Electric Power Systems Research 167 (2019) 39–47

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Critical review of offshore wind turbine energy production and site potential assessment

Iñaki Arrambide[a,*], Itziar Zubia[a], Ander Madariaga[b]

[a] University of the Basque Country (UPV/EHU), Faculty of Engineering, Plaza Europa 1, 20018 Donostia, Spain
[b] Offshore Renewable Energy Catapult, 121 George Street, G1 1RD Glasgow, United Kingdom

ARTICLE INFO

Keywords:
IEC Class
Offshore turbine
Energy production
Capacity factor
Power density

ABSTRACT

One of the most important technical problems among the different challenges of offshore wind farms is to obtain a suitable turbine model for a particular site. Designers of offshore plants can take into account several aspects, such as wind class of the selected site, environment requirements, height restrictions, turbinés price, power capacity, energy production and wake effect/electrical losses. This paper clarifies the concept of power density applied to offshore turbines and shows the correlation between the power density and the selection of the site. Different commercial offshore turbines are analyzed for three different class wind sites. Recently commissioned offshore wind farms and offshore wind turbines are included in the study. The results show greater energy production for low power density turbines and this parameter is more reliable than the capacity factor to select the turbines that match with the site.

1. Introduction

In October 2014 the European Council announced new targeted objectives of the second package of measures to be taken during the period 2020–2030 [1], to fulfill with previous goals related with a joint action plan to face the effects of climate change, security of energy supply, promotion of indigenous energy sources and reducing the excessive dependence on fossil fuels such as gas and oil, or nuclear plants. In order to achieve the aforementioned objectives, it is clear that the development of renewable energies will be decisive in the coming years.

One of the most promising alternatives is offshore wind power, which has experienced significant growth in Europe over the past few years as can be seen in Fig. 1.

Most of offshore wind projects are installed in the North and Irish Seas together with the Baltic Sea, hence, United Kingdom, Denmark, Germany, Belgium, The Netherlands and Sweden constitute most of European offshore wind projects and inversions [3]. This increase has been possible due to important technological developments, low water depths, excellent wind resources, good subsidies, private investors and different national set out energy plans, which allow to Europe to maintain the leadership in offshore business. According to Table 1, that shows offshore wind installed capacity up to now [4] and offshore wind targets for 2030 scenario in European Union [5], it is clear that large scale offshore projects must be developed and it is expected that they will face great technical challenges such as deeper waters, longer transmission distances, intermittent generation, energy storage solutions and onshore transmission reinforcements.

In the same way, a great drop of price of the levelized cost of energy (LCoE) inspired investors to participate in auctions celebrated in recent years. In fact, the prices of energy to be injected in power system during last auctions, are already close to conventional power sources. A reliable political framework and the introduction of the auctioning system for offshore wind by European Commission [6] prompted lower prices of energy. For instance, in The Netherlands Borssele 1 & 2 and Borssele 3 & 4 sites were auctioned by Dutch Government at 72.7 €/MWh and 54.5 €/MWh prices respectively in 2016 [7]. Last offshore tender celebrated in Denmark in 2016, showed even lower price in Kriegers Flak project with 372 DKK/MWh (49.9 €/MWh). In Vesterhav Nord & Syd near-shore sites guaranteed price for developer was set out at 475 DKK/MWh (64 €/MWh) [8]. In 2nd Round of Contract for Difference (CfD) in United Kingdom, Hornsea Project Two together with Moray East OWF reached in september 2017 a strike prices of 57.5 £/MWh (63.31 €/MWh) respectively and 74.75 £/MWh (82.31 €/MWh) for Triton Knoll offshore project [9]. In april 2017 the first auction was held in Germany for a total capacity of 1490 MW, Gode Wind III was a winning tender bid at 60 €/MWh while OWP West, Borkum Riffgrund West II and He Dreiht projects will be the first offshore projects of the world selling generated energy at market prices or without subsidies [10]. In addition to these projects, in March 2018 the first zero subsidy

* Corresponding author.
E-mail addresses: inaki.arrambide@ehu.eus (I. Arrambide), itziar.zubia@ehu.eus (I. Zubia), ander.madariaga@ore.catapult.org.uk (A. Madariaga).

https://doi.org/10.1016/j.epsr.2018.10.016
Received 16 March 2018; Received in revised form 17 October 2018; Accepted 18 October 2018
0378-7796/

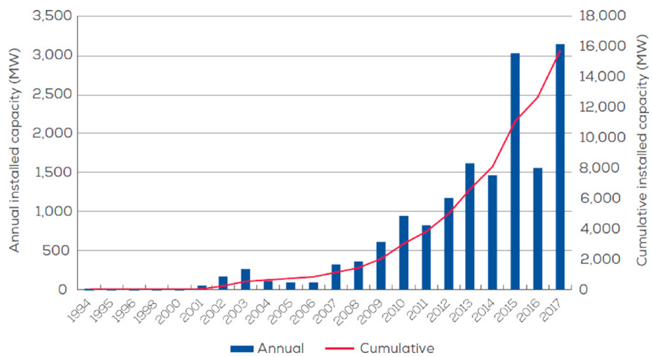

Fig. 1. Offshore wind power in Europe 1994–2017 [2].

Table 1
Installed/expected offshore capacity in EU (MW).

Country	2018	2030
Belgium	988.35	4000
Denmark	1294.1	4300
Finland	86.7	–
France	0	7000
Germany	5349.3	15 000
Ireland	25.2	1800
Netherlands	1117.8	11 500
Poland	0	3200
Portugal	0	150
Sweden	201.4	300
United Kingdom	7139.4	22 500

in The Netherlands for Hollandse Kust Zuid I & II sites was announced, whereby confirming a reduction tendency of wind offshore prices.

On the other hand, this upward trend has also appeared in other countries, albeit more slowly, with the objective of gaining experience and developing equipment related to the offshore wind business. In the 13th Five-Year Plan agreed in 2016, China set a very ambitious target for producing offshore wind energy to mitigate the energetic unbalance between generation-consumption, very concentrated on the coast, and abandon the strong dependence on fossil primary materials. The national plan promoted large-scale energy production, with a target of 5 GW by 2020 [11,12], granting a large number of licenses for the implementation of turbines and developing a specific remuneration policy for offshore wind energy [13]. Previously in 2014, "National Offshore Wind Power Development and Construction Plan (2014–2016)" was released, awarding 44 offshore projects totaling 10.53 GW of planned capacity. To date China has the highest offshore wind installed capacity in Asia (2338.6 MW), followed by Vietnam (99.2 MW), South Korea (35 MW), Taiwan (8 MW) and Japan (21.72 MW), the latter focusing on floating projects because of limited shallow deep water sites for fixed foundations.

Although USA is the second largest market of installed wind power capacity of the world [14], currently it has just one commercial-scale offshore wind farm (OWF) commissioned in 2017. However, 13 areas have already been leased, that could potentially contribute around 14 GW [15].

The selection of the site is one of the most important decision in the development of an OWF [16]. Assessing the wind energy potential at a candidate site and understanding how a wind turbine would respond to the resource fluctuations are the initial steps in the planning and development of a wind farm project.

Among different technical specifications provided by manufacturers of wind turbines, an important indicator is the power density (PD) of turbine, that is, the ratio between rated power output and rotor's swept area [17] expressed in W/m^2 units.

This ratio is clearly associated with capacity factor (CF), electricity production and LCoE as proved in previous works [18,19], besides having a key influence on electrical infrastructure dimension.

The main objective of this paper is to study the effect of different offshore wind turbine classes and PD in the electricity production in different areas that presents low, moderate-medium and high wind speed.

This work is divided into the following sections. Section 2 is focused on turbines currently in use in offshore fully commissioned projects all around the world and main characteristics according to IEC 61400-1 and IEC 61400-27 standards. Section 3 estimates typical wind generation indicators as annual energy production (AEP), CF and annual full hours (AFH) of a single offshore wind turbine. Section 4 analyzes and compares the energy produced by different turbines, dependent on wind speed mean intensity. The last Section resumes the conclusions of the study.

2. Current status of the offshore industry

2.1. Wind turbine design type class

Wind turbine class determines which turbine is suitable for the normal wind conditions of the particular site. It is defined by the International Electrotechnical Commision (IEC) design standard 61400-1 3rd Edition: Design Requirements [20] and corresponds to high, medium and low annual average wind speed. Turbine class is determined by three parameters; the annual average wind speed, extreme 50-year gust, and turbulence intensity, as shown in Table 2.

Turbulence is measured as the mean value measured between 9–25 m/s range wind speed, and quantifies the variation of the wind. By means of this parameter, each one of the classes can be subcategorized in subclasses A, B and C. In subclass A, the standard deviation of wind speed is 16%, in subclass B is 14%, while subclass C is 12%.

2.2. Wind turbines in commissioned OWF

Since the first OWF was commissioned in 1991 in Denmark [21], wind turbineś features have been changing continuously: nominal power, rotor diameter and hub height have been increased. Following on previous researches about fully commissioned OWFs worldwide up to 2012 [22], Table 3 shows detailed 2012–2018 period activity and evolution [4]. A summary of the main characteristics of turbines installed in these OWFs for the period 2012–2018 can be found in Table 4. For turbines installed before 2012 a detailed analysis is presented in Refs. [22,23].

Up to now, 4821 offshore wind turbines have been installed in fully commissioned OWFs with a capacity of more than 25 MW. 2739 turbines (56.81%) correspond to Squirrel Cage Induction Generator (SCIG) type, 984 turbines (20.41%) are Doubly-Fed Induction Generator (DFIG) type while the rest of them 1098 (22.78%) are Permanent Magnet Synchronous Generators (PMSGs). Nowadays, the worldwide offshore turbines market is led by the two biggest companies: Siemens-Gamesa and MHI Vestas, with 65.11% and 19.31% of installed turbines, respectively.

A clear growth in the use of PMSGs can be noticed as an upward trend in OWFs for turbines in the range of 3–8 MW. The PMSGs can be classified according to the rotation speed or performance of the

Table 2
Wind classes according to IEC 61400-1 Ed. 3.

IEC wind class	Annual average max. wind speed (m/s)	50 years wind ref. value (m/s)
Class I	10	50
Class II	8.5	42.5
Class III	7.5	37.5
Class S	Specific design for special conditions	

Table 3
Fully commissioned OWFs with installed power above 25 MW (2012–2018).

Name	State	Power (MW)	Year	MWS (m/s)	Turbines	
					Model	Quantity
Jiangsu Rudong I-IV	China	399.3	2012/15	7.48	SWT-2.3-101	21
					SL3000/113	17
					GW109/2500	40
					W4000/130	25
					EN136/4.0	25
Ormonde	U.K.	152.2	2012	9.79	5M	30
Sheringham Shoal	U.K.	316.8	2012	9.17	SWT-3.6-107	88
Walney I & II	U.K.	367.2	2012	9.79	SWT-3.6-120	102
BARD Offshore I	Germany	400	2013	10.02	Bard VM	80
Thorton Bank II & III	Belgium	295.2	2012/13	10.21	6.2M-126	48
Anholt	Denmark	399.6	2013	8.82	SWT-3.6-120	111
Greater Gabbard	U.K.	504	2013	9.88	SWT-3.6-107	140
Lincs	U.K.	270	2013	9.16	SWT-3.6-120	75
London Array I & II	U.K.	630	2013	9.95	SWT-3.6-120	175
Teesside	U.K.	62.1	2013	9.40	SWT-2.3-93	27
Kårehamn	Sweden	48	2013	8.77	V112-3.0	16
Riffgat	Germany	108	2014	9.87	SWT-3.6-120	30
NorthWind	Belgium	216	2014	10.21	V112-3.0	72
West of Duddon Sand	U.K.	388.8	2014	9.79	SWT-3.6-120	108
Amrumbank West	Germany	302	2015	9.78	SWT-3.6-120	80
Borkum Riffgrund I	Germany	312	2015	9.92	SWT-4.0-120	78
Butendiek	Germany	288	2015	9.79	SWT-3.6-120	80
Dan Tysk	Germany	288	2015	9.97	SWT-3.6-120	80
EnBW Baltic II	Germany	288	2015	8.83	SWT-3.6-120	80
Global Tech I	Germany	400	2015	10.05	M5000	80
Meerwind Süd/Ost	Germany	288	2015	9.78	SWT-3.6-120	80
Nordsee Ost	Germany	295.2	2015	9.78	6.2M-126	48
Trianel Borkum I	Germany	200	2015	9.92	M5000	40
Hydro. Rudong	China	100	2015	7.54	HZ102-2000	10
					SWT-2.5-108	32
Donghai Bridge II	China	97.2	2015	9.68	W3600/116	27
EnecoLuchterduinen	Netherlands	129	2015	9.94	V112-3.0	43
Gwynt y Môr	U.K.	576	2015	9.78	SWT-3.6-107	160
Humber Gateway	U.K.	219	2015	9.19	V112-3.0	73
Kentish Flats Ext.	U.K.	49.5	2015	9.81	V112-3.3	15
Westermost Rought	U.K.	210	2015	9.19	SWT-6.0-154	35
Binhai North H1	China	100	2016	6.87	W4000/130	25
Putian City Flat Bay I	China	50	2016	12.05	XD115 5.0	10
CNG Rudong	China	152	2016	7.48	W4000/130	38
Xiangshui OWF	China	202	2016	6.84	GW140/3000	18
					W4000/130	37
Gemini	Netherlands	600	2016	9.97	SWT-4.0-130	150
Westermeerwind	Netherlands	144	2016	–	SWT-3.0-108	48
Bac Lieu I & II	Vietnam	99.2	2016	8.19	GE 1.6-82.5	62
Sandbank	Germany	288	2017	10.09	SWT-4.0-130	72
Shanghai Lingang II	China	102	2017	8.89	W3600/122	28
Block Island	USA	30	2017	8.78	Haliade 6.0-150	5
Burbo Bank Ext.	U.K.	256	2017	9.78	V164-8.0	32
Gode Wind 1&2	Germany	582	2017	9.88	SWT-6.0-154	97
Belwind 2	Belgium	165	2017	10.16	V112-3.3	50
Veja Mate	Germany	402	2017	10.04	SWT-6.0-154	67
Takhuoloto	Finland	42	2017	9.00	SWT-4.0-130	10
Ajos	Finland	42.4	2017	8.44	SWT-3.3-130	8
					SWT-3.2-113	5
Dudgeon	U.K.	402	2017	9.21	SWT-6.0-154	67
Huaneng Rudong	China	302.4	2017	7.37	W4000/130	38
					HZ151-5000	19
					HZ171-5000	1
					EN 136/4.2	12
Luneng Dongtai	China	200	2017	7.29	W4000/130	50
Tamra OWF	South Korea	30	2017	9.60	WinDS 3000TM	10
Hywind Floating	U.K.	30	2017	10.31	SWT-6.0-154	5
Nordergründe	Germany	110.7	2017	9.95	6.2M-126	18
Nordsee One	Germany	332.1	2017	9.9	6.2M-126	54
Blyth Array 2	U.K.	41.5	2017	9.46	V164-8.0	5
Wikinger	Germany	350	2018	8,6	AD 5-135	70
Race Bank	U.K.	573.3	2018	9.12	SWT-6.0-154	91
Nissum Bredning	Denmark	28	2018	10.20	SWT-7.0-154	4
Galloper	U.K.	352.8	2018	9.88	SWT-6.0-154	56
Rampion	U.K.	400.2	2018	9.77	V112-3.45	116
Binhai North H2	China	400	2018	7.41	W4000/130	100

Table 4
Offshore wind turbines in fully commissioned OWFs capacity above 25 MW[a].

Manufacturer	Model	Power (MW)	Diameter (m)	P. D. (W/m^2)	IEC Class	Type	Gearbox
Senvion	6.2M 126	6.15	126	493.22	IB	DFIG	3
Siemens	SWT-2.3-101	2.3	101	287.07	IIB	SCIG	3
Goldwind	GW109/2500	2.5	109	267.91	IIIA	LS-PMSG	DD
General El.	GE 1.6-82.5	1.6	82.5	299.31	IIB	DFIG	3
Bard	VM	5.0	122	427.72	TC IC	DFIG	3
Vestas	V112-3.0	3.0	112	304.50	IIA/IIIA	HS-PMSG	4
CSIC Haiz.	HZ102-2000	2.0	102	244.75	IIIA	DFIG	3
Siemens	SWT-4.0-120	4.0	120	353.67	IA	SCIG	3
Siemens	SWT-2.5-108	2.5	108	272.89	IIB	SCIG	3
Siemens	SWT-4.0-130	4.0	130	301.35	IB	SCIG	3
Envision	EN 136/4.0	4.0	136	275.35	S	SCIG	3
Shanghai El.	W3600/116	3.6	116	340.64	IIA	DFIG	3
MHI Vestas	V112-3.3	3.3	112	334.95	IIA/IB	HS-PMSG	3
Siemens	SWT-6.0-154	6.0	154	322.12	IA	LS-PMSG	DD
XEMC- D.	XD115 5.0	5.0	115	481.37	IC	LS-PMSG	DD
Goldwind	GW140/3000	3.0	140	194.88	IIIA	LS-PMSG	DD
Siemens	SWT-3.0-108	3.0	108	327.48	IA	LS-PMSG	DD
Shanghai El.	W3600/122	3.6	122	307.95	IIIB	DFIG	3
General El.	Haliade 6.0-150	6.0	150	339.53	IB	LS-PMSG	DD
MHI Vestas	V164-8.0	8.0	164	378.71	S	MS-PMSG	2
Siemens	SWT-3.3-130	3.3	130	248.62	IIA	LS-PMSG	DD
Siemens	SWT-3.2-113	3.2	113	319.08	II	LS-PMSG	DD
CSIC Haiz.	HZ151-5000	5.0	151	279.20	IIIB	HS-PMSG	3
CSIC Haiz.	HZ171-5000	5.0	171	217.71	III	HS-PMSG	3
Doosan H.	WinDS 3000	3.0	91.6	455.24	IA	HS-PMSG	3
Adwen	AD 5-135	5.0	135	349.31	IB	MS-PMSG	1
Siemens	SWT-7.0-154	7.0	154	375.80	IB	LS-PMSG	DD
MHI Vestas	V112-3.45	3.45	112	350.18	IA	SCIG	3

[a] Turbines under test or prototype purpose offshore wind sites are not included.

gearbox:

- Low Speed PMSGs, without gearbox or direct drive (DD) turbines (4–20 r.p.m.) are currently developed by Alstom/General Electric, Siemens (D3/D6/D7/D8 platforms), Goldwind, United Power (3 MW platform) and XEMC-Darwind [24–28].
- Medium Speed PMSGs with 1 or 2 stages in their gearbox (20–500 r.p.m.) are widely used in offshore wind farms recently developed. Adwen, Areva, Hitachi, Mingyang (5 MW platform), Gamesa and MHI Vestas V164 platform are included in each different portfolios [29–34].
- High Speed PMSGs have usually 3 or 4 stage gearboxes depending on the number of poles and grid's frequency. These multi stage drivetrains are used by MHI Vestas (3.3 MW platform), Vestas (3 MW platform), Hyundai, Doosan and Haizhuang (5 MW platform) [34–37].

In contrast, Sinovel, Shanghai Electric, 2B Energy and Senvion offer DFIGs for powers of 3.6–6.2 MW range [38–41]. Envision, Siemens (G2/G4 platform) and Vestas (3.3 and 3.45 MW platforms) are the only ones offering SCIGs for offshore applications [42,25,34].

Offshore turbine's specifications can be observed in detail in Table 4. Up to now, in general DD turbines are focused on Classes I & II, whereas Class III design type is mainly for geared turbines except for Goldwind manufacturer.

2.3. PD and IEC class analysis

According to the turbines launched onto the market by the wind offshore industry during last decade, two main trends can be observed nowadays. On the one hand Siemens along with MHI Vestas are unveiling higher PD turbines, while Asian manufacturers such as Hitachi, Doosan, CSIC Haizhuang and Shanghai Electric are taking the opposite way.

For instance, MHI Vestas portfolio shows V164 platform from 7.0 MW to 9.5 MW (331.37 W/m^2–449.72 W/m^2), Siemens platforms D6, D7 and D8 present a diameter of 154 m from 6.0 MW to 8.0 MW (322.12 W/m^2–429.49 W/m^2), that is, for a constant diameter the rated nameplate power is increased. However, the second trend presents just the contrary concept, increasing bladeś length keeping the rated power of generator unchanged. CSIC Haizhuang 5 MW wind turbine is provided with 127 m, 151 m and 171 m (394.70 W/m^2–217.71 W/m^2) versions, whereas Doosan 3 MW platform is offered for 91.6 m, 100 m and 134 m (455.24 W/m^2–212.72 W/m^2) options.

Currently installed turbine data listed in Tables 3 and 4 indicate that there are two trends in offshore technology. On the one hand, European manufacturers are leading the production of Class I and Class S turbines for high average wind speed typical in the waters of the North Sea and the Baltic Sea, which intensity is above 8.5 m/s. Adwen, General Electric (6 MW platform), Areva, Senvion, Siemens and MHI Vestas include Class I or S in their portfolios, without offering Class III turbines.

On the other hand, Asian countries such as China, South Korea, Japan and Vietnam are in the early stages of development on offshore projects. Since the mean wind speed (MWS) in some territorial waters of above mentioned countries is moderate-low intensity type [43–45] Asian manufacturers developed Class I, Class II and Class III type turbines. Shanghai Electric, Ming Yang, Guodian United Power and Goldwind represent most of Class II and Class III turbines production in Asia, while Sinovel, XEMC-Darwind, Doosan Heavy Industries, Hyundai, Haizhuang Wind and Envision (4 MW platform) present a catalog of turbines wide enough to cover a wide range of wind speeds.

Recently, Chinese manufacturers Goldwind and Envision unveiled new turbines for ultra-low wind conditions: 6.45 MW platform with 164 m and 171 m (305.33 W/m^2–280.85 W/m^2) and 4.5 MW with 148 m (261.57 W/m^2), respectively. In the same way, in Europe, Siemens-Gamesa announced SG-8.0-167 turbine model, that is a reduction of PD to 365.23 W/m^2, compared with Siemens SWT-8.0-154 turbine (429.49 W/m^2).

Fig. 2 represents the installed offshore turbines from Table 3

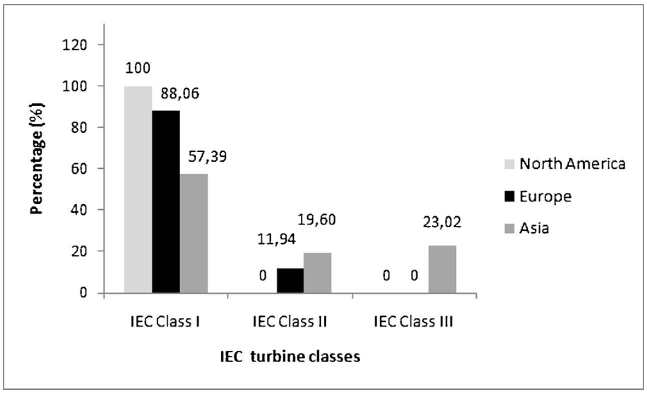

Fig. 2. Worldwide installed offshore turbineś class distribution.

according to IEC design type class in European, Asian and American waters.

It can be observed that Class II and Class III turbines are widely used in Asia.

For instance, deserve to mention different wind potential areas in Asia [46,47]. In Fujian province just one OWF was inaugurated in 2016 where MWS is 12.05 m/s, so very high PD turbine Class I model was installed (481.37 W/m^2). In contrast, in Jiangsu province of China measured MWS is in the 6.84 m/s–7.54 m/s low range, so low PD wind turbines were needed (194.88 W/m^2–301.35 W/m^2). In medium-moderate wind area of Shanghai City two OWF are full commissioned, with 307.96 W/m^2 and 340.64 W/m^2 PD turbines for 8.89 m/s and 9.68 m/s respectively. It should be noted that some projects in China (Jiangsu Rudong I–IV and Hydropower Rudong) and Vietnam (Bac Lieu) are located in intertidal areas where onshore type turbines were installed, typically IEC Class II and III designed turbines.

Class I turbines correspond with high values of PD while low values are typical of Class III ones. Most of European turbines belong to IEC Class I type design, being PD > 300 W/m^2 widely installed in European high wind conditions. In contrast, Asian manufacturerś offer includes most of IEC Class III turbines with lower values of PD than 280 W/m^2 according to lower MWSs in some China, South Korea and Vietnam territorial waters.

As an exception, SWT-4.0-130 Class I wind turbine is being installed in all wind class conditions. It presents 301.35 W/m^2 PD having great behavior in Class I wind sites. In fact, this turbine is widely used in low mean wind speeds in China, and it is sold under W4000/130 model in Chinese market licensed to Shanghai Electric.

3. Energy production indicators calculation

In order to analyze and calculate some indicators related with AEP classical methodology has been applied. To carry out the feasibility study of an OWF, it is first necessary to make an adequate estimation of the electric energy to be produced at the site. It is essential to have data that reflect wind characteristics such as average speed, turbulence, standard deviation, atmospheric pressure, temperature and direction of the dominant wind. The data collected for the evaluation of the wind resource in the site studied is summarized by the wind rose, which reflects the distribution of directions and the frequency distribution of speeds.

After collecting wind data, these are treated statistically, modeling the wind behavior by a probability curve whose more important values are the average speed and the variance, which have the following expressions [48]:

$$\bar{v} = \int_0^{\infty} v f(v) dv \tag{1}$$

$$\sigma = \int_0^{\infty} (v - \bar{v})^2 f(v) dv \tag{2}$$

Once the average speed velocity and its variance are known, there are different ways of representing the nature of the wind depending on the chosen distribution [49]. The most widely used at present is the Weibull distribution which represents the statistical distribution of the wind by means of the probability density function with only two parameters, as follows:

$$f(v; k, c) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \tag{3}$$

where, v is the random variable (wind speed) (m/s), k is the form factor, and c is the scale factor (m/s).

The calculation of both parameters can be done in different ways as analyzed in Ref. [50] where k indicates the uniformity of the wind or the shape of the Weibull distribution, while c indicates the wind potential of the site.

Because there is a vertical variation of the wind, if wind measurements are not available at the height at which the turbine is to be installed it is necessary to extrapolate this measurement. To determine the vertical wind variation the following expression can be used:

$$v = v_0\left(\frac{h}{h_0}\right)^n \tag{4}$$

where, h_0 is the reference height (m), v_o is the mean velocity measured at the reference height (m/s), h is the height at which the wind is desired (m) and n is the shear factor.

The power output of the turbine offered by the manufacturer is expressed as:

$$P_{output} = \frac{1}{2}\rho A v^3 \eta_{effective} \tag{5}$$

The effective performance $\eta_{effective}$ corresponds to the total efficiency of the turbine, including the performance of electrical, electronic, aerodynamic and mechanical systems, so it represents the overall efficiency of turbine in one single factor.

In this way, the gross AEP per turbine is estimated [51]:

$$AEP = \int_0^{v_{max.}} P(v_i) f(v_i)\ 8760\ dv \tag{6}$$

Another key factor in the selection of the turbine is its availability. Availability factor is defined as the percentage of the time in which a turbine operates freely without interrupting the total or partial production of electrical energy for a specific period of time, usually one year, taking into account both planned (regular maintenance) and unplanned (fault event, component failure,…) stops.

In Refs. [52,53] the fault ratios are precisely detailed, classified according to the nature of the faults and their associated costs. One of the main causes of failure in a turbine is the gearbox, which has according to Ref. [52], the highest rate of serious and costly faults. In this way it is logical the tendency to use multipole low speed turbines because the smaller number of stages in the gearbox the greater the availability of the turbines.

For a specific offshore site and certain period of time, CF could be defined as the ratio of the energy produced to the energy that would be produced if turbine works at rated power during the entire period of time.

CF definition clearly shows how much power is possible to extract from wind: the higher this value, the more suitable is the turbine for this specific site in terms of production. If considered period of time is one year, CF can be calculated as follows:

$$C.F.(\%) = \frac{\text{Net annual energy production(MWh)}}{\text{Installed power(MW)} \times \text{Annual hours}} \times 100 \tag{7}$$

At this point it should be mentioned that AEP and CF are related to a single turbine. In order to build the entire offshore wind farm, there are several issues that may be considered in the initial stages: turbine prices, wake losses, inner-array performance, marine logistics costs, overall plant expected CF, grid connection costs, etc…

In order to choose the most suitable turbine, CF is not the unique selection criteria. In general, different objectives in optimization of OWFs are used, aiming cost-effective design or maximizing energy delivered to the grid. Last researches indicate an optimization of economic factors as objective functions, such as LCoE, internal rate of return (IRR) and net present value (NPV) [54–60] or a combination of some of different main objectives [61,62]. Therefore, it could be considered that large energy production is the key factor for initial stage on development of OWFs, i.e. long-term average CF of whole wind plant at lowest cost is the most common goal.

CF may theoretically vary from 0 to 100%, but in practice it ranges from 31% to 56% in United Kingdom, Germany and Denmark [63–65]. According to values presented in Ref. [63–65], it can be noted that oldest OWFs present worse CF, new power plants commissioned in 2015 in Germany achieve largest CF percentages, in particular those that use low PD ratio turbines. Similar results can be observed for United Kingdom and Denmark wind farms.

In the same way, larger bladés lengths ensure additional capture of wind power, therefore, higher production is expected improving at the same time CF ratio and increasing annual full hours (AFH).

$$\mathrm{AFH} = \frac{\mathrm{NEP(MWh)}}{\mathrm{Rated\ \ Power\ (W)}} \tag{8}$$

4. Case studies

For this study three different sites were took into account with different wind classes according to IEC 61400-1. These 3 case studies correspond to Younggwang (South Korea), Maryland (USA) and Borssele (The Netherlands) which represents low, medium and high MWS values respectively [15,45,66]. Fig. 3 shows yearly wind speed distributions at 100 m height for each site selected for this analysis.

The first case corresponds to low MWS Class III site example in Younggwang location in South Korea, upgraded at 100 m hub height, wind distribution for $c = 8.06$ and $k = 1.919$ is showed, where average wind speed is 7.145 m/s. The interval 5–6 m/s accumulates highest amount of hours, totaling about 900 h/year. Moreover these peak increases more and more according to lower MWS.

Second wind offshore site was selected from Maryland Lease OCS A-0489 area in United States which MWS is 7.5–8.5 m/s. An average wind speed of 8 m/s is assumed with shape factor $k = 2$, which represents Rayleigh wind distribution for Class II emplacement. This second curve shows the wind speed distribution of the site, where 6–7 m/s wind speed will blow about 830 h/year.

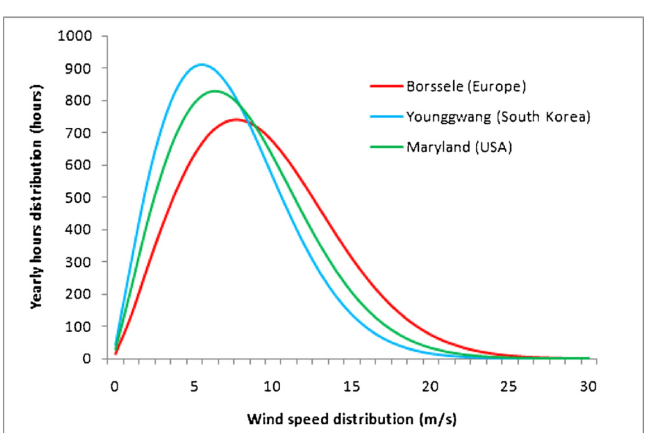

Fig. 3. Yearly wind speed distributions for 3 cases.

The last case corresponds to Borssele site in North Sea with Weibull parameters $c = 10.46$ m/s and $k = 2.09$ for a mean wind speed of 9.26 m/s. These wind characteristics belong to Class I conditions. Maximum duration corresponds to the interval of 7–8 m/s being slightly greater than 700 h/year.

As explained before, Class II and Class III design type turbines are unsuitable for this Class I site, even if they have highest CF, so this type of inappropriate turbines must be ruled out as shown in Ref. [20].

In this section, the behavior of the commercial turbines in the 3 sites described above will be analyzed. Table 5 presents the selected turbines with their main specifications including IEC Class design type, PD, rated power, rotor diameter, generator type and gearbox stages. Each turbine has a hub height according to the information delivered by their manufacturer. All those offshore turbines have been selected based on the possibility of obtaining their power curve on the web site, discarding the turbines whose manufacturers do not offer this information, because AEP cannot be calculated.

Regarding values of PD in commercial offshore turbines, most of installed in European waters have about 400 W/m^2 or higher PD for first offshore wind farms. From 2012 year, manufacturers focused on lower values around 300–380 W/m^2 in offshore sites and between 190–340 W/m^2 in near shore projects, especially in Asian intertidal cases.

Applying the methodology and equations of Section 3, including availability characteristics, the net AEP, CF and AFH of 15 commercial turbines have been calculated and shown in Table 6. As can be seen, turbines with a lower PD, have better CF and as a result more AFH are achieved. However this does not mean that the production is greater, because the production will depend on the power of the generator, control system, availability factor, mechanical–electrical losses and its better adaptability to the site.

For the first case study, the turbines that produce more energy correspond to those that has higher nominal power V164-9.5 (25.73 GWh) and V164-8.0 (23.14 GWh), however, it does not correspond to the higher value of CF. On the other hand, it is observed that the highest values of CF correspond to turbines with a lower PD for SWT-4.0-130 (36.7%), SL3000/113 (36.2%) and HZ151-5.0 (36.1%).

Analyzing the results corresponding to a more intense wind location, as Case 2, it can be observed that the variation of CF for Class II and Class I turbines is higher than Class III turbines. It should be noted that Class III turbines are not suitable for this environment (data indicated in grey color) because they would be exposed to overloads for which they have not been designed and their useful life would be reduced.

On average, the increase of the AEP of the Class IEC I turbines is +51.71%, the Class S is +47.1%, Class II is +49.49% and the lowest is Class III with +45.23% of variation, this is, bigger PD makes higher energy production variations. Deserve to be mentioned that the biggest variations of AEP corresponds to biggest PD values for 6.2M 126 and M5000 turbines with +59.18% and +58.37% respectively.

The relationship between PD and CF is still clearer, values greater than 400 W/m^2 of PD present an average CF growth of +54.89%, values 350–400 W/m^2 present +48.16%, figures 300–350 W/m^2 an average increase of +47.04% and finally PD below 300 W/m^2 have +44.16% rise.

In the third case, in the same way that the CF has increased, the AFHs of all turbines have also experienced an increase due to the increase in wind speed at this location in Borssele, North Sea. Thus, it is vital to know the annual hours that the turbine is supplying its rated power, especially for storage installations cost-effective design and optimization.

On the other hand, the most efficient Class I type turbines are low PD turbines, with a CF of 52.9% for the Siemens SWT-4.0-130 turbine and 50.5% for the General Electric Haliade 6.0–150 case, which doesn't mean necessarily that they represent the most cost effective option in optimization of LCoE.

Table 5
Analyzed turbineś technical specifications.

Manufacturer	Model	IEC Class	P.D. (W/m^2)	Power (MW)	Rotor (m)	Type	Gearbox
Senvion	6.2M 126	IB	493.2	6.15	126	DFIG	3
Areva	M5000	IA	473.1	5.0	116	MS-PMSG	1 Hybrid
MHI Vestas	V164-9.5	S	449.7	9.5	164	MS-PMSG	2
Repower	5M	IA	400.1	5.0	126	DFIG	3
XEMC- D.	XE 128-5.0	IIB	388.5	5.0	128	LS-PMSG	DD
MHI Vestas	V164-8.0	S	378.7	8.0	164	MS-PMSG	2
Adwen	AD 5-132	S	365.3	5.0	132	MS-PMSG	2
Hyundai	HQ5500/140	IB	357.2	5.5	140	HS-PMSG	4
Sinovel	SL3000/105	IIA	346.4	3.0	105	DFIG	3
Shanghai El.	W3600/116	IIA	340.6	3.6	116	DFIG	3
General El.	Haliade 6.0-150	IB	339.5	6.0	150	LS-PMSG	DD
Shanghai El.	W3600/122	IIIB	307.9	3.6	122	DFIG	3
Siemens	SWT-4.0-130	IB	301.3	4.0	130	SCIG	3
Sinovel	SL3000/113	III	299.1	3.0	113	DFIG	3
CSIC Haiz.	HZ151-5.0	III	279.2	5.0	151	HS-PMSG	3

If the ratio of CF is expressed relative to the PD of each turbine, it can be seen a direct relationship between the two magnitudes in the three case studies studied. The turbines with a PD above 400 W/m^2 (Senvion and Areva) present lowest ratio of CF. The low values of PD around 300 W/m^2, have the highest values of CF and correspond almost to Class III turbines, except for the Siemens SWT-4.0-130 turbine which has a high CF thanks to its low PD value, despite being Class I type turbine.

If data obtained in Younggwang site are collected and represented in a graph, it can be observed the relationship between PD and CF in Fig. 4. Turbines with PD > 400 W/m^2 reach low CF zone while PD < 310 W/m^2 turbines are in high CF area. Meanwhile, medium values of PD cover central part of the graph with medium values of CF.

In Fig. 4 all wind class turbines have been presented keeping in mind that the wind conditions of Younggwang doesn't put them mechanically at risk. However, Borssele and Maryland wind sites present an obvious risk for Class III turbines.

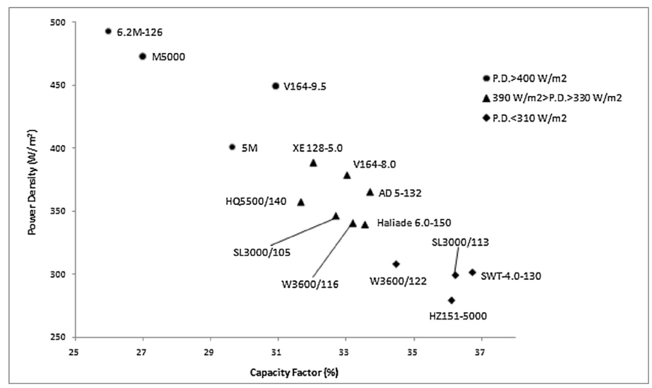

Fig. 4. Power density vs capacity factor in Younggwang site.

5. Conclusions

In this paper the effect of PD in the CF and the AEP of a turbine has been analyzed together with OWFs and offshore wind turbines currently commissioned worldwide.

Applying the methodology described in Section 3, AEPs for different wind class sites have been assessed for available wind turbines in the market, offering various PD rates.

Wind speed distributions have been modeled by Weibull method in three different wind conditions according to IEC 61400 standard, low, medium and high MWS. The energy production of 15 commercial turbines has been assessed and compared based on PD of each turbine. Additionally, offshore wind turbineś availability has been kept in mind.

According to commissioned OWFs, there is a clear relationship between MWS and selected turbines. A brief evaluation of installations currently working reveals that offshore turbines design class fits the

Table 6
Results of three case studies.

Model	Case1 (Younggwang)		Case 2 (Maryland)			Case 3 (Borssele)			
	Net AEP (GWh)	C.F.	Net AEP (GWh)	C.F.	C.F. Var. (%)	Net AEP (GWh)	C.F.	C.F. Var. (%)	A F H
6.2 M 126	13.99	0.259	17.33	0.321	+23.87	22.27	0.413	+59.14	3621
M5000	11.82	0.269	14.63	0.334	+23.82	18.72	0.427	+58.39	3744
V164-9.5	25.73	0.309	31.61	0.379	+22.86	38.24	0.459	+48.60	4025
5M	12.98	0.296	15.83	0.361	+21.96	19.92	0.454	+53.44	3984
XE 128-5.0	14.02	0.320	16.99	0.387	+21.14	21.14	0.482	+50.74	4228
V164-8.0	23.14	0.330	28.29	0.403	+22.22	33.98	0.484	+46.77	4247
AD 5-132	14.76	0.337	17.65	0.403	+19.54	21.55	0.492	+45.93	4310
HQ5500/140	15.25	0.316	18.40	0.381	+20.66	22.75	0.472	+49.22	4136
Haliade 6.0-150	18.42	0.346	22.00	0.418	+20.94	26.57	0.505	+46.05	4428
SL3000/105	8.59	0.327	10.34	0.393	+20.39	12.79	0.486	+48.86	4263
W3600/116	10.47	0.332	12.62	0.400	+20.47	15.59	0.494	+48.87	4330
W3600/122	10.87	0.344	13.05	0.413	+20.00	16.03	0.508	+47.37	4452
SWT-4.0-130	12.87	0.367	15.27	0.435	+18.67	18.54	0.529	+44.05	4635
SL3000/113	9.52	0.362	11.33	0.431	+19.01	13.78	0.524	+44.79	4593
HZ151-5.0	15.82	0.361	18.87	0.430	+19.29	22.71	0.518	+43.54	4542

MWS of the emplacements, so an overall consistency can be highlighted during last decades. Meanwhile, the previous limited variety of turbines has extraordinarily improved in recent years. Nowadays even ultra-low MWS sites are considered for offshore wind generation together with very low PD turbines in Class III design. In fact, emerging Asian market is focusing on different rotor diameters in order to achieve suitable PD values for specific wind site conditions.

Overall, case studie's results indicate that the following main ideas could stand out.

The first is that PD affects CF. Lower PD leads to higher value of CF, consequently more AFHs are achieved. But depending on the offshore policy of the country, this solution is not the most suitable option to achieve a competitive price of energy. Low ratio of PD means that rotor's swept area is big enough to catch necessary wind power capable to produce energy at nameplate capacity of wind turbine. As shown in Subsection 2.3, todaýs offshore wind farms fit with the main idea that high PD turbines are adequate for high MWS sites.

The second is that the highest AEPs are obtained by combining the following two factors; higher rated power and not a relatively high CF, such as MHI Vestas V164-8.0 (33.98 GWh), V164-9.5 (38.24 GWh) and General Electric Haliade 6.0–150 (26.57 GWh).

The third conclusion is about the wind variation. In general, the greater the intensity of the wind the greater AEP and CF values are achieved. However, the variation of these parameters is different depending on the PD: for turbines with a high PD the variation of AEP and CF rates are greater with respect to the turbines with lower PD.

Funding

This research was co-financed by the Spanish Ministry of Economy and Competitiveness under the project DPI2015-64985-R FEDER Funds and EU.

References

[1] A policy framework for climate and energy in the period from 2020 to 2030, 2014. http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52014DC0015. (Accessed 19 January 2018).
[2] The European offshore wind industry. Key trends andstatistics 2017, 2017. https://windeurope.org/about-wind/statistics/offshore/european-offshore-wind-industry-key-trends-statistics-2017/. (Accessed 8 February 2018).
[3] S. Rodrigues, C. Restrepo, E. Kontos, R. Teixeira Pinto, P. Bauer, Trends of offshore wind projects, Renewable Sustainable Energy Rev. 49 (2015) 1114–1135.
[4] 4COffshore . Offshore windfarms database. www.4COffshore.com/windfarms. (Accessed 19 January 2018).
[5] WindEurope, Wind energy scenariosfor 2030, 2017. https://windeurope.org/about-wind/reports/wind-energy-scenarios-2030/. (Accessed 19 January 2018).
[6] European Commission, Guidelines on State aid for environmental protection and energy 2014–2020 (2014/C 200/01), 2014. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52014XC0628%2801%29. (Accessed 19 January 2018).
[7] Government of The Netherlands, Dutch consortium to construct second Borssele offshore wind farm, 2016. https://www.government.nl/latest/news/2016/12/12/dutch-consortium-to-construct-second-borssele-offshore-wind-farm. (19 January 2018).
[8] Danish Energy Agency, Danish Experiences from Danish Wind Development, 2017. https://ens.dk/sites/ens.dk/files/Globalcooperation/offshore_wind_development_0.pdf. (Accessed 19 January 2018).
[9] Department for Business, Energy & Industrial Strategy, Contracts for Difference Second Allocation Round Results, 2017. https://www.gov.uk/government/publications/contracts-for-difference-cfd-second-allocation-round-results. (Accessed 19 January 2018).
[10] Bundesnetzagentur, Ergebnisse der 1. Ausschreibung vom 01.04.2017, 2017. https://www.bundesnetzagentur.de/DE/Service-Funktionen/Beschlusskammern/1BK-Geschaeftszeichen-Datenbank/BK6-GZ/2017/2017_0001bis0999/BK6-17-001/Ergebnisse_erste_Ausschreibung.pdf?_blob=publicationFile&v=3. (Accessed 19 January 2018).
[11] M. Korsnes, Chinás Offshore Wind Industry 2014. An overview of current status and development. Centre for Sustainable Energy Studies, 2014.
[12] X. Zhao, L. Ren, Focus on the development of offshore wind power in China: has the golden period come? Renewable Energy 81 (2015) 644–657.
[13] Z. Xiliang, Z. Da, M. Stua, Kickoff of Offshore Wind Power in China: playoffs for China wind power development, Procedia Environ. Sci. 12 (2012) 166–173.
[14] Global Wind Energy Council, Global Wind Report 2016, 2017. Annual market update http://gwec.net/publications/global-wind-report-2/global-wind-report-2016/. (Accessed 19 January 2018).
[15] Bureau of Ocean Energy Management, Renewable Energy Programs-Lease and Grant Information, 2017. https://www.boem.gov/Lease-and-Grant-Information/. (Accessed 1 January 2018).
[16] S. Mathew, G.S. Philip, C.M. Lim, Advances in Wind Energy Conversion Technology, Springer, Berlin, 2011 (page 71).
[17] The European Wind Energy Association, Powering Europe: wind energy and the electricity grid, 2010.
[18] J.K. de Boer, The influence of power density on the value chain. An offshore case study, Wind Integration Workshop (2015) (page 3–4).
[19] J.P. Molly, Rated Power of Wind Turbines: What is Best?, Dewi Magazine No. 38, 2011.
[20] Wind turbines. Part I: Design requirements. IEC 61400-1 Edition 3, 2005.
[21] Vindeby Offshore Project. https://orsted.com/en/Media/Newsroom/News/2017/03/The-worlds-first-offshore-wind-farm-is-retiring. (Accessed 19 January 2018).
[22] A. Madariaga, I. Martínez de Alegría, J.L. Martín, P. Eguía, S. Ceballos, Current facts about offshore wind farms, Renewable Sustainable Energy Rev. 16 (2012) 3105–3116.
[23] A. Madariaga, J.L. Martín, I. Zamora, I. Martínez de Alegría, S. Ceballos, Technological trends in electric topologies for offshore wind power plants, Renewable Sustainable Energy Rev. 24 (2013) 32–44.
[24] General Electric. https://www.gerenewableenergy.com/wind-energy/turbines.html. (Accessed 1 December 2017).
[25] Siemens. https://www.siemens.com/global/en/home/markets/wind/turbines-and-services.html. (Accessed 1 December 2017).
[26] Goldwind. http://www.goldwindamericas.com/. (Accessed 1 December 2017).
[27] Guodian United Power. http://www.gdupc.com.cn/productEN.aspx?cataId=51. (Accessed 1 December 2017).
[28] XEMC-Darwind. http://www.xemc-darwind.com/. (Accessed 1 December 2017).
[29] Adwen. http://www.adwenoffshore.com/products-services/products/. (Accessed 1 December 2017).
[30] Areva http://www.areva.com/ (accessed 1 December 2017).
[31] Hitachi. http://www.hitachi.com/rev/pdf/2014/r2014_07_104.pdf. (Accessed 1 December 2017).
[32] Ming Yang. http://www.mywind.com.cn/English/program/products.aspx?MenuID=05030301&ID=30. (Accessed 1 December 2017).
[33] Gamesa. http://www.gamesacorp.com/en/products-and-services/wind-turbines/catalogue/. (Accessed 1 December 2017).
[34] MHI Vestas. http://www.mhivestasoffshore.com/innovations/. (Accessed 1 December 2017).
[35] Hyundai. https://en.wind-turbine-models.com/turbines/1180-hyundai-hq5500-140. (Accessed 1 December 2017).
[36] Haizhuang Wind Power. http://www.hzwindpower.com/. (Accessed 1 December 2017).
[37] Doosan Heavy Industries. http://www.doosanheavy.com/en/products/energy/green/. (Accessed 1 December 2017).
[38] Sinovel. http://www.sinovel.com/english/list/?43_1.html. (Accessed 1 December 2017).
[39] Shanghai Electric. http://www.shanghai-electric.com/Pages/pns/details.aspx?pid=38. (Accessed 1 December 2017).
[40] 2B Energy. http://2benergy.com/. (Accessed 1 December 2017).
[41] Senvion. https://www.senvion.com/global/en/wind-energy-solutions/wind-turbines/. (Accessed 1 December 2017).
[42] Envision-energy. http://www.envision-energy.com/wind-power/. (Accessed 1 December 2017).
[43] D.L. Nguyen, A brief overview on assessments of wind energy resource potential in vietnam, J. Fundam. Renewable Energy Appl. 4 (2014) 132.
[44] U. Hellberg, S. Snickare, Wind power in China. A study of the Chinese distributed market through the example of Guangdong province, KTH School of Industrial Engineering and Management, 2012 (page 41).
[45] M.E. Lee, G.W. Kim, S.T. Jeong, D.H. Ko, K.S. Kang, Assessment of offshore wind energy at Younggwang in Korea, Renewable Sustainable Energy Rev. 21 (2013) 131–141.
[46] 4COffshore.Wind speeds database. http://www.4coffshore.com/windfarms/windspeeds.aspx. (Accessed 19 January 2017).
[47] J. Yang, Q. Liu, X. Li, X. Cui, Overview of wind power in China: status and future, Sustainability 9 (2017) 1454.
[48] S.H. Jangamshetti, V.G. Rau Billinton, Site matching of wind turbine generators: a case study, IEEE Trans. Energy Convers. 14 (No.4) (1999) 1537–1543.
[49] E.C. Morgan, M. Lackner, R.M. Vogel, L.G. Baise, Probability distributions for offshore wind speeds, Energy Convers. Manage. 52 (2011) 15–26.
[50] A.K. Azad, M.G. Rasul, M.M. Alam, S.M. Ameer Uddin, S. Kumar Mondal, Analysis of wind energy conversion system using Weibull distribution Analysis of wind energy conversion system using Weibull distribution, ICME 2013, 10th International Conference on Mechanical Engineering, vol. 90, 2014, pp. 725–732.
[51] P. Lakshmanan, J. Liang, N. Jenkins, Assessment of collection systems for HVDC connected offshore wind farms, Electr. Power Syst. Res. 129 (2015) 75–82.
[52] J. Carroll, A. McDonald, D. McMillan, Failure rate: repair time and unscheduled O&M cost analysis of offshore wind turbines, Wind Energy 19 (2016) 1107–1119 (pages 1111 & 1116).
[53] J. Carroll, A. McDonald, J. Feuchtwang, D. McMillian, Drivetrain availability of offshore wind turbines, European Wind Energy Conference, Barcelona, Spain, 2014.
[54] A.G. González-Rodríguez, Review of offshore wind farm cost components, Energy Sustainable Dev. 37 (2017) 10–19.
[55] A. Ioannou, A. Angus, F. Brennan, Stochastic prediction of offshore wind farm LCoE through an integrated cost model, Energy Procedia 107 (2017) 383–389.

[56] Ajit C. Pillai, J. Chick, M. Khorasanchi, S. Barbouchi, L. Johanning, Application of an offshore wind farm layout optimization methodology at Middelgrunden wind farm, Ocean Eng. 130 (2017) 287–297.
[57] G. Caralis, P. Chaviaropoulos, V. Ruiz Albacete, D. Diakoulaki, V. Kotroni, K. Lagouvardos, Z. Gao, A. Zervos, K. Rados, Lessons learnt from the evaluation of the feed-in tariff scheme for offshore wind farms in Greece using a Monte Carlo approach, J. Wind Eng. Ind. Aerodyn. 157 (2016) 63–75.
[58] L. Parada, C. Herrera, P. Flores, V. Parada, Wind farm layout optimization using a Gausian-based wake model, Renewable Energy 107 (2017) 531–541.
[59] J. Serrano González, A.L. Trigo García, M. Burgos Payán, J. Riquelme Santos, A.G. González Rodríguez, Optimal wind-turbine micro-siting of offshore wind farms: a grid-like layout approach, Appl. Energy 200 (2017) 28–38.
[60] G. Giebel, C.B. Hasager, An overview of offshore wind farm design, in: W. Ostachowicz, M. McGugan, J.U. Schröder-Hinrichs, M. Luczak (Eds.), MARE-WINT New Materials and Reliability in Offshore Wind Turbine Technology, Springer, 978-3-319-39095-6, 2016, pp. 337–346.
[61] S. Rodrigues, C. Restrepo, G. Katsouris, R. Teixeira Pinto, M. Soleimanzadeh, P. Bosman, A. Bauer, Multi-objective optimization framework for offshore wind farm layouts and electric infrastructures, Energies 9 (2016) pp. 216.
[62] A. Tesauro, P.E. Réthoré, G.C. Larsen. State of the art of wind farm optimization, Proceedings of EWEA 2012 – European Wind Energy Conference & Exhibition. European Wind Energy Associaton (EWEA), 2012 (page 10).
[63] Capacity factors at Danish offshore wind farms. http://energynumbers.info/capacity-factors-at-danish-offshore-wind-farms. (Accessed 1 December 2017).
[64] Capacity factors at German offshore wind farms. http://energynumbers.info/germanys-offshore-wind-capacity-factors. (Accessed 1 December 2017).
[65] Capacity factors at British offshore wind farms. http://energynumbers.info/uk-offshore-wind-capacity-factors. (Accessed 1 December 2017).
[66] Netherlands Enterprise Agency, Site Studies Wind Farm Zone Borssele. Metocean Study for the Borssele Wind Farm Zone Site II, 2015.