€/MWh**	**84€/MWh**

Table 7 gives the calculated annual CAPEX, OPEX and AEP of Vesterhav Nord and Syd during full lifetime. Figure 16 is the key output of the modeling process.

Year		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Beginning of period		2016/1/1	2017/1/1	2018/1/1	2019/1/1	2020/1/1	2021/1/1	2022/1/1	2023/1/1	2024/1/1	2025/1/1	2026/1/1	2027/1/1	2028/1/1	2029/1/1
End of period		2016/12/31	2017/12/31	2018/12/31	2019/12/31	2020/12/31	2021/12/31	2022/12/31	2023/12/31	2024/12/31	2025/12/31	2026/12/31	2027/12/31	2028/12/31	2029/12/31
Year		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
Capital expenditure(CAPEX)	**mEUR**	8.80	8.80	290.40	572.00	20.23	20.23	0.00	20.23	0.00	0.00	0.00	0.00	0.00	0.00
Operational expenditure(OPEX)	**EUR**	-	-	-	23,499,353	23,969,340	24,448,727	24,937,701	25,436,455	25,945,185	26,464,088	26,993,370	27,533,237	28,083,902	28,645,580
AEP	**MWh**	0	0	0	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740

Year		2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044
Beginning of period		2030/1/1	2031/1/1	2032/1/1	2033/1/1	2034/1/1	2035/1/1	2036/1/1	2037/1/1	2038/1/1	2039/1/1	2040/1/1	2041/1/1	2042/1/1	2043/1/1	2044/1/1
End of period		2030/12/31	2031/12/31	2032/12/31	2033/12/31	2034/12/31	2035/12/31	2036/12/31	2037/12/31	2038/12/31	2039/12/31	2040/12/31	2041/12/31	2042/12/31	2043/12/31	2044/12/31
Year		*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*
Capital expenditure(CAPEX)	**mEUR**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Operational expenditure(OPEX)	**EUR**	29,218,492	29,802,862	30,398,919	31,006,897	31,627,035	32,259,576	32,904,767	33,562,863	34,234,120	34,918,802	35,617,178	36,329,522	37,056,112	37,797,235	1,811,999
AEP	**MWh**	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	1,208,740	56,811

Figure 15 Annual CAPEX, OPEX and AEP of Vesterhav Nord and Syd Wind Farm

LCOE		
PV(CAPEX)	862.52	mEUR
PV(OPEX)	384.87	mEUR
PV(Production)	16,232,032	MWh
LCOE	**77**	**EUR**

Figure 16 LCOE of Vesterhav Nord and Syd

$$\textbf{LCOE}_{\textbf{Vesterhav Nord and Syd}} = \frac{(862.52m€+384.87m€)*10^{\wedge}6}{16232032MWh}$$

$$= 77€/MWh$$

Figure 17 gives the calculated annual CAPEX, OPEX and AEP of Borssele 1 and 2 during full lifetime. Figure 18 is the key output of the modeling process.

Year		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Beginning of period		2016/1/1	2017/1/1	2018/1/1	2019/1/1	2020/1/1	2021/1/1	2022/1/1	2023/1/1	2024/1/1	2025/1/1	2026/1/1	2027/1/1	2028/1/1	2029/1/1	2030/1/1
End of period		2016/12/31	2017/12/31	2018/12/31	2019/12/31	2020/12/31	2021/12/31	2022/12/31	2023/12/31	2024/12/31	2025/12/31	2026/12/31	2027/12/31	2028/12/31	2029/12/31	2030/12/31
Year		*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
Capital expenditure(CAPEX)	**mEUR**	20.23	20.23	667.55	1314.87	20.23	20.23	0.00	20.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Operational expenditure(OPEX)	**EUR**	-	-	-	76,010,537	77,530,748	79,081,363	80,662,990	82,276,250	83,921,775	85,600,210	87,312,214	89,058,459	90,839,628	92,656,420	94,509,549
AEP	**MWh**	0	0	0	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108

Year		2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044
Beginning of period		2031/1/1	2032/1/1	2033/1/1	2034/1/1	2035/1/1	2036/1/1	2037/1/1	2038/1/1	2039/1/1	2040/1/1	2041/1/1	2042/1/1	2043/1/1	2044/1/1
End of period		2031/12/31	2032/12/31	2033/12/31	2034/12/31	2035/12/31	2036/12/31	2037/12/31	2038/12/31	2039/12/31	2040/12/31	2041/12/31	2042/12/31	2043/12/31	2044/12/31
Year		*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*
CAPEX	**mEUR**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OPEX	**EUR**	96,399,740	98,327,735	100,294,289	102,300,175	104,346,179	106,433,102	108,561,764	110,732,999	112,947,659	115,206,613	117,510,745	119,860,960	122,258,179	5,861,057
AEP	**MWh**	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	2,793,108	131,276

Figure 17 Annual CAPEX, OPEX and AEP of Borssele 1 and 2 wind farm

LCOE		
PV(CAPEX)	1918.81	mEUR
PV(OPEX)	1244.90	mEUR
PV(Production)	37,508,341	MWh
LCOE	**84**	**EUR**

Figure 18 LCOE of Borssele 1 and 2

$$\text{LCOE}_{\text{Borssele 1 and 2}} = \frac{(1918.81m€+1244.90m€)*10^6}{37508341MWh}$$

$$= 84€/MWh$$

It is seen that, based on the results of two reference projects, the LCOE of an offshore wind farm is higher than that of a nearshore wind farm; however, the conclusion is draw on the premise of same financial assumptions (inflation rate, WACC). In practice, the financial assumptions may vary case to case, in addition, other factors, such as subsidy scheme, policy and regulations, also play a significant role on cost of wind energy. In the following Chapter 4, the LCOE of offshore wind energy for different countries is elaborated comprehensively.

4 Cost of Offshore Wind Energy in Different Markets

In this Chapter, the cost of offshore wind energy in four countries, United Kingdom, China, South Korea, Japan, has been analysed from the point of view of technique and policy and regulation, as well as the development trend of wind power. The purpose of this chapter is to elaborate how the input parameters affect LCOE offshore wind power; besides the input parameters above, how the policies and regulations influence the cost level of wind power as well.

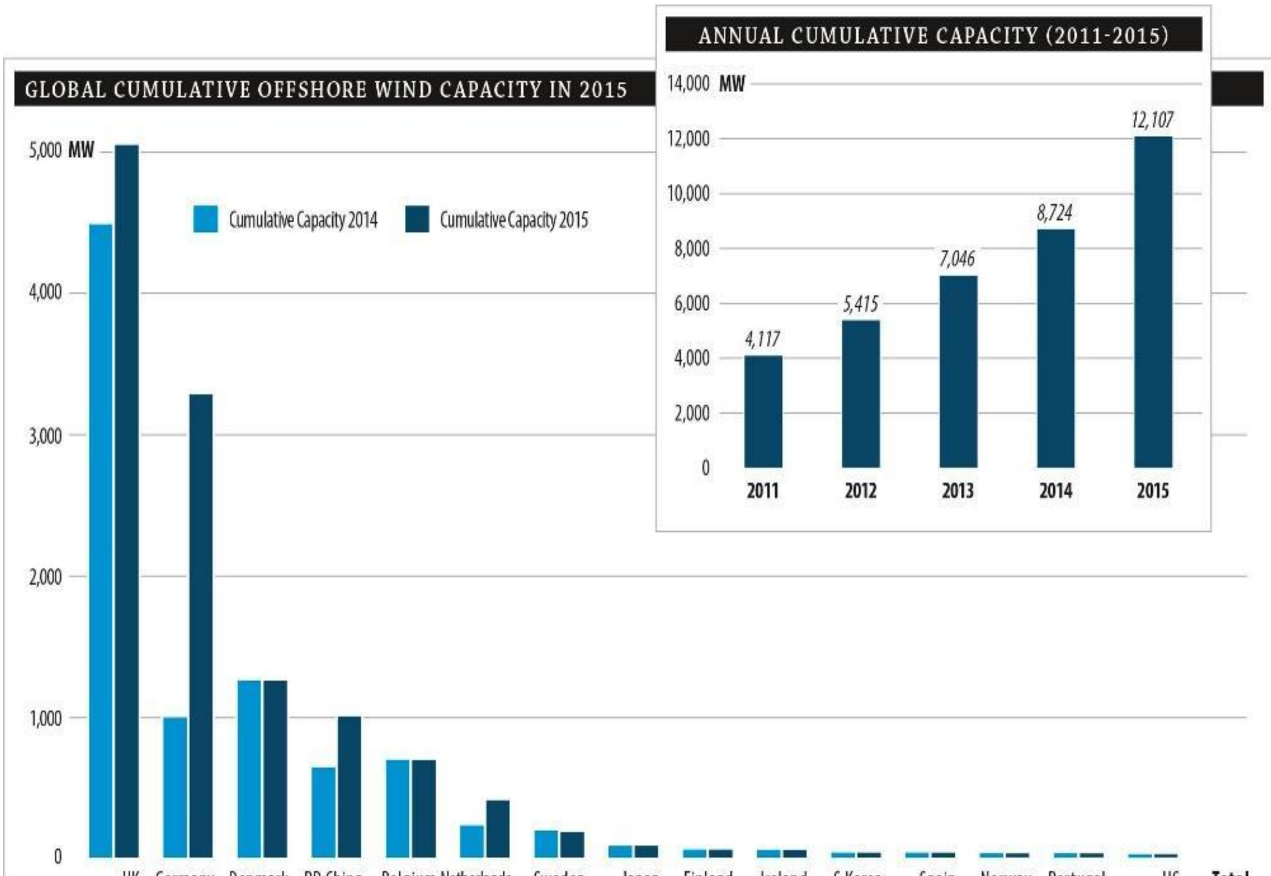
4.1 United Kingdom

4.1.1 Overview

The UK holds the leading position of offshore wind industry across the world in terms of design, development, financing, construction and operation. With the implementation of numerous offshore wind farms, the UK has emerged as the most prominent offshore wind energy market in Europe.

- Highest share of consented offshore wind capacity

- Largest installed capacity of offshore wind power (5,067MW in total by 2015, see Figure 19 and 10,000MW on track by 2020)
- Wind energy is the biggest single source of renewable energy (10% of the UK's electricity supply is provided by wind energy).
- 11% of the UK's total electricity supply was provided by wind power in 2015



	UK	Germany	Denmark	PR China	Belgium	Netherlands	Sweden	Japan	Finland	Ireland	S Korea	Spain	Norway	Portugal	US	Total
Total 2014	4,500.4	1,012	1,271	654	712	247	212	50	26	25	5	5	2	2	0.02	8,724
New 2015	572.1	2,282.4	0	360.5	0	180	0	3	0	0	0	0	0	0	0	3,398
Total 2015	5,066.5	3,294.6	1,271.3	1,014.7	712.2	426.8	201.7	53	26.3	25.2	5	5	2.3	2	0.02	12,107

Figure 19 Global Cumulative Offshore Wind Capacity in 2015 and Annual Cumulative Capacity (2011-2015) [6]

By the end of 2015, there were 29 offshore wind farms in UK with operational capacity over 5,1GW and further 4,5GW are under construction. The location of the UK's offshore wind resource provides for geographical diversification across the UK territorial waters and the Continental Shelf. Figure 20 illustrates the distribution of the UK offshore wind farm. Most offshore wind farms (over 80%) are located in English waters.

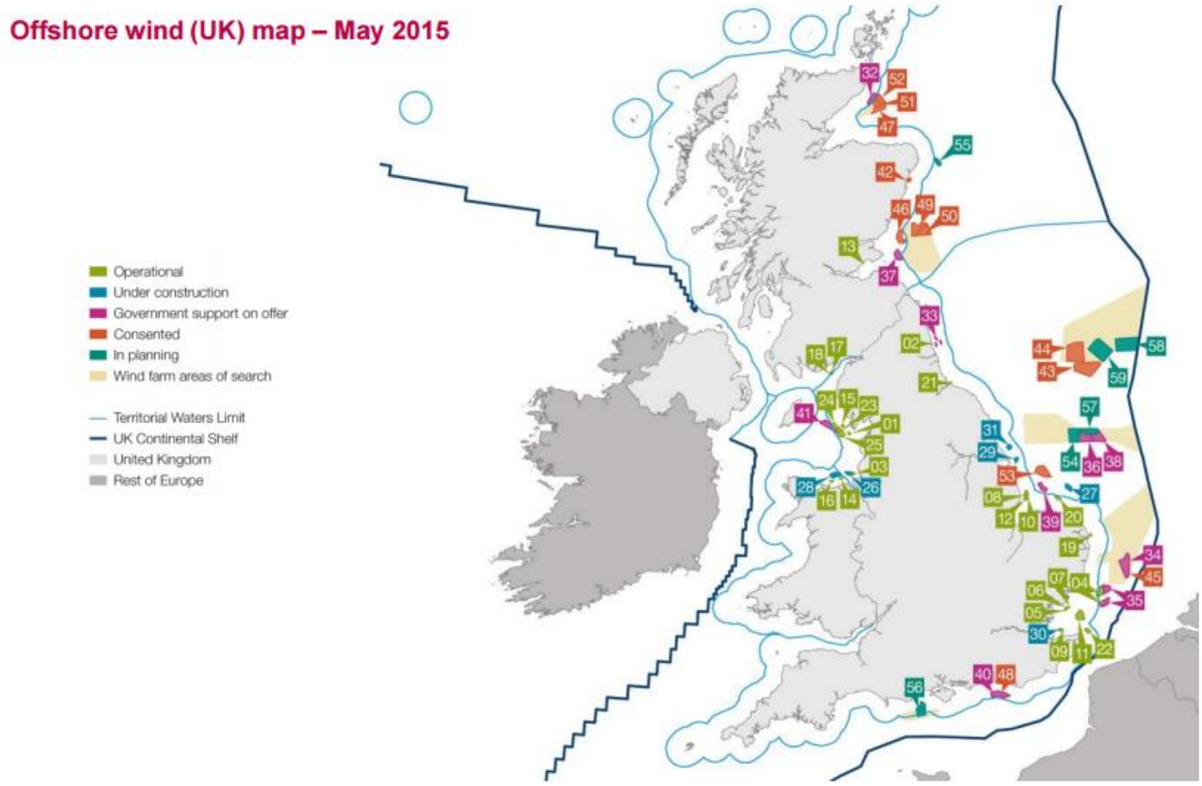


Figure 20 UK Offshore Wind Map 2015 [12]

By the end of 2016, the offshore cost data has shown that the average of LCOE of the UK offshore wind farm is £97/MWh, achieving 32% reduction of £142/MWh on the end of 2011 [9]. Larger rated turbines and innovation of installation pose the largest impact on reduction of LCOE. Figure 21 demonstrates the reduction of LCOE for projects reaching Final Investment Decision (FID) from 2010 to 2016 [9]. In addition, the UK government has committed to reduce the strike price so as to ensure further cost reduction.

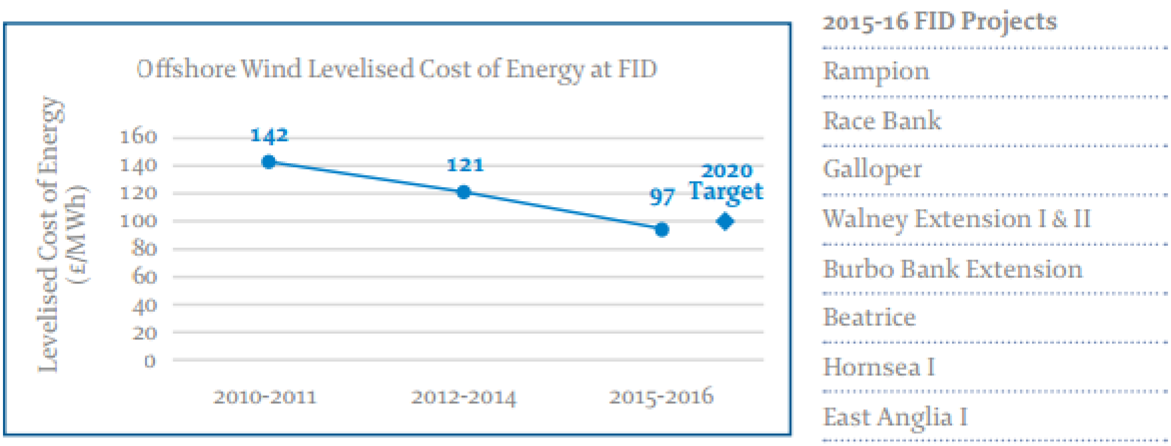


Figure 21 UK Offshore Wind Levelized Cost of Energy at FID

Figure 22 has illustrates the advantages of offshore wind market in the UK and competitiveness, mainly reflecting in 4 aspects, wind resources, offshore technology, supply chain and policy and regulation. Each aspect was discussed thoroughly in following paragraphs.

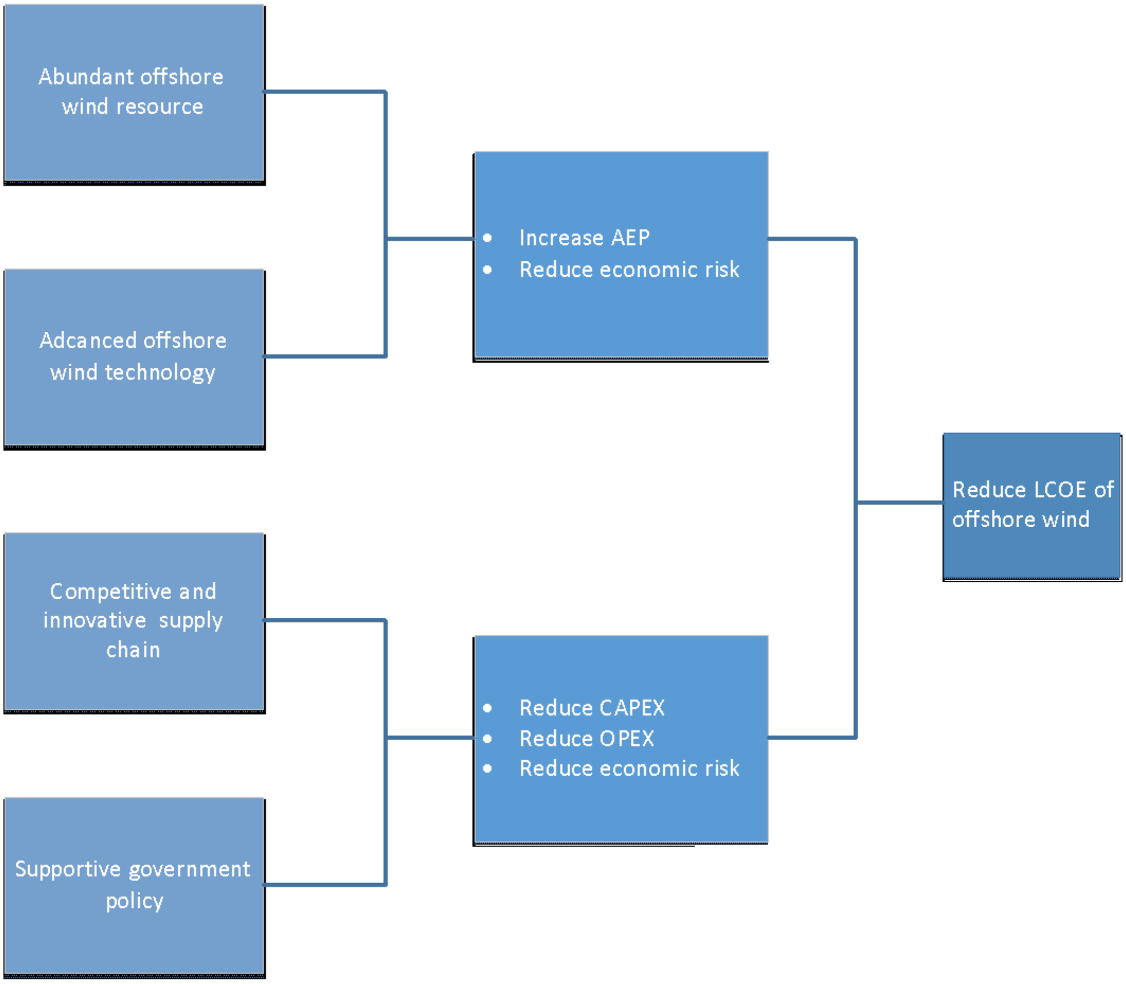


Figure 22 Advantages and Competitiveness of the UK Offshore Wind

4.1.2 Wind resources

The location of the UK makes it owns extremely rich wind resources, and most of it are concentrated in the north and west area, especially in Scotland which has higher w and lower population density. [14] See Figure 23.

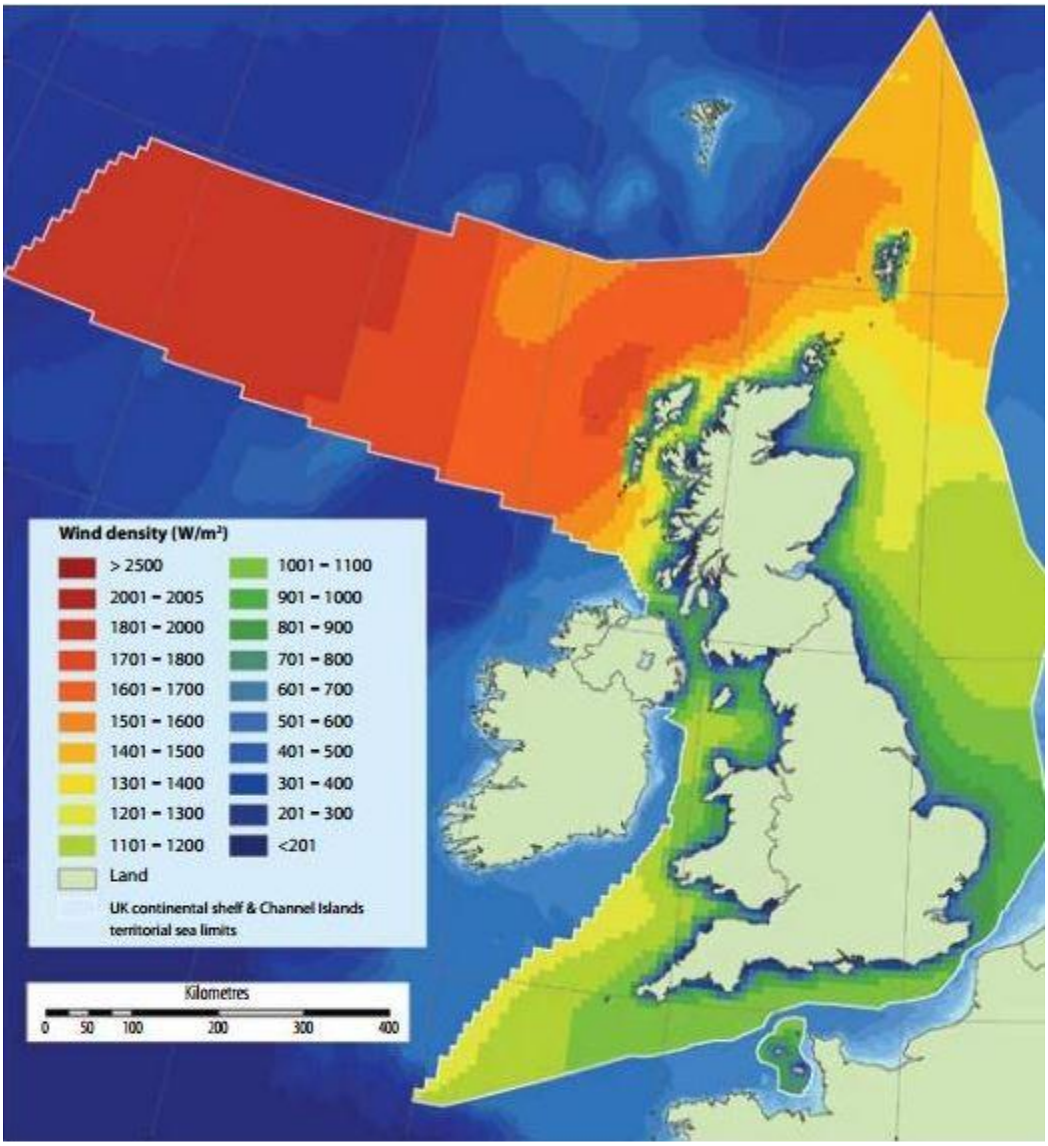


Figure 23 UK Annual Mean Wind Power Density at 100m Above Sea Level (W/m2) [14]

4.1.3 Technology

Turbine

The biggest driver of wind cost reduction in the UK is the larger rated turbine. Walney Extension (659MW) and Burbo Bank Extension (254MW) offshore wind farms have adopted turbines with 8MW nameplate capacity. With improved turbine technology, larger wind turbine, such as 8MW, almost as twice size as the previous standard, is becoming the development tendency in offshore wind industry. The generation cost is lower in the long run due to less foundation, subsea cables and maintenance cost to produce same power as multiple small-sized turbines.

Furthermore, energy generation is largely depends on availability, reliability and longevity of the wind turbines. Larger offshore turbines with optimized rotor diameter and control system deployed in UK boost wind turbine productivity and reliability. Design and manufacturing improvements notably promoted turbine reliability thereby reducing the frequency and cost of unscheduled maintenance.

With increased availability & reliability and prolonged life-span of turbines, the capacity factor and the capacity operation of OWF keep increasing, further mitigating OPEX through better energy capture and conversion. Figure 24 has shown a depiction of the OWF capacity factor distribution and how the capacity factor in the UK changes over time. In this chart, data of 22 UK offshore wind farms which are currently in operation is collected and plotted, see Table 8 and Figure 24 [10]. The x-axis represents the operation years for each OWF and the y-axis represents the corresponding capacity factor. It can be clearly seen that the primary trend of the capacity factor of offshore wind power is growing over time; to be specific, the OWF which started operating before 2010 have lower CP (below 40%); with improved offshore technology, the capacity factor increases over 40% for OWF which started operating after 2010.

Table 8 Operation Years and Capacity Factors of OWF in UK [10][9]

OWF	Years of operation	Capacity Factor
Kentish Flats Extension	1,1	43,30%
Humber Gateway	1,6	41,10%
Westermost Rough	1,6	42,90%
West of Duddon Sands	2,2	44,20%
Lincs	3,3	42,00%
Sheringham Shoal	3,3	40,70%
Greater Gabbard	3,4	42,20%
London Array	3,7	41,10%
Walney phase 2	4,5	47,50%
Ormonde	4,9	40,10%
Walney phase 1	5,5	40,70%

[9] All the data in Table 8 was collected by the end of January, 2017. Data in the original source is updated every month.

Robin Rigg	6,3	35,10%
Thanet	6,3	32,80%
Gunfleet Sands	6,5	36,70%
Rhyl Flats	7,1	32,80%
Inner Dowsing	7,8	34,10%
Lynn	7,8	34,50%
Burbo Bank	9,2	35,80%
Barrow	10,3	35,90%
Kentish Flats	11,1	31,20%
Scroby Sands	12,1	30,60%
North Hoyle	12,5	31,80%

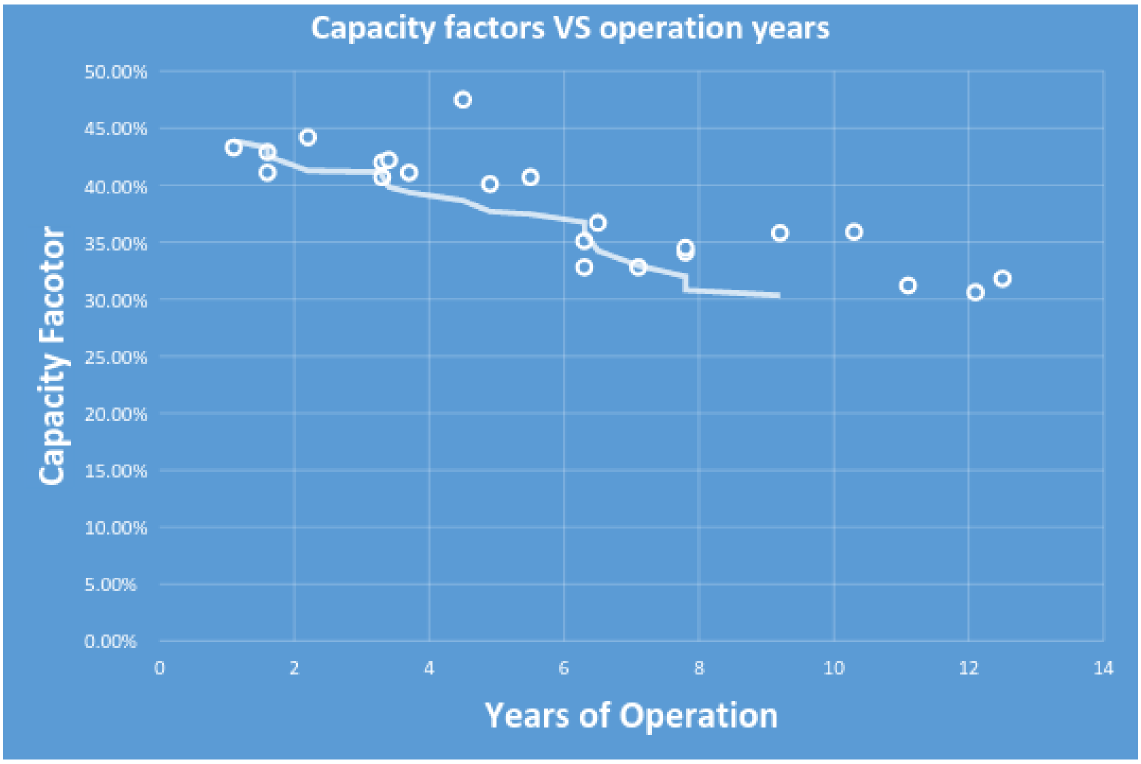


Figure 24 Capacity Factor Distribution of OWF in the UK

BOP

Improved balance of plant (BOP) components, such as electrical infrastructure and foundation, are also critical to drive the offshore LCOE down. With the increased rated capacity of offshore turbine, 33kV inter-array cables is replaced with the higher voltage IAC (66kV) step by step. AC/DC transmission solution with integrated/limited offshore platforms reduce the grid losses and improve the power transmission efficiency between the high-power large turbines, as well as diminish the transmission cost. Additionally, for offshore wind farms in the UK, the lighter transformer greatly cut down the cost of bespoke substation.

The latest foundation technology is applicable to wider range of site characteristics and higher capacity turbines. Foundation with improved foundation design enables installation of larger turbines in offshore area further always from coastline without increasing the cost of energy.

Supply chain

The offshore industry, cooperated with the UK government, has built a competitive and innovative supply chain, and mainly covering 6 elements as:

- Project management and development
- Turbine supply
- Balance of plant supply
- Installation and commissioning
- Operation, maintenance and service (OMS)

The competitiveness of the UK offshore supply chain is embodied in the following aspects:

- Great number of the UK based manufactures, saving transportation cost due to logistical advantages
- Strong track record and capability to deliver improved turbine, foundation, cable which suitable for various site characteristics.
- Attract both domestic and foreign developers while intensive competition drives the cost down at developer level.

Increased competition at developer level drives higher cost efficiency while the pressure is deflected to supply chain where margin is reduced. The offshore cost in the UK is continuously diminishing through technology innovation, delivering economic benefits.

Supply chain has been built through expansion. See Figure 26. The UK offshore expertise has been exported across the world. The UK is a strong platform to boost manufacturing capability and the government is also supportive to develop the capabilities and capacity of the UK based companies, keeping the UK in a strong position to access the largest global market for offshore wind. Figure 25 has demonstrates the share of export contracts by activity until 2020. [11]

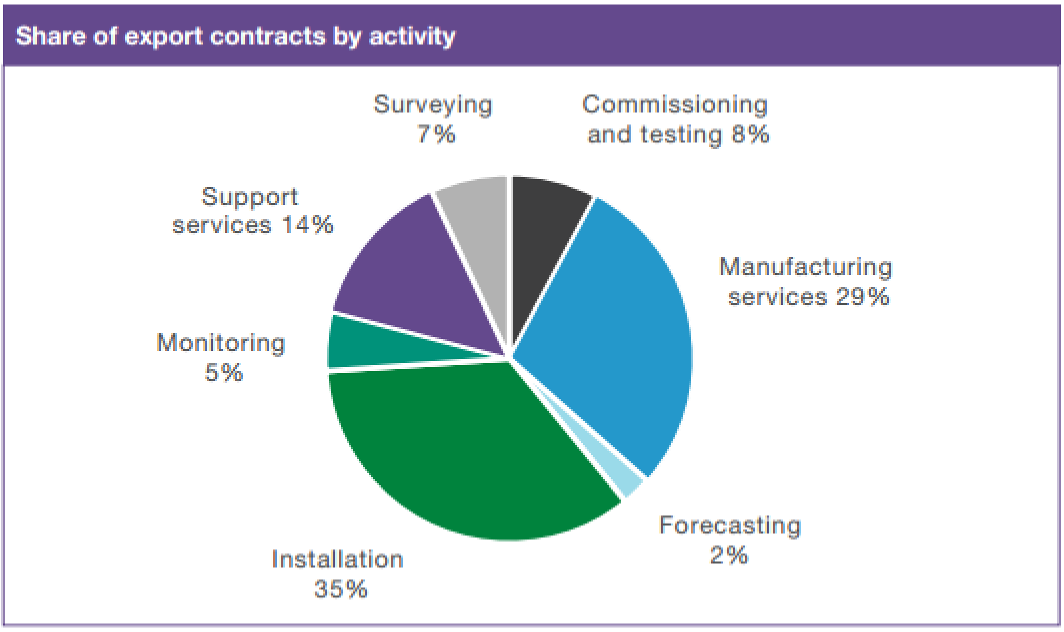


Figure 25 Share of UK Export Contract of Wind Industry by Activity [11]

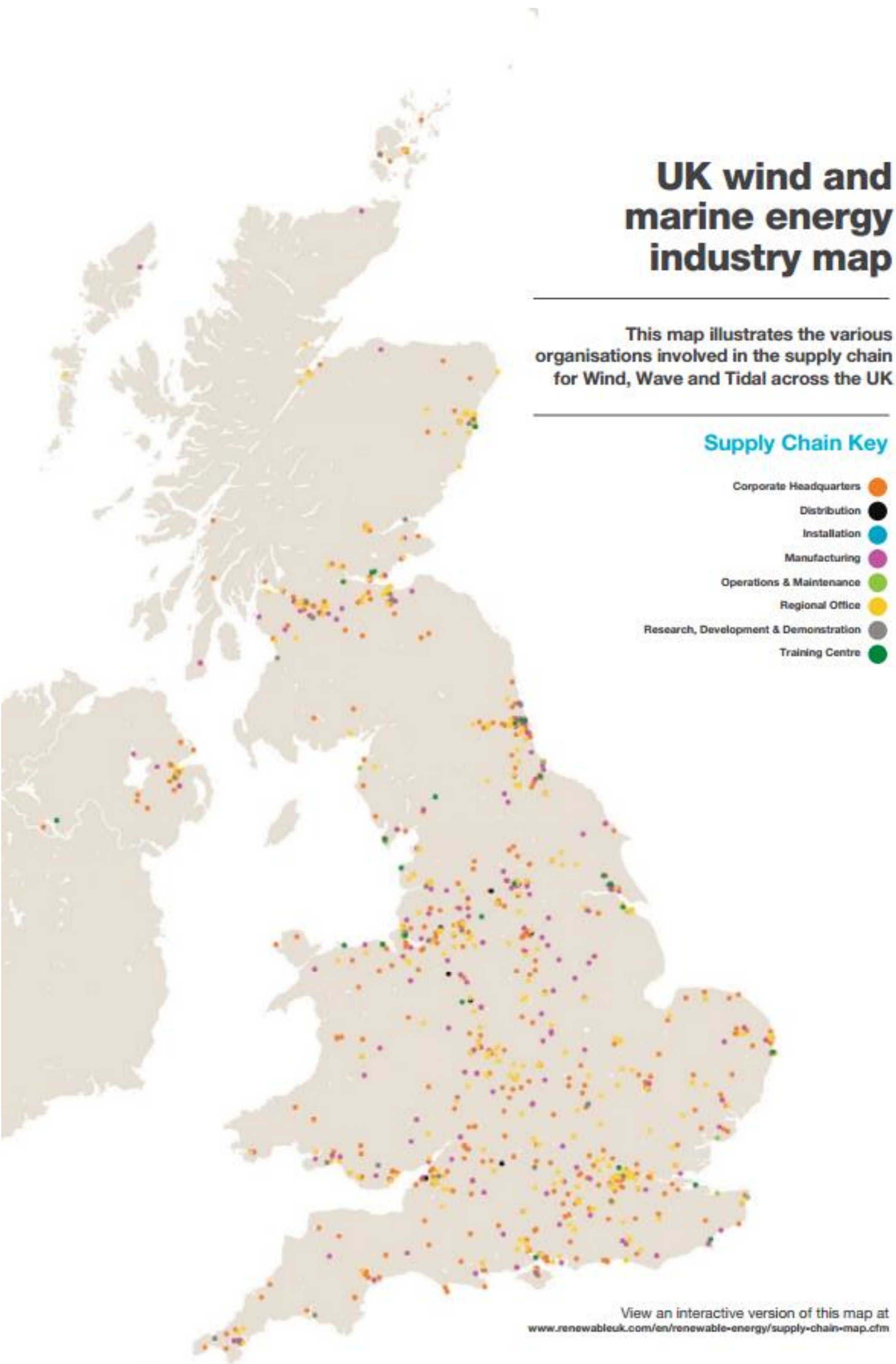


Figure 26 UK Wind and Marine Energy Industry Map

Offshore logistics

Offshore logistics and installation play an essential role for offshore wind project, representing around 15% of project life cycle expenditures. The UK offers significant offshore logistic advantages and mature supply chain in the UK enables faster installation and less weather. Asset accessibility is a pivotal factor during installation work considering deeper water, higher wave and weather limitations.

Besides of various OEMs, competitive advantage of the UK offshore market also lies in the advanced vessels covering survey, construction & installation, operation & maintenance. Multipurpose vessels with higher capability and availability is applicable for wind farms being farther offshore and capable to minimize and combine offshore activities. Meanwhile, advanced vessel design allows to accommodate more turbines or/and foundations per vessel which increasing installation efficiency and optimizing O&M performance, hence lowering the LCOE of offshore wind.

Operations & Maintenance

As a fundamental contributor to the cost of energy, O&M cost accounts for approximately 25% of the life-time expenditure and occurs throughout the lifetime of wind farm. Due to the rapid growth of the UK offshore wind industry, the enormous market for Operation & Maintenance service is emerging, being able to cover the full range of O&M activities, making the UK competitive with other countries. Reducing the cost of electricity from offshore wind farms is a primary focus for O&M, and competitiveness also promotes companies to bring solutions to the market which reduce costs and boost revenue.

Generally speaking, compare to other countries, the UK cost-effective O&M strategy enables fewer breakdowns and less response time, which are two fundamental factors to lower OPEX. To be specific, except higher turbine availability and reliability which minimize breakdowns as mentioned above, advanced remote monitoring and control system adopted, less transit time and higher accessibility to the site promote OWF performance and enable to make unscheduled activities more predictable, thereby reducing OPEX and diminishing the offshore LCOE.

4.1.4 Policies and Regulations

The UK government has been supportive to wind industry, and the primary activities include [12]:

- Providing market confidence and demand visibility
- Building a competitive supply chain
- Supporting innovation (vital to achieve cost reduction)
- Finance
- Building a highly skilled workforce

In order to reduce the costs of offshore wind continuously, the UK government has established and introduced various policies and financial supports to advocate technology development, and leveraging the power of partnership and collaboration to accelerate cost reductions, see Table 9.

Table 9 The UK Renewable Energy Support Policies

Support Types	Support Policies
Financial Support Scheme	Renewables Obligation (RO)
	Contracts for Difference (CFD)
Government-Industry Collaboration Programmes	Electricity Market Reform
	Carbon Trust's Offshore Wind Accelerator programme
	Offshore Renewable Energy Catapult
	Offshore Wind Cost Reduction Task
Other economic incentives	The removal of exemption from the Climate Change Levy
	Enterprise zone funding

Renewable Obligations (RO)

Introduced in 2002 (RO) was the financial mechanism applied for renewable energy projects [10] before April, 2017, and its tenure is 20 years support period. Electricity suppliers are obligated to source an increasing proportion of the electricity they supply from renewable sources. [11]

> For accredited renewable generating stations, renewables obligation certificates (ROC) are issued to the operators. ROCs are certificates issued to operators of ac-

[10] RO is only applied for large scale, smaller scale wind power plants are mainly supported by FIT.
[11] Renewable Obligations (RO) is replaced with Contract for Difference (CfD) from April, 2017.

credited renewable generating stations for the eligible renewable electricity they generate. Operators can trade ROCs with other parties. ROCs are ultimately used by suppliers to demonstrate that they have met their obligation. (Source: GOV.UK)

Figure 27 illustrates principle mechanism of RO financial mechanism.

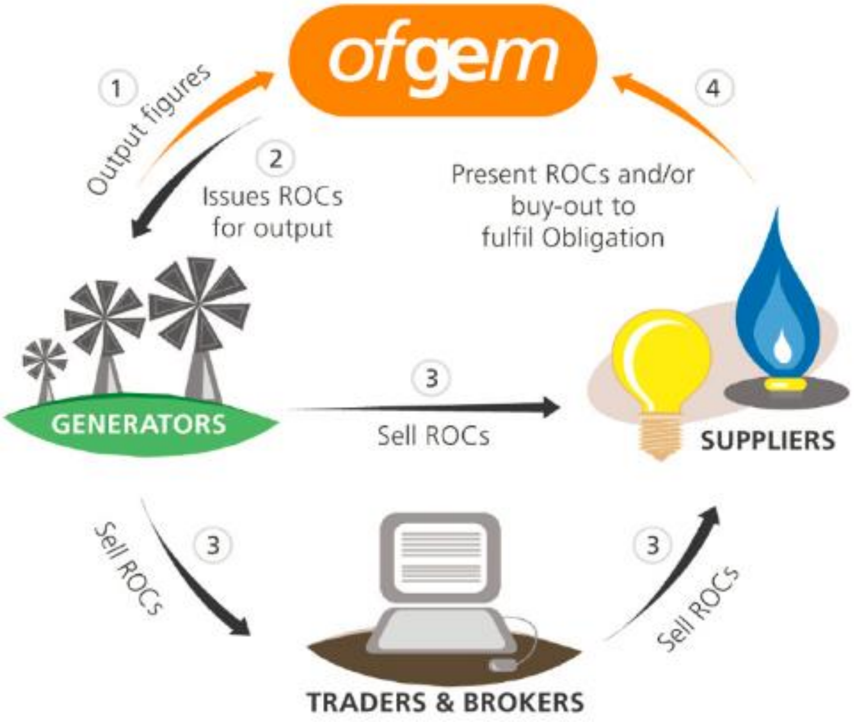


Figure 27 Renewable Obligations (RO) [18]

According to the regulations, per unit wind power (MWh) equals to 0.9 Renewable Obligation Certificates (ROCs) for onshore wind farm; and 1.8 ROC per MWh for offshore wind farm. Each ROC is worth 40£ (46€) and ROC income is on top of wholesale power revenue, in the range 30£ - 40£/MWh (35€-46€).

CFD

As a key part of Electricity Market Reform introduced by government, Contract for Difference (CfD) is an incentive mechanism to promote renewable energy in the UK. Contract for Difference (CfD) is a 15-year fixed price contract and it provides greater certainty and stability of revenues to electricity generators, offering relatively low risk profile. By attracting more wind energy investments, the generation cost keeps bringing down, with competitive bids submitted. According to Department for Business, Energy & Industrial Strategy of UK:

Contract for Difference (CfD) is a private law contract between a low carbon electricity generator and the Low Carbon Contracts Company (LCCC), a government-owned company. A generator party to a CFD is paid the difference between the strike price and the reference price. Strike price may be an administered price set by the government or, in circumstances of high demand for contracts, the clearing price from a competitive auction, see Figure 28.

Offshore Wind Strike price (£/MWh) (2012 prices)

14/15	15/16	16/17	17/18	18/19
155	155	150	140	140

Figure 28 Offshore Wind Strike Price (2012 prices) [12]

Figure 29 below has demonstrated principle mechanism of CfD. When the market price of electricity is lower than strike price, then the payments are made by LCCC to the electricity generator to make up the difference and vice versa.

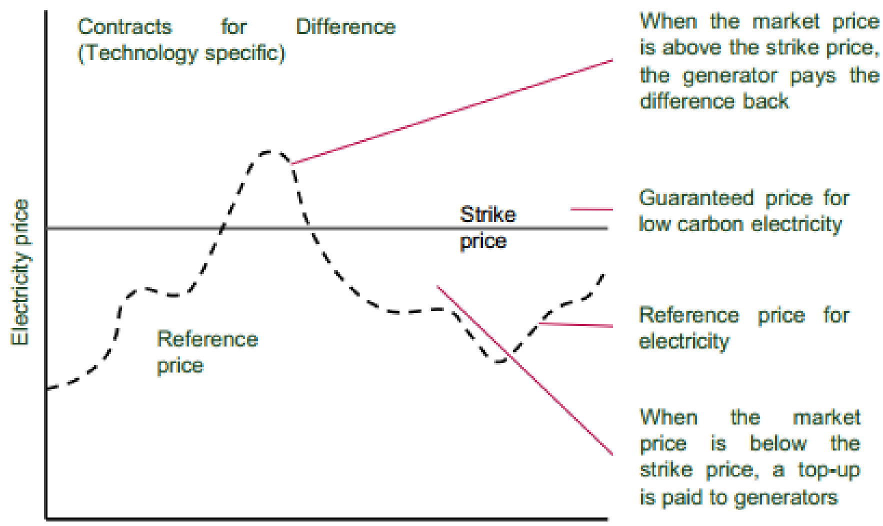


Figure 29 Principle of Contract for Difference[12] [12]

The economic benefits of CfD include:

- A feed-in tariff that provides a top-up payment above the wholesale price of electricity up to a fixed price, referred to as strike price.

[12] Strike price is a price for electricity reflecting the cost of investing in a particular low carbon technology. Reference price is a measure of the average market price for electricity in the GB market. Source: GOV.UK

- A competitive allocation process for generators.
- Linked to a fixed Levy Control Framework which sets the amount of funding available.
- Attracts more investment to wind energy.
- Reduce capital cost as much as possible (lowest possible cost for consumer)

Besides of RO and CfD, revenues for renewable generators are also supported through, first, the exemption from the UK's Climate Change Levy – realized through the sale of Levy Exemption Certificates (LECs); secondly, EU Emissions Trading Scheme and the UK's Carbon Price Floor to achieve avoided costs of carbon emissions. [13]

Consenting process for offshore

The consenting period for offshore wind in the UK is much shorter than that of other countries, and it takes around 22 months. The approval rates is also considered high, around 90% [14], bringing market confidence and lower project risks. Consenting process for the offshore wind project includes two key stages:

- An Agreement for Lease (AfL)
- Lease

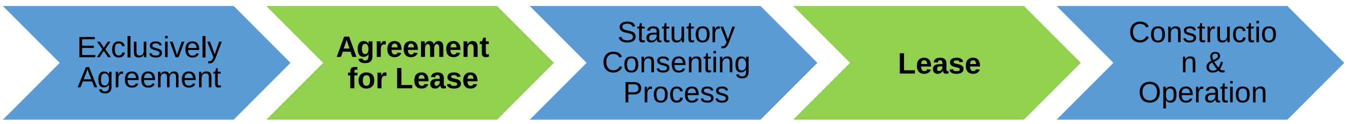


Figure 30 Consenting Process for Offshore Wind Project UK [12]

4.2 China

4.2.1 Overview

Offshore wind power in China is still at the primary stage, and cost has been a major deterrent for the offshore wind development. According to the statistics from Carbon Trust, deployment cost of OWF with shore distance less than 15km in China is ranging from €1.5m/MW to €1.6m/MW, showing a bit higher than the deployment cost in the UK. The current development is facing both opportunities and challenges, and constrained by weaknesses, causing the relative high LCOE for offshore wind.

Most of China’s energy demand is concentrated along the east costal area; and by utilizing the offshore wind resources efficiently could significantly relieve the pressure of eastern electricity supply. Nevertheless, unlike onshore wind, which contributes the majority of wind power generation, offshore wind is developing slowly. The total installed wind capacity until 2015 is 145,362MW, for which offshore wind accounts merely 0.7% (cumulative capacity for offshore is 1,014.68MW until 2015). However, 200GW of offshore wind power at water depth between 5 and 25 meters has been identified, with additional 300GW offshore wind at water depth between 25 and 50 meters, showing huge potential of offshore wind power development and cost reduction.

Challenges that contribute to the high development cost are summarized as technical barriers and non-technical barriers, followed with detailed discussion. See Table 10 and Table 11. Technical barriers mainly focus on turbines, foundations, installation and O&M of offshore wind farms. Non-technical barriers are explained from the perspective of developers, policies and regulations.

4.2.2 Wind resources

Compare to European countries, China has relatively poorer wind resources. Figure 31 has shown the distribution of annual average wind power density in 5-50m depth sea areas of China [15].The wind speed increases from north to south along China’s east coast; wind resources sufficient for offshore wind power deployment are mainly located in the southeast coast areas. The most abundant wind resources are based in the area of Taiwan Strait. Average wind speed of coast area of Fujian is between 8-10 m/s, and the neighboring provinces, such as Zhejiang, Jiangsu, Guangdong, have slightly lower wind speed, around 6-7.5 m/s, where are also rich in wind resources and largely influenced by typhoon and tropical monsoon.

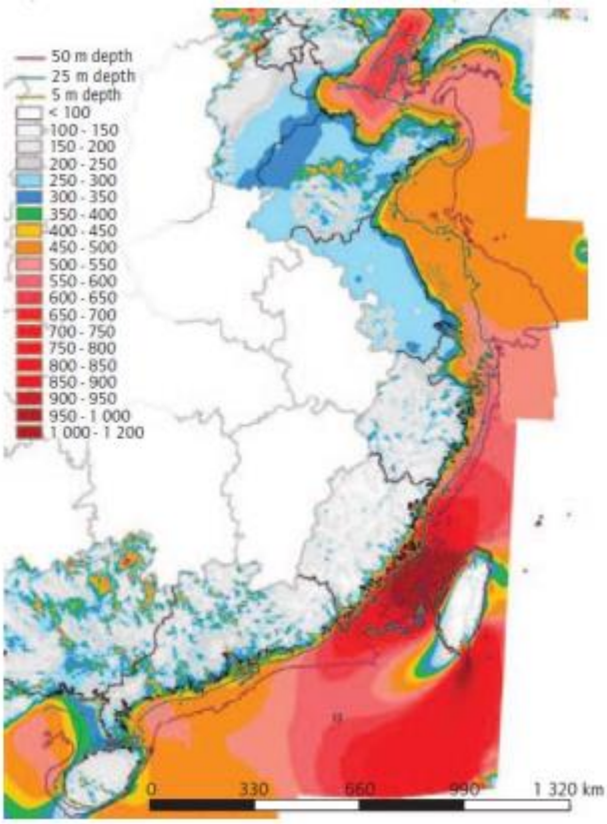


Figure 31 Average Wind Power Densities in 5-50m Depth Sea Areas of China [15]

4.2.3 Technical barriers

Table 10 has summarized the technical barriers of offshore wind development in China.

Table 10 Technical Barriers of Offshore Wind Development in China

Category		Current Situation	Impact On Lifetime Expenditure
Turbine	Turbine size	Turbines with lower rated capacity, ranging from 3MW-5MW	High CPAEX and OPEX
	Turbine availability	Lower rate of availability, normally below 95%	High OPEX
	Turbine corrosion	Anti-corrosion solution	Extra cost on CAPEX
Foundation	Water depth	Shallow water and smooth submarine topography	Reduce CAPEX
	Seabed condition	Weak and unconsolidated seabed	Increase installation cost and OPEX
	Extreme weather condition	Typhoon mostly in Taiwan Strait	Increase installation cost and OPEX
	Foundation corrosion and fatigue problem	Corrosion resistant coating; Lack of standard for quality verifying	Increase CPAEX
Installation	Vessel availability	Lack of installation vessels	Increase installation cost
	Seabed condition	Too soft to use traditional installation vessel but floating installation vessels	
Operation & Maintenance	O&M experience	More frequent repair and maintenance work due to lower turbine availability	Increase OPEX
	Access vessels	Lack of access vessels and limited capability	

	Monitoring software	Adopt monitoring tools developed by European countries	

Turbines

- Turbine size

  Currently the majority of turbines installed for offshore wind farm are 3MW, even though a number of Chinese manufacturers are developing larger turbines with capacity 5MW or 6MW, they are not deployed in large scale so far. Compare with large turbine, the current employed offshore turbines in China mostly are small ones in terms of name-plate capacity, which may increase the cost including extra cable cost, installation cost and further O&M cost.
- Turbine availability

  Most of offshore turbines are supplied by Chinese OEM. From the cost perspective, although the Chinese turbine is cheaper than turbines manufactured by European OEMs, turbine availability, a key driver for achieving favorable project economic benefit, is lower than that of European offshore wind turbines whose TA can achieve over 95%. High availability is the pivotal factor for the economics of any OWF due to the high O&M cost. The lower rate of availability of Chinese offshore turbine, namely, low system reliability and insufficient maintenance capability, directly causes lower production and more repair and maintenance work that further increase the OPEX.
- Turbine corrosion

  Given the fact that China has quite unique coastal characteristics, turbines installed in such areas are subjected to corrosion issue which may reduce turbine availability. Therefore, in order to expand the lifetime of OWF in China, anti-corrosion solutions are necessary to meet the geographical and climate conditions in China, causing extra cost of turbines.

Foundations

- Water depth

As an advantage, China has shallow water and relative smooth submarine topography off the coast which is suitable for various adoption of foundation types. In comparison, unlike South Korea or Japan where the more expensive floating foundation is favored, diverse cheaper foundations can be adopted for offshore wind farm in China, namely, lower CAPEX can be implemented. Additionally, during the operation phase, shallow water depth and short distance from shore decrease the OPEX owing to the ease of access.

- Sea bed condition

  The sea bed condition in China is another site characteristic different from European countries. Unlike the firmer sea bed condition in Europe, the upper layer of sea bed in China contains muddy and silty clay from 0-25m, showing unconsolidated characteristic. A very thick layer of soft soil is laying beneath the upper layer (See Figure 32).

Figure 32 Typical Sea Bed Condition in Coastal Area of China [24]

Additionally, due to the weak and soft sea bed condition, accurate preparation of seabed and cable protection are crucial for OWFP development, thereby causing additional expenditure. Considering both the seabed characteristics and the ability to withstand turbulent movement of ocean, currently, types of WTG foundation are limited and the most popular foundation for offshore wind farm in China are high-rise pile caps and monopiles. More offshore foundation types are still under demonstration stage.

- Extreme weather condition

  For the coastal area where are largely influenced by typhoon and tropical monsoon as mentioned above, offshore foundation should be designed specifically to resistant extreme weather condition, thereby reducing economic risks.

- Foundation corrosion and fatigue

As similar as offshore turbines, foundations are confronted with corrosion and fatigue problems. Special coatings for foundation can be effectively corrosion resistant, which is not a critical issue. However, fatigue issue increases economic risk greatly as currently there is no standards or third party surveillance in place to verify the quality of offshore foundations in terms of strength and reliability.

Installation

- Installation is the major cost for offshore wind farms in China due to the lack of offshore wind supply chain. The shortage of expertise and bespoke installation vessels greatly increase project cost. Currently, there are only 6 vessels for turbine and foundation installation and 2 vessels for cable installation.
- Additionally, due to the soft sea bed condition, types of installation & maintenance vessel are limited and traditional jack-up vessel which dominate in Europe market is not a favored option in China. By using floating installation vessel may resolve the difficulty, yet, it results in higher cost of installation.

Operation & Maintenance

- As mentioned above, lower availability and reliability of Chinese turbine and foundation significantly increase O&M cost of OWF.
- So far, there is no sufficient access vessels and transfer systems to carry out the repair and maintenance work. A lack of expertise also limits the operation window for conducting the relative work.
- Currently, there is no software tools developed by Chinese company used for monitoring the operation of OWF. In China, most monitor software applied for offshore wind farm O&M are developed by European companies, adding extra cost to OPEX.

4.2.4 Non-technical barriers

Table 11 has summarized the non-technical barriers of offshore wind development in China.

Table 11 Non-Technical Barriers of Offshore Wind Development in China

Category	Current Situation	Impact On Lifetime Expenditure
Developers	Dominated by Chinese SOEs and lack of competitiveness	High CAPEX
	Centrally controlled economy and lower profitability	
	Limited offshore project development experience	
Consenting Process	Lack of government coordination	High CAPEX
	Conflicts between multi government departments	
	Lengthy and complicated consenting process	
Feed-in tariff	Lower feed-in tariff price	Reduce LCOE of offshore
	Unable to cover the costs of OWF completely	
Other economic incentives	Reward for OWF from local government	Reduce LCOE of offshore
	Reduction of VAT and EIT	

Developers

Different from European offshore market, offshore wind farms in China are mostly developed by state-owned power utilities, therefore, most of offshore projects are invested to meet the government targets instead of getting profit. Lack of foreign developers involved in market reduces wind industry competitiveness of China. Central planned wind economy and lower project profitability contributed to less motivation for wind developers to reduce offshore CoE. 98% of wind capacity has been installed by 8 Chinese SOEs, most of them have rich experience from onshore and oil & gas industry.

Consenting

Consenting process involves several government departments, together with insufficient coordination, causing project delay and extra cost. Lack of government coordination during consenting process is one of policy challenge in China. For instance, the consenting process of first concession round projects last 3 years. Although the regional governments have been issued for certain authorities to process application, they often lack experiences to evaluate project proposal and thereby transferring consenting process back to central government.

The fundamental obstacle is various conflicts among multi government agencies, especially between National Energy Administration (NEA) and State Oceanic Administration (SOA). From cost and technical challenge perspective, NEA prefers OWF to be installed closer to the shore; on the contrary, in order to preserve wildlife conservation zone, fishing zone, and military zone, SOA prefer OWF to be installed as far as possible. To resolve the conflict, according to regulations released jointly by NEA and SOA for the development, construction and management of offshore wind project, offshore wind farms should be located no less than 10 km from the shore and 10 meters water depth if the tidal flat is more than 10 km wide. The layout of offshore wind farms shall not be planned in all kinds of marine nature reserves, special marine protected areas, important fishery waters, typical marine ecosystems, estuaries, gulfs and natural historical relics protection areas.

Feed-in tariff

The overly low feed-in tariff price is one of the major bottleneck for large scale offshore wind development. For non-bidding offshore projects that operated before 2017(not including 2017), the feed-in tariff price of intertidal zone and nearshore zone, announced by NDRC in June of 2014, are €0.1/kWh(¥0.75) and €0.12/kWh(¥0.85)(tax included) respectively [16]. For offshore projects operated after 2017, the feed-in tariff price will be decided later based on technology improvement and concession bidding condition.

Compare to the countries with well-developed offshore wind market, the current FIT price is fairly low in China, see Table 12. Even though the investment cost of offshore wind per MW is estimated to be 2 times of onshore wind, offshore FIT is just around 30% higher than onshore FIT (€0.08/kWh), resulting in weak project economy.

Table 12 Comparison of FIT Price between China and European Countries

Country	Feed-in Tariff Price for offshore wind (2016)
China	0.10€ - 0.12€/kWh
Germany	0.17€ - 0.22€/kWh
United Kingdom	0.21€/kWh
Denmark	0.15€/kWh
Italy	0.20€/kWh

For Fujian coastal area where wind speed is higher (8.5m/s) and more stable, the current FIT is able to achieve certain economic benefit, however, for the area where wind speed is slightly lower (7.5m/s), the current FIT price can't cover the cost of OWF completely and it is difficult for project developers to make commercial returns against such low FIT price. Nevertheless, it is worth stressing that due to the immaturity of offshore industry in China and limited numbers of commercial OWF in operation, the level of FIT is still in an exploratory stage. For the OWF operating from 2017, the FIT price will be adjusted more objective and reasonable based on the current OWF operation situation.

Other economic incentives

To support offshore wind industry development, there are also relevant subsidy policies issued by provincial government such as

- For the electricity generated from offshore wind, Shanghai government rewards 0.027EUR per kWh to OWF owner for five consecutive years. For each offshore wind farm, the annual incentive mount should be no more than CNY 50 million.
- Since 2009, central government has issued preferential tax policy for renewable energy investment, including the reduction of value added tax (VAT) and enterprise income tax (EIT). For wind power investment, VAT has been reduced from 17% to 8.5% and EIT has been reduced from 33% to 15% [15].

4.3 South Korea

4.3.1 Overview

As a peninsula country, South Korea possess enormous wind energy potential provided by 2,413km coastline and mountainous terrain. Wind industry can benefit greatly from the immense wind resource due to its high wind speed [17](see Figure 33). From Figure 33, it is seen that, for offshore wind area, the sea area around Jeju Island offers the strongest air currents and has the highest average wind speed (around 8 – 9 m/s), therefore, vast majority of offshore wind farms, both in operation and under development, are located in this area (See Figure 34).

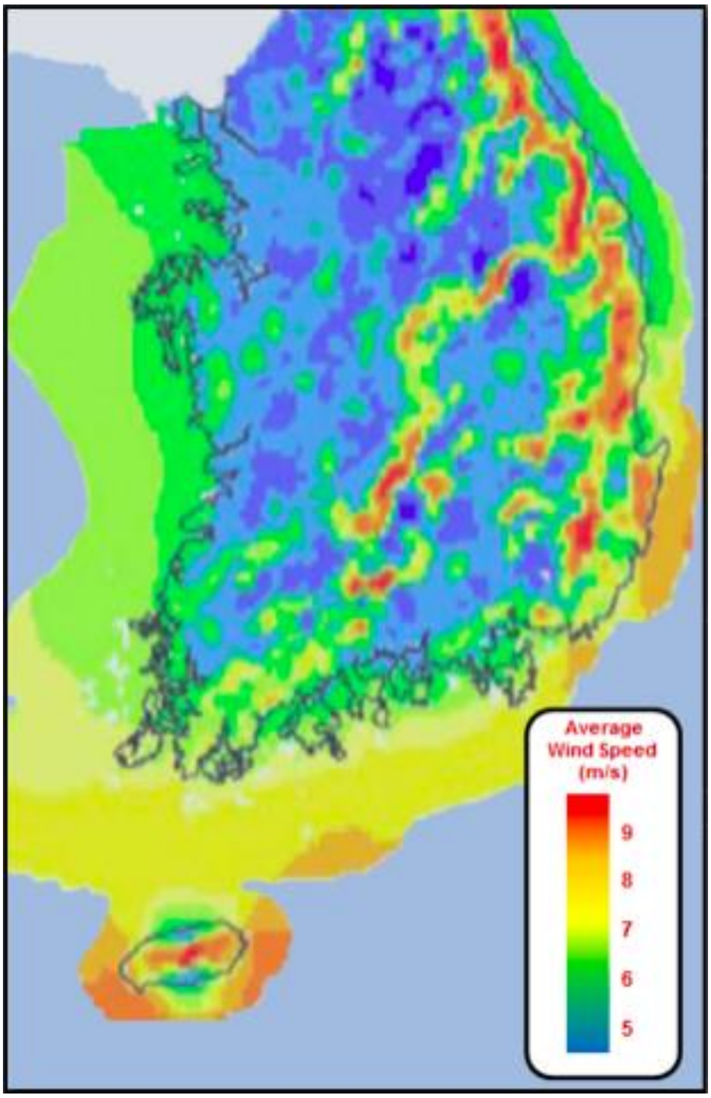


Figure 33 Average Wind Speed in South Korea [17]

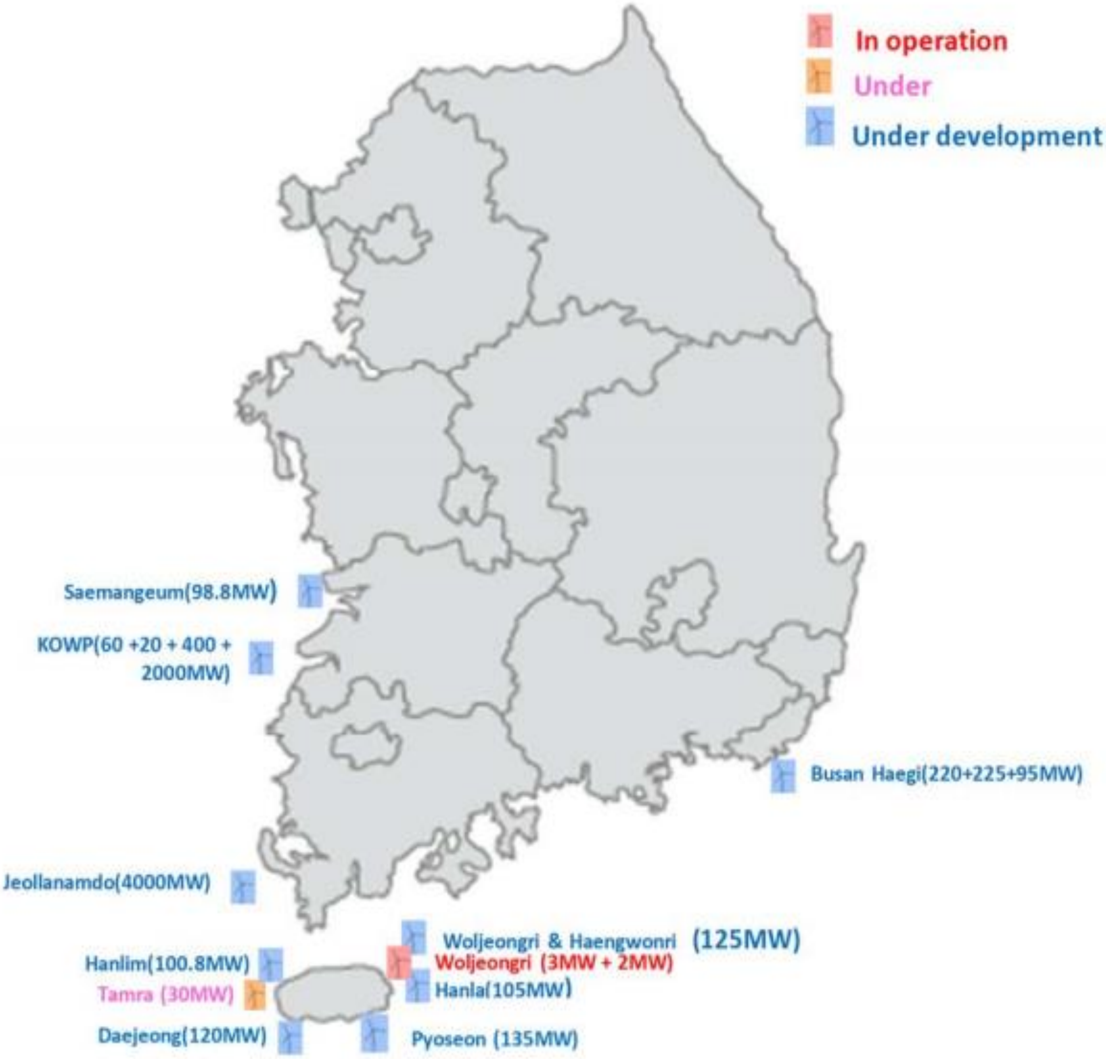


Figure 34 South Korea Offshore Wind Farms Distribution Map

SOURCE: K2M

Considering the geographical accessibility to construct wind farm, the available wind resource potential (both onshore and offshore) is estimated at 294 million TOE annually, which is equivalent to installation capacity of 433GW [17]. However, offshore wind market is not developed as expected, until the end of 2015, the total installed capacity for offshore wind in South Korea is only 5MW. The only one fully commissioned offshore project is the demonstrative offshore windpark of Jeju island (*Woljeongri 3MW +2MW*), located at northeast of Jejudo.

The major obstacle of offshore wind development is the lower electricity price, due to several reasons, including geographical environment, policies and regulations and relatively higher CAPEX. Key drivers effecting the cost of offshore wind energy in South Korea are discussed in following paragraph, including geographical environment, policies and regulation, turbine and logistic.

4.3.2 Environmental factor

The main effect caused by environmental factor is that available sea area for offshore wind development is strictly limited by considering both geographic and ecological factors. The limited size of wind farm eventually results in relative high LCOE than other countries inasmuch as annual electricity production deceases. Due to the lower power price, industry competition and economies of scale are extremely limited.

Water depth

Surrounded by Yellow Sea and East Sea, South Korea owns tremendous wind resources (see Figure 33), yet, the available sea area suitable for installation of offshore wind farm is strictly limited. For offshore wind farm installation, preferred water depth ranges from 10m to 25m, nevertheless, it is only located within limited distance from South Korea coast. The water depth suddenly rise up instantly in further offshore area, and the cost (*mainly for foundation cost*) largely increases with the increasing water depth, diminishing the project feasibility.

Sea bed

The optimal sea bed condition for wind farm construction is identified as strong sand without silt and clay. In the project area, silt layer whose thickness ranges from 30m to 70m is located at the bottom of sea. The fact of seabed characteristics greatly increase the cost of foundation owing to special construction condition, construction process and difficult degree for construction.

Furthermore, in the sea area around Jeju Island, sea bed is characterized as volcanic rock type. Due to the physical properties of volcanic rock, cable installation in terms of methodology and burial depths is more challenging than normal soil and sand sea bed. Traditional subsea cable installation vessel and equipment are not applicable under this circumstances, resulting in higher installation costs and cable maintenance cost during operational phase ultimately.

Coastal animal

During the whole lifetime of offshore wind farm, each different phase including construction, operation and decommissioning, poses negative effect on coastal mammals and fish. For instance, noise and vibration would cause individual and population disturbance for acoustic species; construction work results in turbidity problem.

Due to the consideration of nearshore ecology environment protection, South Korea government has set rules for offshore wind industry in which offshore wind energy cannot be constructed within the sea area 1km away from coast line.

4.3.3 Policies and regulations

In order to promote the development of renewable energy, South Korea government has set up a series of supporting measures, including regulatory policies, fiscal incentives and public financing support. Table 13 has demonstrated the specific support policy from each different category. [17]

Table 13 South Korea Renewable Energy Support Policies [17]

Support Types	Support Policies
Regulatory Policies	Electric utility quota obligation/RPS
	Net metering
	Tradable REC
Fiscal Incentives	Capital subsidy, grant, or rebate
	Investment or production tax credits
	Reduction in sales, energy, CO_2, VAT, or other taxes
Public Financing Support	Public investment, loans, or grants

Renewable Portfolio Standard (RPS)

From January of 2012, South Korea government has replaced the previous subsidy scheme Feed-in Tariff (FIT) with renewable portfolio standard (RPS) to support the development of renewable energy. Until the year of 2016, there are 18 power companies are identified as RPS obligators who should secure the price scheme. According to RPS scheme and regulations, the 18 obligators are required mandatorily to generate a specific fraction of electricity by using renewable energy source. The RPS obligation rate increases each year and the latest obligation rate issued by Korean New and Renewable Energy Center of the Korean Energy Management Corporation is shown as Table 14:

Table 14 RPS Ratio from 2016 To 2024

Year	2016	2017	2018	2019	2020	2021	2022	2023	2024
RPS Ratio in Power Generation (%)	3.5	4.0	5.0	6.0	7.0	7.0	8.0	9.0	10.0

SOURCE: K2M

Renewable Portfolio Standard (RPS) is the sum of System Marginal Price (SMP) and Renewable Energy Certificate (REC).

Renewable Portfolio Standard (RPS) = System Marginal Price (SMP) + Renewable Energy Certificate (REC)

= 0.069EUR/kWh + 0.089EUR/kWh

= 0.158EUR/kWh

The current market price of SMP is approximate 0.069EUR/kWh and REC is approximate 0.089EUR/kWh, while the previous FIT was a fixed price at around 0.08EUR /kWh (*Source: K2M*). Figure 35 has shown the wind power price from February 2012 to March 2016.

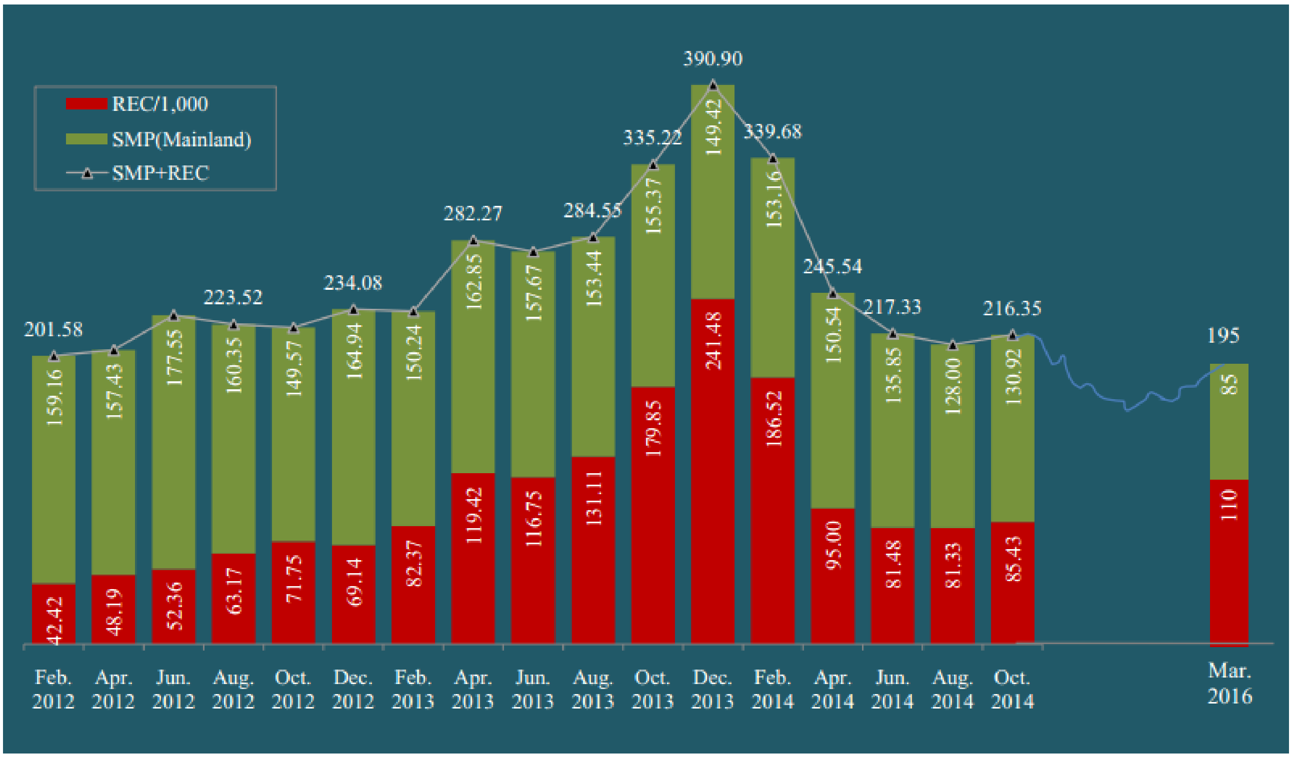


Figure 35 Wind Power Price (2.2012-3.2016 Currency: KRW)

SOURCE: K2M

Under RECs system, renewable-generated power receives price above the market rate based on the price of the REC multiplied by the weight value of the renewable energy source, depending on its type, with offshore wind, tidal and fuel cells receiving the highest multiplier. To be specific, 1 MWh power corresponds to 1.5 REC for offshore wind farm located within 5km from shore; for further located offshore wind farm, 2REC is received for generating 1MWh power. From March 2017, issued officially by Ministry of Trade, Industry and Energy (MOTIE), a new REC system will be implemented. See table 15. The new REC system is divided into fixed scheme and varying scheme, chosen by OWF owner to secure project profit.

Table 15 Current and New REC System, South Korea

	Current REC System		New REC System			
	Distance From OWF to Shore		REC Weight Application Period			
	<5km	≥5km		1-5 years	6-15 years	>16 years
1MWh =	1.5 REC	2 REC	Fixed Scheme	2.0 REC		
			Varying Scheme	2.5 REC	2.0 REC	1.0 REC

SOURCE: K2M

Wind Tax Regulation

On the macro level, the tax of renewable energy poses a positive impact on decrease of LCOE of offshore wind. Nevertheless, due to various local tax policies, for instance, wind tax levied by Jeju provincial government, offshore wind economy is fairly weak. According to wind tax of Jeju provincial government, 7% of sales or 17.5% of profit is required to pay on top of normal taxes by offshore wind farm owners. From the project owner's point of view, LCOE of offshore wind increases in some ways accounting wind tax (profit sharing policies).

Other related regulations

There are still some other applicable regulations limiting or prohibiting offshore wind farm project. For instance, military exercising area is prohibited to develop OWFP, which results in the smaller size of project, eventually increasing LCOE.

4.3.4 OWF components and installation equipment & vessel

WTG, Foundation and Substation

Almost all of offshore wind project both in operation and under development chose local WTG suppliers, such as Samsung, Daewoo. Compare with foreign suppliers, local WTG supplier is not competitive both in technology and price. Hence, the cost per WTG in South Korea market is in quite high level comparing to the other counties.

As mentioned above, due to geographic reasons (unfavorable water depth and harsh sea bed condition), most of offshore foundations are required to specially designed, bringing to the higher foundation cost.

Regard to substation, since most of OWFPs under development are quite close to the coast, contrary to large scale OWFPs, offshore substations (OSS) are not required to be installed, which results in the decrease of BOP cost.

Installation equipment & vessel

Due to the lack of local offshore construction experience and suitable construction equipment such as jack up vessels and cable laying equipment, installation cost of OWFP in South Korea is much higher than other countries. Furthermore, as stated, the complex sub-sea terrain further rise up the installation cost due to difficulty of burying, and correspondingly, O&M cost as well during operation stage.

Table 16 has illustrated a summary of South Korea OWF project cost key drivers and corresponding impact on each of them.

Table 16 Summary of South Korea OWFP Cost Key Drivers and Corresponding Impact

Key Drivers	Impact on cost
Turbine	• Local turbine manufacturer • Average price higher than other countries • Increase of project capital cost
Foundation	• Unfavorable sea-floor terrain • Increase of project capital cost due to special designed foundation
Inter Array Cable	• Silt layer under sea • Increase of installation cost due to difficulty of subsea burying • Increase of O&M cost
Offshore Substation	• OWF located at nearshore • Unnecessary for South Korea OWFP • Decrease of BOP cost
Installation	• Lack of local installation vessels • Unfavorable sea-floor terrain • Increase of installation cost

4.4 Japan

4.4.1 Overview

Instead of having sufficient fossil fuels as China, Japan, given the abundant wind resources in the geography of conditions and marine, which is also the island country, owns tremendous offshore wind resources and the world's 6th largest sea space.

According to the report published by Japan Wind Power Association on 2012, an estimation of offshore wind potential would be 600 GW, and it is worth stressing that, unlike South Korea most of its wind resources is located far away from shore and in deep water (water depth larger than 50m) [18]. As reported by JWPA, 85% of it could apply floating foundation technology.

Until the end of 2015, the total cumulative installed capacity for offshore wind in Japan is 52.6MW, see Figure 36. Even though Japan is the second largest offshore wind country in Asia, Japanese developers still lack experience on both construction and management of off-shore wind projects.

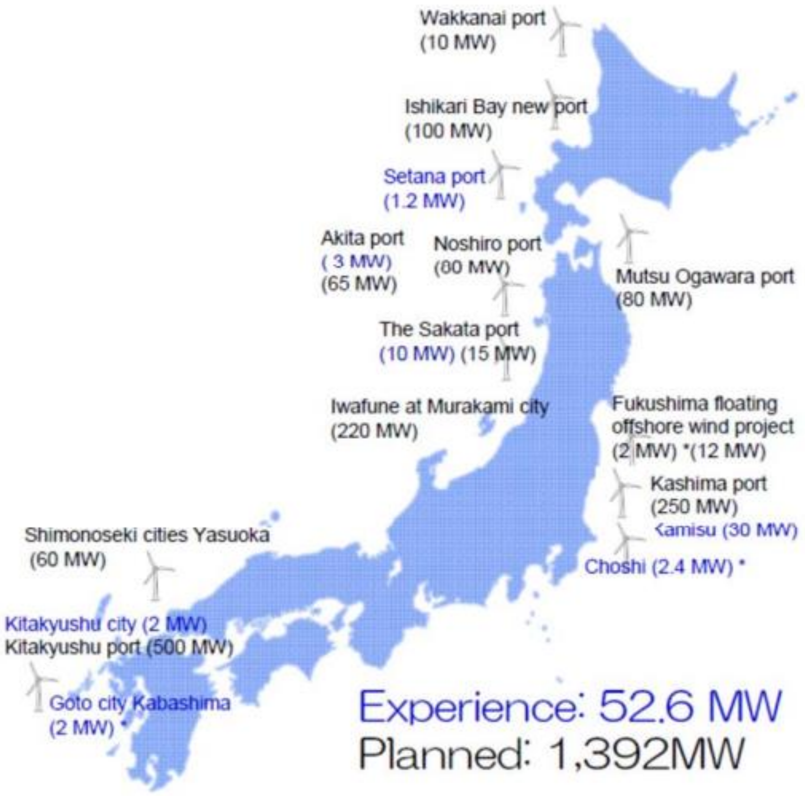


Figure 36 Offshore Wind Projects in Japan [28]

Estimated by JWPA, there will be installed capacity of 1,407MW OWF operating until the end of 2020 [4], and offshore wind will be deployed in a large scale after 2020 based on the new national energy plan, as shown in Figure 37.

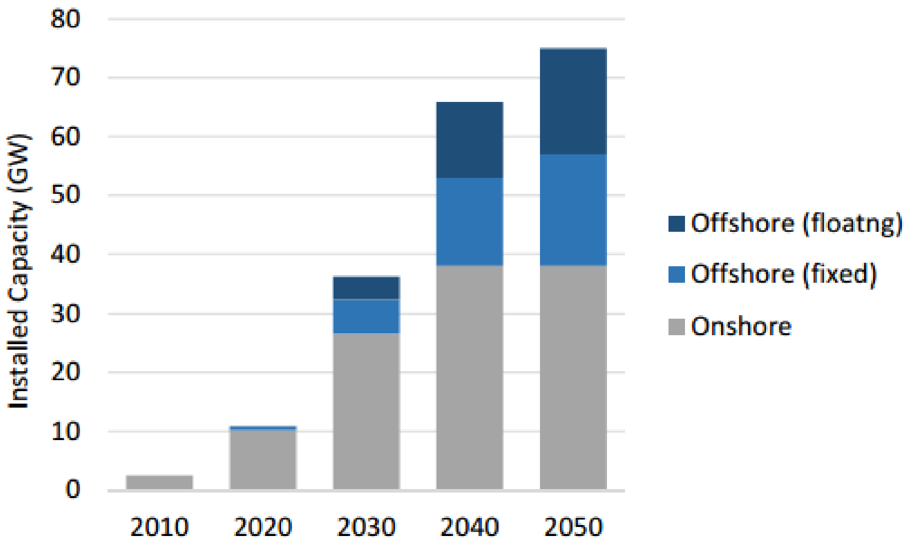


Figure 37 Wind Power Installation Plan [19]

CAPEX and OPEX for Offshore Wind Projects

For the purpose of setting procurement price of offshore wind power, METI conducted a study refer to the comparison of CAPEX and OPEX between fixed-bottom project and floating project. Table 17 has shown both CAPEX and OPEX per kW are higher in floating project, largely due to the unfledged floating technology and current demonstration scale.

Table 17 METI Analysis of CAPEX and OPEX for OWP in Japan [19]

	Assumption	CAPEX (€/kW)	OPEX(€/kW)
Fixed-bottom	- Deep waters - More developed technology - Larger turbines and more expensive foundations	6777.14	197.19
Floating	- Wind farm consist of 20-50 turbines - Adopting data from demonstrations at Fukushima and Kabashima	9602.43	265.78

Offshore Power Generation Cost

The current generation cost for offshore power (2016) in Japan is 0.21€/kWh (¥24.6/kWh). By taking the considerations of capacity factor, discount rate, CAPEX and OPEX, JWPA has estimated the offshore power generation cost in 2030 to be 0.15€/kWh (16.9¥/kWh). Based on the assumptions, by the end of 2030, 5% increase of capacity factor, together with 20% reduction on both CAPEX and OPEX, the offshore power generation cost will reduce by 28.6%. See Table 18.

Table 18 Estimation of Power Generation Cost of Offshore Wind in 2030

		2016	2030
Offshore Power Generation Cost (€/kWh)		0.21	0.15
Assumption	Capacity Factor (%)	30	35
	Discount Rate (%)	3	3
Cost	CAPEX (€/kWh)	4900	3920 (20% reduction)
	OPEX (€/kWh)	195	156 (20% reduction)

SOURCE: K2M

Figure 38 has shown the comparison of power generation cost from different resources by 2030 [20]. According to the estimation from JWPA, power generation costs for onshore and offshore wind are 0.07-0.10€/kWh (8-12¥/kWh), 0.15€/kWh (16¥/kWh) respectively.

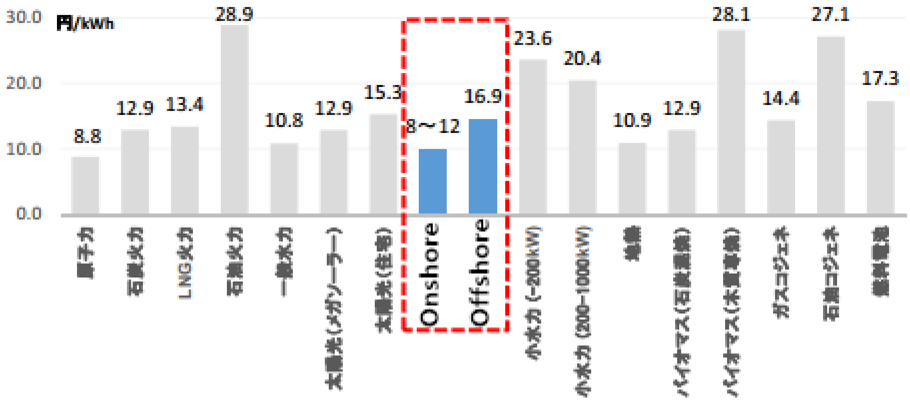


Figure 38 Comparison of Power Generation Cost by 2030 [20]

Nevertheless, currently, power generation cost for offshore is too high for developers to invest on a large scale. The key drivers effecting the cost of offshore wind energy in Japan are discussed in following paragraph, including environmental factor, policy and regulation, and OWF components & supply chain.

4.4.2 Environmental factor

Climatic and geological factor

As an island country, Japan has tremendous favorable offshore wind resources. Figure 39 has illustrated the offshore wind speed distribution map of Japan and it is seen that east coast of Japan shares the optimal wind resource [19].

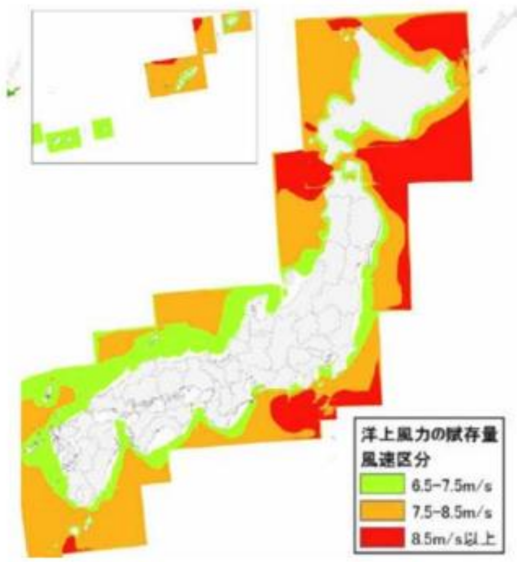


Figure 39 Offshore Wind Resource Map, Japan

Given the location near three major tectonic plate boundaries, Japan is the area of high seismicity and has a long history of seismic and tsunami activity. Specific geotechnical and met-ocean conditions vary in deep water, especially given the added threat of earthquakes and typhoons in Japan. Due to that fact, in certain region of Japan, both turbine and foundation installed for OWF are necessarily designed to withstand giant waves, powerful tsunamis and frequent lighting, in order to increase turbine availability as well as project economics. Floating wind turbine is considered as the most suitable type, nevertheless, in terms of cost, compare to the traditional fixed bottom structure, floating technology is not competitive and needs further R&D.

Water depth

For offshore project in Japan, water depth is also an obstacle. Fixed bottom foundation can only be applied in flat shallow water area where water depth is fairly low. Few nearshore wind projects have been installed or under development by adopting monopiles and jacket foundations. However, wind speed in such area is relatively low, which decrease energy production and increase generation cost correspondingly. As mentioned above, most of wind resources are located at sea area with water depth larger than 50 meters. Wind speed gets higher with the increased water depth and therefore leads to the only option which is semi-floating or floating foundation for OWFP, bringing about much higher CAPEX and later O&M cost during operation phase. For instance, the electricity generated from Fukushima wind farm which employs floating advanced spar floating foundation is so far nearly twice as much as expected [21].

4.4.3 Policies and regulations

Negative factor

In Japan, solar power is more favored energy resource compare to wind energy. Currently there is no specific policies and regulations for offshore wind power development in Japan for undesignated areas.

For offshore wind farm project, consenting Process and Environmental Impact Assessment (EIA) are considered as the current two barriers OWFP in development phase [19].

- Consenting Process
  The consenting process of offshore wind project involves various government departments instead of one central governmental institution. Consenting delays caused by lengthy process may pose extra cost and risk on project.
  Furthermore, negotiation with local powerful fisheries association also contributes to the lengthy consenting process. Additionally, for the purpose of satisfaction of fishermen's interest, agreed compensation is inevitable, further increasing OWFP development cost.
- EIA
  As part of the consenting process, EIA is the most time-consuming step which normally costs almost 100 million euros. For wind farm developer, to build large-scale wind farms, environmental impact assessments takes about three to four years, probably resulting in the delay and extra expenditure on the wind project.

Positive factor

Nevertheless, given the fact of long coast line and high cost of onshore wind, it is logically for government to shift the focus to offshore wind by considering the tremendous offshore potential. By the end of 2015, government has published future plan of wind industry development, mainly focusing on the reduction of offshore wind generation cost and increase of AEP by technology improvement. Table 19 has shown the government support plan of offshore wind in order to increase the total installed capacity and eventually reduce wind power generation cost [20].

Table 19 Measures to Expand OWF Installation [20]

1	Medium and long term offshore wind promotion goal setting (Basic Energy Plan, etc.)	
2	Establishment of master plan (Renewable energy and other related ministerial meeting, etc.)	
3	Maintenance of substation and access line (Transmission line)	
4	Environmental improvement to promote the use of general sea area	Rules of general sea area utilization
		Identification of development zones for offshore wind
		Implementation of the environmental assessment, control of stakeholders
5	Establishment and maintenance of port infrastructure	Development of base harbor
		Development of SEP vessels
6	Technology development support of wind turbine which is suitable for local natural conditions	Development of high-performance wind turbine
		Development of wind turbine with larger capacity to reduce installation base
		Technical development of foundation (shape, design approach)
		Offshore wind map development (Suitable site selection)
		Development of smart maintenance technology (cut down downtime)
7	Finance support, such as debt guarantee	
8	Related regulations improvement	Extension of sea area utilization for permission period
		Development of safety management standards for maritime construction
		Reduction of environmental assessment period
9	Study of future prospect of generation cost reduction	

In 2012, government introduced the offshore FIT scheme to incentivize private investment and the purchase price and period for offshore wind, published by METI [22], is 0.29EUR/kWh (*36JPY/kWh*) and 20 years, see Table 20. Compare with offshore FIT of South Korea and China, the higher purchase price in Japan improves investment confidence greatly, however, the IRR still cannot be guaranteed for investors, and it is estimated that ¥40 /kWh will be necessary to kick-start the industry in Japan, due to higher base costs and a lack of suitable infrastructure and offshore experience in Japan.

> As obligators, power companies are required to purchase electricity generated from renewable energy sources on a fixed-period contract at a fixed price (purchase price is shown on Table 20 below). Cost for purchasing is paid by electricity users in the form of a nationwide equal surcharge. And electric power companies pay a part of the cost (the equal amount to the generation cost that they could

avoid to pay by purchasing renewable electricity from the producers). Purchase price is re-examined and published in each year. [22]

Table 20 Purchase Price under FIT System for Wind Energy [22]

			Purchase price (JPY/kWh)(tax excluded)					Purchase period
			FY2012	FY2013	FY2014	FY2015	FY2016	
Wind	Onshore	<20 kW	55	55	55	55	55	20 Years
		≥20 kW	22	22	22	22	22	
	Offshore				36	36	36	

4.4.4 Technical challenges & supply chain

Compare with the more developed European offshore wind industry, offshore technology in Japan lags behind. Due to the lack of offshore experience, both local WTGs technology and supply chain are still under development. Immature design, combine with challenging climatic and geological factors, contribute to lower offshore power generation, further leading to higher generation cost.

JWPA identified the effect on power generation cost for 2030 through improving the major WTG components technology, see Table 21 [20].The basic assumptions applied for the estimation are shown as Table 22.

Table 21 Effect on Power Generation Cost by Technology Improvement

No.	Contents	Effect On Power Generation Cost 2030 (JPY/kWh)
1	50% increase of swept area	-1.99
2	OWF lifetime extension (20 years to 25 years)	-1.88
3	Improved capacity factor and equipment utilization by adopting CMS	-1.69
4	20% decrease of weight of nacelle	-1.28
5	Improvement of maintenance efficiency	-0.51
6	5% increase of WTG efficiency	-0.39
7	25% increase of height of tower	-0.25

Table 22 Basic Assumption Applied For Cost Estimation

Parameters	
OWF installed capacity	2MW * 10 turbine = 20 MW
CAPEX	300,000 JPY/kW
OPEX	6000 JPY/kW/year
Capacity Factor	20%
Lifetime	20 years

Turbine

Contrary to onshore wind, Japanese turbine manufacturers are dominated in offshore wind industry, accounts for nearly 86% share of offshore turbine market [19]. See Figure 40.

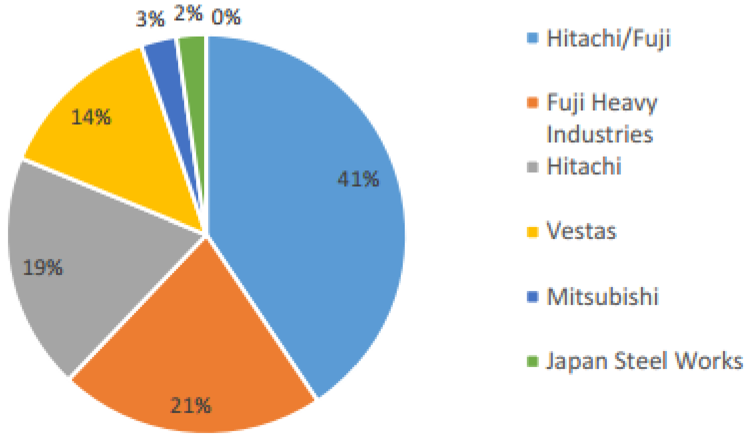


Figure 40 Offshore Wind Turbine Market Share in Japan 2013 [19]

Compared with 8MW offshore turbine from Vestas, so far, the largest turbine in commercial scale by domestic manufacturer is merely 2MW. With a relatively small rated capacity, domestic turbine generates less electricity at higher relative cost. In addition, reliability of domestic turbine is fairly low, resulting in lower project economics. As OWFPs move further from shore, the number of turbine installed is necessary to reduce through raising the rated capacity of turbine, decreasing both CAPEX and OPEX per unit.

On the other hand, unlike other countries, given the extreme weather condition in Japan, typhoon and lightning storm pose greatest threat to offshore turbine, particularly lightning storm, identified the most common cause of failures, accounts for 31% [19]. See Figure 41. Such failures results in the raise on both financial cost and maintenance cost.

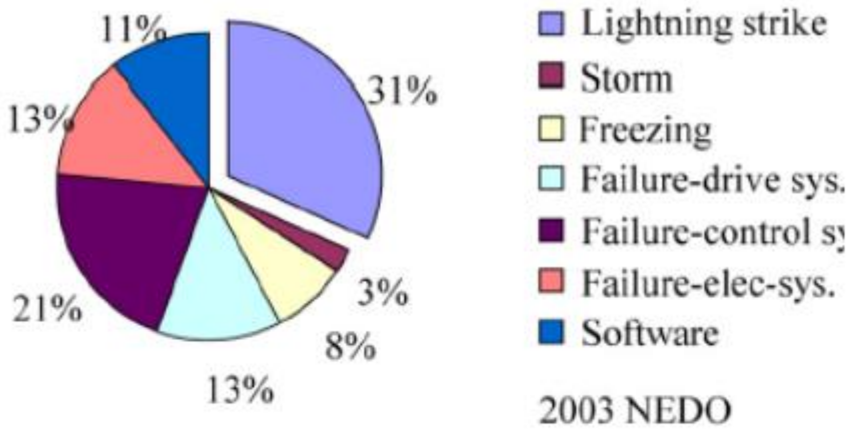


Figure 41 Source of Turbine Failures in Japanese Wind Farms [28]

Foundation

Even though Japan is a leading country in floating technology and having over 20 years' experience of R&D in it, out of 27 turbines installed by the end of 2015, only few turbines adopted floating foundation. Given more mature and lower cost of fixed-bottom technology, fixed-bottom foundation is still estimated to dominate OWFP from 2020-2025. Yet, the capital cost of fixed-bottom costs in Japan are still slightly higher than in Europe markets [28].

- Fixed-bottom foundation

  In terms of capital cost, fixed-bottom foundation is extremely lower than floating foundation. However, it is only applied for Japanese nearshore projects where the wind speed is not high, causing lower AEP, namely, higher LCOE of offshore wind.

- Floating foundation

  Compare with fixed-bottom type, both capital and maintenance cost of floating foundation are significantly more expensive and it hasn't been applied in commercial scale in Japan. Particularly, moorings of floating structures are subject to great pressure from typhoons, and maintenance of mooring is excessively expensive, also leads to costly delays.

  Nevertheless, floating foundation is more suitable for Japanese offshore wind development due to its specific bathymetry of Japan's coastline. Wind speed is higher and more stable far away from shore resulting in the increase of power generation per year. Floating foundation has long-term cost competitiveness which can further greatly reduce LCOE.

Cables and Installation

Due to the lack of cable manufacturer and low availability and capability of installation vessel for offshore turbine and foundation installation, cable and installation costs in Japan is extremely higher than Europe market.

Besides the higher purchase price of cables, maintenance of submarine cables accounts for the higher O&M cost of Japanese OWF in as much as the cable damage poses great potential risk. Dynamic cables can resolve the damage issue, however, it is not cost-competitive yet.

Given the lack of supply chain, installation works for OWF are executed by limited number of vessels from other industries, which becomes a major bottleneck. Insufficient installation experience results in project delay and extra-enormous cost before wind farm starts operating.

5 Conclusion

As mentioned where above, offshore wind is still in a fledging period; as capital intensive project, offshore wind farm would not yield profit as soon as the wind power plant starts generating electricity. Therefore, due to the higher risk of offshore wind, costs for each stage of project should be well analyzed and reduced, in order to lower the financial risk.

With improved technologies of turbine, foundation and updated grid connection system, together with supportive policies and regulations made by government, the total CoE can be reduced and offshore wind power will inevitably become one of the most competitive energy sources in the near future.

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