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Review Paper

Assessment of the potential for the design of marine renewable energy systems

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Abstract. The assessment of the potential for the design of marine renewable energy systems is reviewed and the current situation for marine renewable energy is promising. The most studied forms of marine renewable energy are ocean wind energy, ocean wave energy and tidal energy. Wind turbine generators include mostly horizontal axis type and vertical axis type. But also more exotic ideas such as a kite design. Wave energy devices consist of designs converting wave oscillations in electric power via a power take off equipment. Such equipment can take multiple forms to be more efficient. Nevertheless, the technology alone cannot be the only step towards marine renewable energy. Many other steps must be overcome: policy, environment, manpower as well as consumption habits. After reviewing the current conditions of marine renewable energy development, the authors analyzed the key factors for developing a strong marine renewable energy industry and pointed out the huge potential of marine renewable energy.

Keywords: marine renewable energy; renewable; wind; wave; generator; competitiveness

1. Introduction

Broadly speaking, about two thirds of our planet is occupied by water. Ocean wind, waves and currents are studied and quantified to better understand their potential. But beyond understanding, why not use the power of the ocean? The marine renewable industry tries to use currents, winds, tides, temperature gradient, waves or even solar radiations to provide the energy we all need. Traditionally, oil, gas and coal are the primary energy sources. These types of energy have always been cheap and relatively easy to get into production. Nevertheless, relying on fossil fuel to build our society cannot be possible in a modern society. Surveys have shown that fossil fuels are only providing a short-term solution with a perspective of at most a century. Reserves are dwindling. On top of that, more and more countries are quantifying the impact of pollution on the environment and health. It turns out that using oil, gas and coal bear a huge responsibility in global warming (U.S. Department of Energy, 2011). In addition to this perspective, the price of oil & gas has been very fluctuating for almost ten years (U.S. Department of Energy, 2016) leading to major economic and employment crises. Therefore, it is imperative to find a new way to provide energy

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that minimizes all these issues: a renewable and cheap source of energy with a stable price that also guarantees employment. The only carbon-free solution we have found so far is nuclear energy. However, due to several global catastrophes and nuclear waste issues, the major nuclear producers (such as France, Germany, the U.S. and Japan) are slowly shutting down their plants.

For sure, with these shutdowns, the global energy need will not likewise go down. Therefore, there is a huge expectation for an alternative solution to back up the "Big Power" and reduce global warming. If such a solution is developed, it could be the 21st century's major innovation. On the one hand, great hopes are set on a solution such as Liquefied Natural Gas (LNG) providing a maximum of energy in a very small volume and easily delivered everywhere on Earth. LNG technology is already well-known and mastered. Plants are under construction or in production everywhere: from the frozen lands of Yamal in Siberia to the deep waters of Australia on FPSO – LNG Vessels (aka FLNG). But let us think big. What about an energy source brought from an unlimited resource: the ocean. The questions that come are: are we capable to design efficient generators to fulfil the global energy need, when, where and what will be the cost? In this race to marine renewable energy, the European Union (E.U.), the U.S., Norway, Canada and China seem to be leading. Since the beginning of the millennium, the E.U. has decided to follow a policy based on the integration of renewable energies in the power grid. Every company or laboratory working on these receives a "carte blanche". Even the media are backing up the research in favor of these energies. But how can we explain this will of change in the energy production?

First, we must argue that only a few countries are oil & gas producers and the others must deal with their energy supply (Syndicat des Energies Renouvelables 2015). In addition to that, the fluctuating price of hydrocarbons leads to the conclusion that the main issues of today's fossil fuels are the instability of markets, the supply, the limited resource, energy independence and the environmental cost. All the current research on marine renewable energy is bringing an alternative to solve these five major issues. In this case, marine renewable energy seems to have a bright future to fill the opportunity space for new generation (Fig. 1) between electricity demand and production (Drew *et al.* 2009).

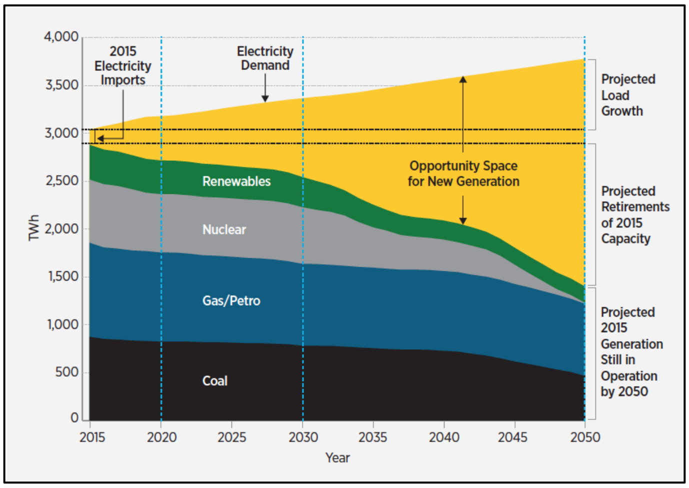

Fig. 1 Electricity demand perspective (U.S. Department of Energy, 2016)

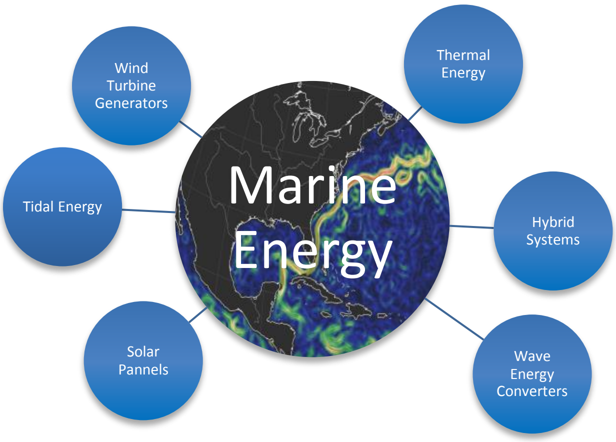

Fig. 2 Different forms of marine renewable energies

The main purpose of this paper is to present an assessment of the potential for the design of marine renewable energy systems. In this paper, we will review the current technologies in developing marine renewable energy, including offshore wind energy and offshore wave energy (Drew *et al*. 2009, Lopez *et al*. 2013). Then, we will extract the key factors in the design of these systems. As conclusions, both the potential and the problem of marine renewable energy are discussed.

2. Current marine renewable energy solutions

"Marine renewable energy" is not an exact term to define a particular form of energy (e.g., wind). Instead, "marine energy" includes all forms of energy present in oceans and seas. Even after we narrow down the source of energy to renewable ones, we still count many. Fig. 2 shows the current engineering forms to utilize the marine renewable energy.

In this paper, we focus exclusively on energy extracted from wind and wave.

2.1 Wind turbine generators

2.1.1 Overview

Companies and governments have been developing onshore wind plants for years. The systems to extract wind energy have developed to a better position than wave energy converters (WECs). The reason why people become increasingly interested in developing offshore wind energy solutions is that:

- Offshore wind speed is usually higher and steadier than onshore wind speed, yielding a great potential for generating more electricity;
- Offshore wind farms are usually farther from the highly-populated areas, so the "Not In My Back Yard" oppositions and government regulations to onshore wind farms are weaker;

- The cost of offshore wind power is gradually decreasing, making it more and more profitable;
- Nevertheless, in the specific case of offshore farms the distance from shore implies other issues. Such farms require array cables, export cables and sometimes offshore substations which must be connected to the local grid via subsea cables (typically for 80 turbines the export cable can easily measure 30 km and the length of all array cables can reach up to 200 km, Syndicat des Energies Renouvelables, 2015). Then, installation, operability and maintainability of equipment are much more demanding. Consequently, the risk of transmission loss is much more significant for offshore wind farms (Houghton *et al*. 2016).

Wind turbine generators, according to their locations, are categorized into three types: floating, grounded and a more exotic one which is flying. However, it is more common to categorize them based on rotation axis (horizontal or vertical) of their generators (see Fig. 3).

2.1.2 Horizontal Axis

Nowadays, the most common type of Wind Turbine Generator (WTG) is the three-bladed horizontal axis. The design is quite simple to explain. Basically, it is a tower gathering at the top a nacelle with electric equipment and three blades. These blades have an adjustable angle of rotation to optimize the airflow. The structure of the equipment is shown in Fig. 4.

Currently, the tower is set on top of a steel pile and the electricity is brought to shore via a subsea cable. Giving an idea of the size of this generator, to extract a power of 3.6 MW (mean power for an offshore WTG today), the diameter of the area swept by the blades is about 100 m and the overall height of the structure can reach 130 m above the sea level (Syndicat des Energies Renouvelables, 2015).

To calculate the power extracted by WTGs we use the following equation

$$P_t = M\omega_r N_b \tag{1}$$

M : (in N.m): torque developed by one blade;
ω_r : (in rad/s): turbine rotational speed;
N_b : the number of blades;

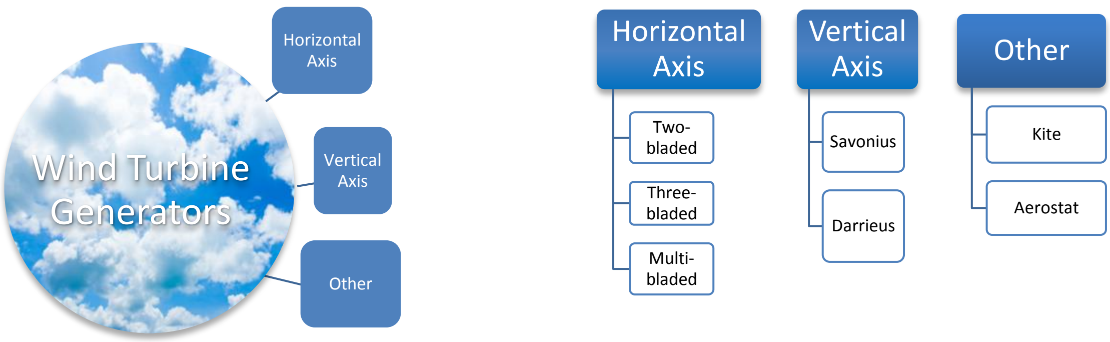

Fig. 3 Structure of a WTG

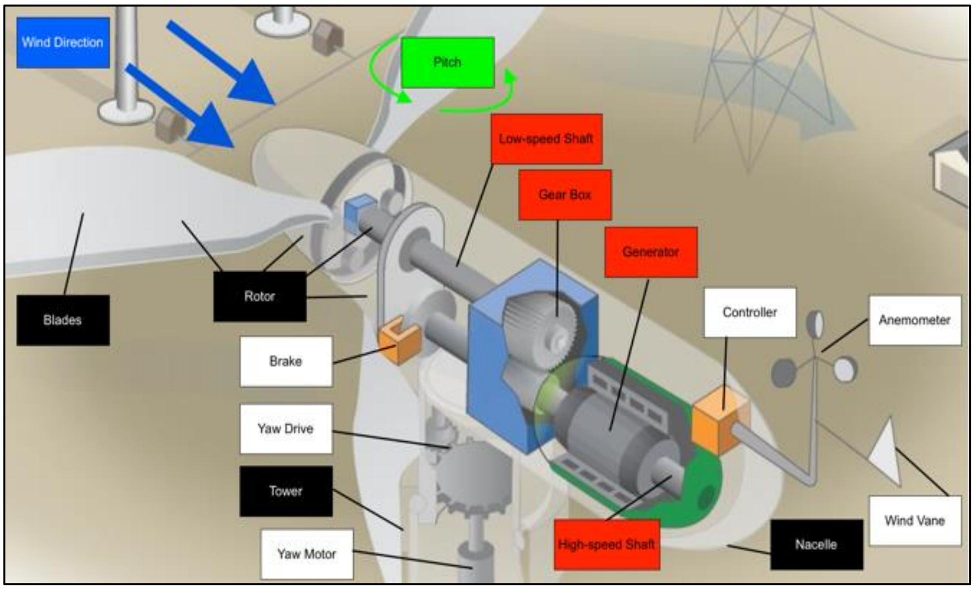

Fig. 4 Structure of a WTG, (U.S. Department of Energy, 2015)

For example, a new WTG is design to have an average rotational speed $\omega_r = 1.57\ rad/s$, each of the three blades measures R = 50 m, the angle of attack α is automatically set to optimize the position of the turbine and the stability of the generated power. If we have v = 20 m/s wind speed, we get M = 74.3 kN.m and finally PT = 3.5 MW (Khrisanov and Dmitrev 2016). But not all WTGs have three blades. The second type coming to mind is the two-bladed WTG. By reducing the number of blades, as an immediate effect, the moment of inertia is reduced. Rotational speed is thus increased and this allows the operator to use a direct-drive synchronous generator. This solution is bringing a cost reduction (less electrical equipment) but also a load of other issues. With the highest rotational speed of the turbine, fatigue is an important parameter that must be considered. A powerful breaking system must also be designed to stop the blades in any situation. Consequently, the maintenance load is transferred from electric equipment to mechanical and structural one. For small turbines on a remote island this can be a solution because it is cheap and the maintenance cost can be mastered. Moreover, this generator can be switched on only when required (Fig. 5).

Fig. 5 Power System (2 blades), (courtesy of Warren Gretz, NREL 1997)

Fig. 6 Swift wind turbines, (courtesy of Cascade Engineering, NREL 2012)

Fig. 7 Aermotor windmill, (courtesy of Jim Green, NREL 2012)

Then, some others are multi-bladed. By multi-bladed, we refer to more than three blades. This is very interesting to master as much as possible the airflow. Each blade can be monitored to fit the flow and extract the most optimized quantity of energy from the wind speed. Nevertheless, this technology is not exploited at a large scale offshore. Only few recent tests have been tried on top of buildings (Fig. 6). So, the main experience we can have is the one coming from the old-style windmill (Fig. 7).

2.1.3 Vertical axis

Savonius (Fig. 8) and Darrieus (Fig. 9) are two different styles of Vertical Axis Wind Turbines (VAWTs) invented in the 1920s. So far, these two technologies have only been used on shore but some laboratories are working on bringing them offshore on floating platforms.

The main advantage of this technology is that VAWTs are omni-directional turbines (Yaakob *et al.* 2008).

This means that they do not have to change direction to follow the wind. Beyond that, it is supposedly much lighter compared to horizontal axis WTGs. All these are made of steel or aluminum. As the weight defines the price, by combining lightness and omni-direction the cost of electricity could be reduced. Then, the design of VAWTs is an enhancement in favor of maintainability. Equipment and moving parts are straightforwardly accessible.

Fig. 8 Four Windside WS-4B wind turbines producing power for a radar station in China, (courtesy of Windside Production Ltd 2009)

Fig. 9 Darrieus VAWT. Quiet Revolution wind turbines, (courtesy of Quietrevolution, NREL 2009)

Table 1 Vertiwind rated weight/power

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
VertiWind WTG	600	5	120

But disadvantages are still legion today. Due to the omni-directional ability of VAWTs, the forces undergone are also omni-directional and cause a fatigue of the entire structure. New materials such as carbon fibers could be used in a close future but they are still under research. In addition to that, VAWTs are harvesting energy at lower altitude than traditional horizontal WTGs. As a consequence, they are facing in average weaker wind than at higher altitude.
We can calculate the power extracted from VAWTs by using the equation

$$P_t = \frac{1}{2} C_p \rho A v^3 \qquad (2)$$

A (m^2): swept area of the turbine
v (m/s): wind speed
Cp: power coefficient of each VAWT calculated with drag, lift, normal and tangential components
ρ (kg/m^3): air density

Nowadays, the best VAWT turbine can produce 1 MW (way less than horizontal axis WTGs), (Khrisanov and Dmitrev 2016).

2.1.4 Other

Eventually, some called aerostats are sent to a height of 300 m with cables to reach stronger winds at high altitude. Very strong tethers are used to both hold tight the structure and carry electricity back to the ground. These ropes are strongly embedded in the seabed throughout heavy concrete structures. This technology has been tested on land. It is not mature enough to be sent offshore and requires too many equipment. So far, the main issues are found in the design and in offshore maintenance. With such a technology, aerostats must be designed to overcome hurricanes and rough sea states without crashing or being dismantled while providing electricity. We must notice that it is impossible to bring aerostats back to the sea level in case of a hurricane as we do it on land. Other solutions must be found to make this technology efficient enough to be developed at a large scale.

Then another exotic solution is to use the power of kite wings to create electricity. The best design so far can expect to create 500 kW with two 50 m^2 kites (Fig. 10). The system is quite simple: kites are attached to the ground via a tether wired on a drum. The traction power of the kite is transmitted to the drum which unwires and creates electricity. Once the highest point is reached, the parameters of the kite are modified to reduce traction and drag; then the drum winches down the kite. Usually those kites are flying between 200 and 800 m high. The main advantage of this system is the absolute lightness of the kite and the production system. This opens an area of very low cost per MWh (about $60 per MWh by 2030, U.S. Department of Energy 2017).

2.1.5 Traditional support structure Vs floater

Today, the main part of the construction cost of WTGs (up to 30%) is occupied by the construction of support structures. These are Gravity foundations, Monopiles or Jacket Structures (Fig. 11).

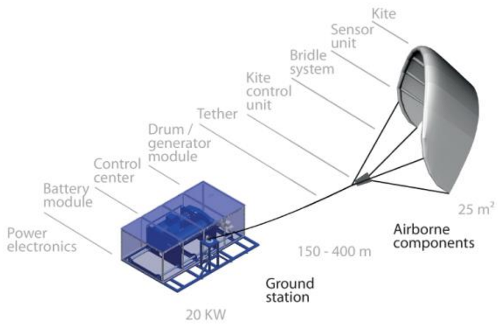

Fig. 10 Kite Power Systems Limited 2017

Table 2 Kite Power System Rated Weight/Power (Kite Power Systems Limited 2017)

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
KPS	20	0.5	40

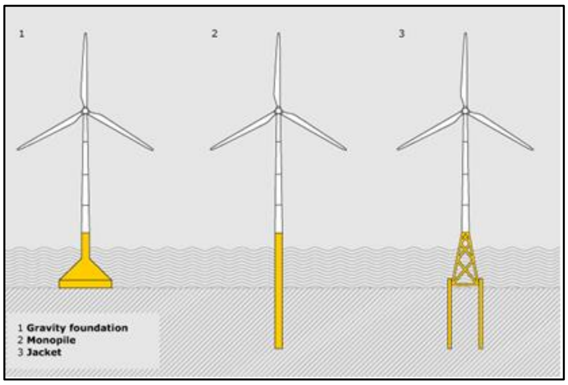

Fig. 11 Offshore WTGs Foundations, (courtesy of Züblin 2010)

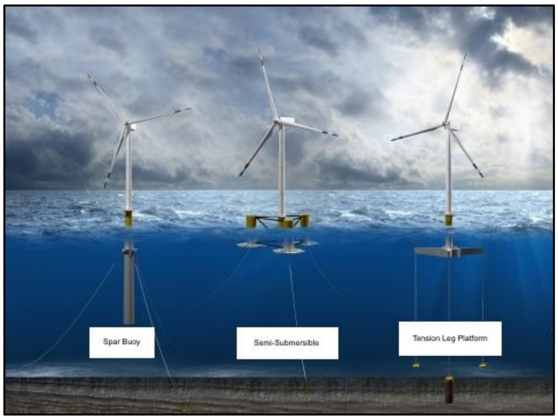

Fig. 12 WTGs Floating Solutions, (courtesy of DNV GL 2016)

Fig. 13 Windmill Floater (SBM Offshore 2015)

Table 3 Typical Offshore Wind WTG Rated Weight/Power

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
Typical Offshore WTG	1300	6.0	216.7

With the techniques brought from the Oil & Gas industry, it is possible to adapt technologies we currently use to create floaters and welcome WTGs. Such platforms are very similar to traditional Spars, Tension Leg Platforms (TLPs) and Semi-Submersible (Figs. 12 and 13). This step forward is a major condition to reach deeper water, stronger winds and be out of sight from the coast. A deep-water WTGs farm can be up to 40 % more powerful than one in shallow water (U.S. Department of Energy 2017).
Today, the vast majority of horizontal axis WTGs under exploitation offshore is the one in shallow water (< 30 m of water depth) and based on monopiles (about 95%) or jacket platforms. Many of them have already been installed in the North Sea, the Baltic Sea, the English Channel, Maine or China. From a floating point of view, one farm has been launched off the coast of Scotland (5 WTGs on SPARs in 2017). Four other commercial farms will be launched soon in Europe (in the Atlantic Ocean and the Mediterranean Sea) using other technologies: a semi-submersible (steel or concrete) and a TLP.

2.1.6 Global benchmark

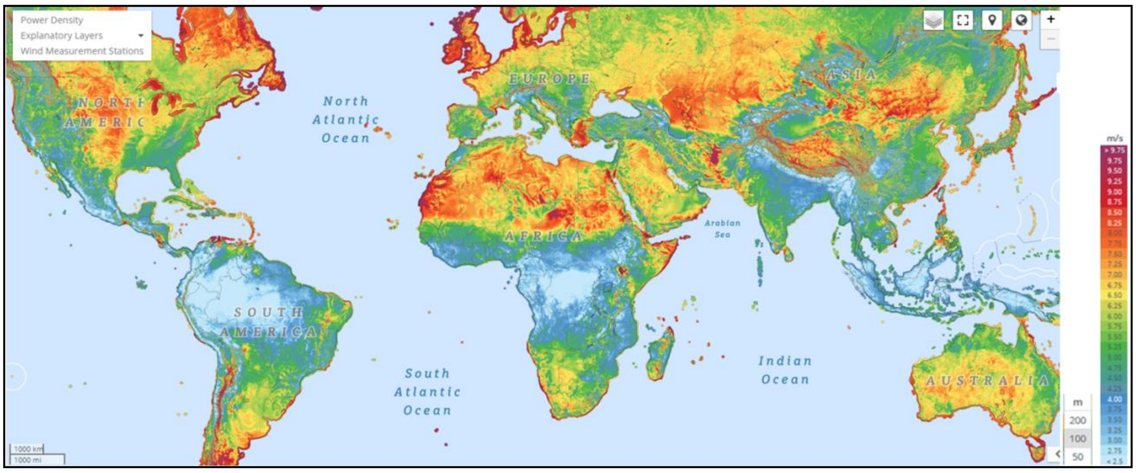

Fig. 14 Average Wind Speed Chart (Global Wind Atlas 2017)

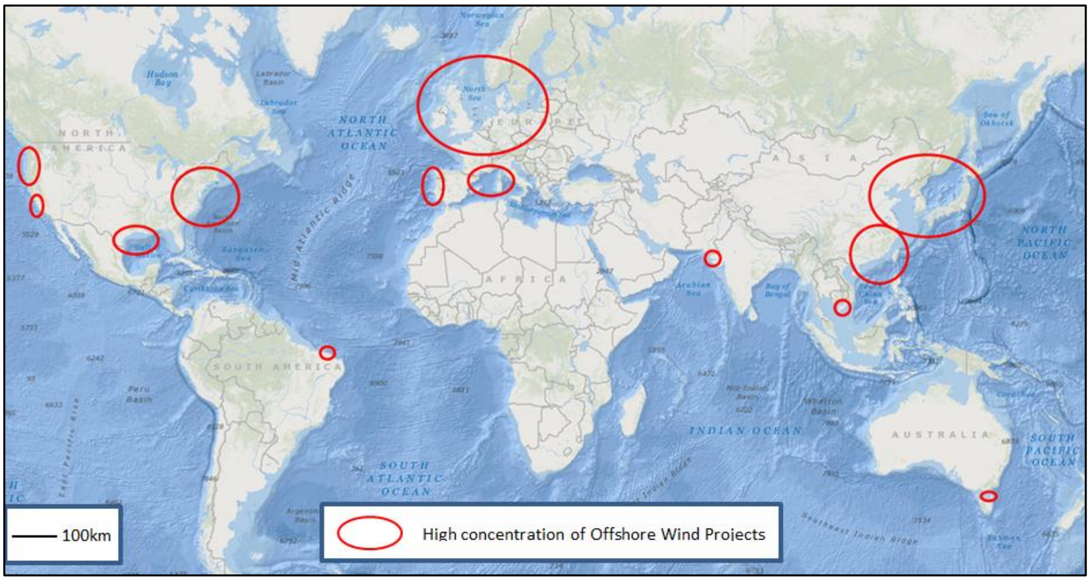

Fig. 15 Global Offshore Wind Projects Locations (4COffshore 2018)

Table 4 Main Offshore Wind Projects in America, Asia and Australasia

Name	**Country Name**	**Windfarm Status**	**Offshore Construction Starts**	**Capacity MW (Max)**	**Turbine Model**	**Foundation**	**CAPEX (in local currency)**	**WaterDepthM (Max)**	**ExpectedLife Years**
AMERICA									
NaiKun - Haida Energy Field	Canada	Consent Authorised	1-Jan-20	396	Preferred supplier agreement signed with Siemens in 2012	Grounded:	CAD 2000m	20	
St George's Bay	Canada	Concept/Early Planning	1-Jan-21	180	Estimate: SWT-8.0-154 (Siemens Gamesa)	Grounded: Gravity-Base	CAD 466m		
Deepwater ONE - South Fork Project	United States	Concept/Early Planning	1-Jan-21	96	12 x 8MW favoured over 15 x 6MW	Grounded:	USD 740m	36	
DeepCwind Consortium - VolturnUS - Dyces Head Test Site	United States	Decommissioned	31-May-13	0.02	Renewegy VP-20	Floating: Semi-Submersible Platform	USD 12m	18.2	
New England Aqua Ventus I	United States	Consent Application Submitted	1-Jan-19	12	8MW turbine also in consideration	Floating: Semi-Submersible Platform	USD 96m	110	20

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Coastal Virginia Offshore Wind	United States	Consent Application Submitted	1-Jan-20	12	Haliade 150-6MW (GE Energy)	Grounded: Monopile	USD 300m	26.5	
Icebreaker	United States	Consent Application Submitted	1-Jan-19	20.7	V126-3.45MW (MHI Vestas Offshore Wind)	Grounded: Suction Bucket	USD 126m	18.8	20
Fishermen's Atlantic City Windfarm	United States	Consent Authorised	1-Jan-20	24	SWT-4.0-130 (Siemens)	Grounded: Jacket	USD 188m	11.8	
Block Island Wind Farm	United States	Fully Commissioned	22-Jul-15	30	Haliade 150-6MW (GE Energy)	Grounded: Jacket (Piled)	USD 360m	28	20
ASIA									
Dongtai Four (H2) 300MW	China	Under Construction	7-Jul-17	302.4	63 x SWT-4.0-130 12 x EN-136 / 4.2	Various	CNY 4712.91 m	17	
Jiangsu Rudong 150MW Offshore (Intertidal) Demonstration Wind Farm - phase II	China	Fully Commissioned	2-Jul-12	50	GW 109/2500 (Goldwind)	Grounded: Monopile	CNY 790m	0.2	
Jiangsu Rudong 150MW Offshore (Intertidal) Demonstration Wind Farm – extension	China	Fully Commissioned	1-Nov-12	50	GW 109/2500 (Goldwind)	Grounded: Monopile	CNY 796m	0	
Longyuan Putian Nanri Island 400MW Project - Phase 2 - 184MW	China	Consent Authorised	1-Jan-19	184	SWT-4.0-130 (Siemens)	Grounded: High-Rise Pile Cap	CNY 4026.82 m	30	
Huaneng Jiaxing	China	Consent Authorised	1-Dec-18	400	China Windey	Grounded:	CNY 7492m	9.1	
Hydropower Rudong Offshore Wind Farm (intertidal) 100MW demonstration project - phase 1	China	Fully Commissioned	5-Jul-12	20	H 102-2.0MW (CSIC Haizhuang Windpower Equipment), 32X2.5	Grounded: Gravity-Base	CNY 329.6m	0	
Laoting Yuetuo Island 300MW Demonstration (Tangshan - Area 3)	China	Consent Authorised	1-Jan-19	300	Sinovel	Various	CNY 5539m	20	
Fujian Putian City Flat Bay - 50MW	China	Fully Commissioned	1-Mar-15	50	XE128-5MW (XEMC - Darwind)	Grounded: High-Rise Pile Cap	CNY 1161.18 m	13.5	

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Datang Jiangsu Binhai 300MW offshore wind farm	China	Under Construction	19-Dec-16	300	MingYang SCD 3MW (MingYang), 50xGW3.0MW 1xSinovel 3.0MW	Grounded:	CNY 4860m	15	
Longyuan Rudong Intertidal Trial Wind Farm – Extension	China	Fully Commissioned	2-Jul-12	49.2	CSIC Haizhuang 5MW x 2, DEC 5.5MW x 1, Mingyang 6.5MW X 1, Envision 4MW X 7	Various	CNY 790m	2	
Jiangsu Longyuan Chiang Sand H1 300MW	China	Under Construction	1-Jan-17	300	EN-4.0-136 (Envision Energy)	Various	CNY 4950m	7.8	
CGN Pingtan Island 300MW offshore windfarm	China	Under Construction	25-Feb-17	300	SWT-4.0-130 (Siemens)	Various	CNY 609.33m	23.5	
Rudong Offshore Wind Farm Demonstration Project - Expansion Project (200MW)	China	Fully Commissioned	25-Nov-14	200	25x Siemens 4MW 25x Envision 4MW -136	Various	CNY 2992m	9.2	
Longyuan Jiangsu Dafeng (H12) 200MW offshore wind power project (Concession)	China	Under Construction	25-Nov-16	200	Estimate: GW 109/2500 (Goldwind)	Grounded: Jacket	CNY 3548m	11	26
Jiangsu Luneng Dongtai 200MW Concession	China	Fully Commissioned	16-Jan-16	200	SWT-4.0-130 (Siemens)	Grounded: Monopile	CNY 3280m	10	
Fujian Putian City Flat Bay Two (Zone B)	China	Under Construction	14-Jul-17	264	SWT-6.0-154 (Siemens)	Grounded: Jacket	CNY 4959.82 m	24.5	
Fujian Putian City Flat Bay (Zone F) - 200 MW	China	Pre-Construction	1-Jun-18	200	SWT-7.0-154 (Siemens Gamesa)	Grounded:	CNY 3780m	10	
Longyuan Jiangsu Dafeng (H7) 200MW offshore wind power project	China	Consent Authorised	1-Jan-18	200	GW 109/2500 (Goldwind)	Various	CNY 3650m	14.6	
Sinohydro Tianjin Nangang Phase 1	China	Pre-Construction	1-Jan-18	90	Gamesa G132-5.0MW	Grounded: High-Rise Pile Cap	CNY 1158m	1.5	
SPIC Binhai North H1 100MW	China	Fully Commissioned	3-Oct-15	100	SWT-4.0-130 (Siemens)	Grounded: Monopile	CNY 1644.11 m	7.6	
Huaneng Rudong 300MW - South	China	Fully Commissioned	30-Apr-16	146.4	12 X Envision 4.2 MW(EN-136), 24 X Siemens 4.0MW	Various	CNY 2566m	8.2	

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Donghai Bridge Offshore Wind Farm Phase II (Extension) project	China	Fully Commissioned	27-Sep-11	102.2	W3600-116 (Shanghai Electric Wind Power Equipment Co., Ltd. (Sewind)), 1 x SL5000/LZ62/HH100 27 x W3600M-116	Grounded: High-Rise Pile Cap	CNY 1940m	9.5	
Xiangshui Demonstration	China	Fully Commissioned	17-Apr-15	202	18 x Goldwind 3.0 37 x Siemens SWT-4.0	Grounded: Suction Bucket	CNY 3540m	11.2	
Jiangsu Rudong 150MW Offshore (Intertidal) Demonstration Wind Farm - phase I	China	Fully Commissioned	17-Jun-11	99.3	17 Sinovel 3M (SL3000/90) + 21 Siemens SWT-2.38-101	Various	CNY 2500m	3.1	
Hydropower Rudong Offshore Wind Farm (intertidal) 100MW demonstration project - phase 2	China	Fully Commissioned	1-Oct-14	80	SWT-2.5-108S (Siemens)	Various	CNY 1318.4m	7.4	
Laoting Bodhi Island 300MW Demonstration	China	Under Construction	30-Apr-16	300	SWT-4.0-130 (Siemens)	Various	CNY 5280m	25.5	
Huaneng Rudong 300MW - North	China	Fully Commissioned	30-Apr-16	156	14x Siemens 4.0MW, 19 x Haizhuang 5MW (H154), 1 x Haizhuang 5MW (H171)	Various	CNY 2734m	14.6	
Zhuhai Guishan Hai Demonstration	China	Partial Generation/Under Construction	8-Sep-16	120	34 x 3MW (MingYang SCD 3MW), 3 x 6MW (United Power 6MW)	Various	CNY 4450m	9.4	
Longyuan Putian Nanri Island 400MW Project - Phase 1 - 200MW	China	Partial Generation/Under Construction	1-Sep-17	200	SWT-4.0-130 (Siemens)	Grounded:	CNY 4198.17 m	16.4	
Choshi Offshore Demonstration Project	Japan	Fully Commissioned	28-Jun-12	2.4	MHI 2.4 MW (Mitsubishi Heavy Industries)	Grounded: Gravity-Base	JPY 5000m	10	
Kashima Port - North - phase 1	Japan	Consent Authorised	1-Apr-20	93.6	HTW5.0-126 (Hitachi Ltd)	Grounded: Monopile	JPY 53000m	18	20
Fukushima Floating OffshoRe Wind FARm Demonstration Project (Forward) Phase 2	Japan	Partial Generation/Under Construction	1-Jun-14	12	HTW5.0-126 (Hitachi Ltd), MHI 7MW Sea Angel	Floating:	USD 58m	125	
Kitakyushu Offshore Demonstration Project	Japan	Fully Commissioned	13-Nov-12	2	JSW J82 2MW (Japan Steel Works)	Grounded: Gravity-Base	JPY 5000m	14.5	

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Kashima Port – South	Japan	Consent Authorised	1-Apr-20	93.6	HTW5.2-136 (Hitachi Ltd)	Grounded: Monopile	JPY 49000m	10	20
Murakami Iwafune	Japan	Concept/Early Planning	1-Apr-23	45	V117 3MW	Grounded:	JPY 143m	30	20
Tamra Offshore Wind Farm Project	South Korea	Fully Commissioned	15-Apr-15	30	WinDS 3000TM (Doosan Heavy Industries)	Grounded: Jacket (Piled)	KRW 165000m	20	
Southwest Offshore Demonstratio n	South Korea	Under Construction	8-May-17	60	7 x WinDS3000/100, 13 x WinDS3000/134 (Doosan Heavy Industries)	Grounded: Jacket	KRW 425500m	9.7	
Southwest Offshore Phase 2	South Korea	Concept/Early Planning	1-Jan-20	400	Various Models (5-7MW)	Grounded:	KRW 2e+006m	13.4	
Saemangeum	South Korea	Pre-Construction	1-Jan-19	99.2	24 x 3.6 4 x 3.0-3.2	Grounded:	KRW 404000m	6.1	
Jeonnam 4GW Offshore Zone - Sinan-300MW Phase 1	South Korea	Concept/Early Planning	1-Jun-19	300	Estimate: Siemens and/or Doosan Heavy Industries	Grounded:	KRW 500000m		
Aiguille Flat	South Korea	Concept/Early Planning	1-Jan-19	0.75	UNISON 750/U57 (UNISON)	Floating: Semi-Submersibl e Platform	KRW 16000m	80	
Formosa 1 OWF Phase 2	Taiwan	Consent Application Submitted	1-Mar-19	120	SWT-6.0-154 (Siemens)	Grounded: Monopile	TWD 20000m	28.5	
Formosa 1 OWF Phase 1	Taiwan	Fully Commissioned	15-Aug-16	8	SWT-4.0-120 (Siemens)	Grounded: Monopile	TWD 2500m	16.8	
Bac Lieu - phase I (intertidal)	Vietnam	Fully Commissioned	1-May-12	16	GE 1.6-82.5 (GE Energy)	Grounded: High-Rise Pile Cap	USD 40.32m	0	
Bac Lieu - phase II (intertidal)	Vietnam	Fully Commissioned	1-Feb-14	83.2	GE 1.6-82.5 (GE Energy)	Grounded: High-Rise Pile Cap	USD 195m	0	
AUSTRALASIA									
Global Renewable Solutions - Power Platform	Australi a	Dormant		7	Not Decided	Grounded: Gravity-Base			
Star of the South Energy Project	Australi a	Concept/Early Planning		2000	Not Decided	Grounded:	AUD 8000m	50	

Table 5 Main Offshore Wind Projects in Europe

Name	Country Name	Windfarm Status	Offshore Construction Starts	Capacity MW (Max)	Turbine Model	Foundation	CAPEX (in local currency)	WaterDepthM (Max)	ExpectedLife Years
EUROPE									
Northwind	Belgium	Fully Commissioned	7-Apr-13	216	V112-3.0 MW Offshore (MHI Vestas Offshore Wind)	Grounded: Monopile	EUR 851m	23	
Norther	Belgium	Pre-Construction	1-Jun-18	369.6	V164-8.0 MW (MHI Vestas Offshore Wind)	Grounded: Monopile	JPY 150000m	26	
Rentel	Belgium	Under Construction	29-Jun-17	309	SWT-7.0-154 (Siemens Gamesa)	Grounded: Monopile	EUR 1100m	34	20
Nobelwind	Belgium	Fully Commissioned	11-May-16	165	V112-3.3 MW Offshore (Vestas)	Grounded: Monopile	EUR 655m	33	20
Thornton Bank phase II	Belgium	Fully Commissioned	25-Nov-10	184.5	6.2M126 (Senvion)	Grounded: Jacket (Piled)	EUR 812.5m	20	
Thornton Bank phase III	Belgium	Fully Commissioned	1-Apr-11	110.7	6.2M126 (Senvion)	Grounded: Jacket (Piled)	EUR 487.5m	21.5	
Northwester 2	Belgium	Consent Authorised	1-Sep-19	224	V164-9.5 MW (MHI Vestas Offshore Wind)	Grounded:	EUR 1000m	37	
DanTysk	Germany	Fully Commissioned	20-Jan-13	288	SWT-3.6-120 (Siemens)	Grounded: Monopile	EUR 1000m	29	
Borkum Riffgrund 1	Germany	Fully Commissioned	1-Jan-13	312	SWT-4.0-120 (Siemens)	Grounded: Monopile	EUR 1190m	29	25
Amrumbank West	Germany	Fully Commissioned	26-Oct-13	302	SWT-3.6-120 (Siemens)	Grounded: Monopile	EUR 1000m	25	
Nordsee Ost	Germany	Fully Commissioned	30-Jul-12	295.2	6.2M126 (Senvion)	Grounded: Jacket (Piled)	EUR 1300m	25	25
Meerwind Süd/Ost	Germany	Fully Commissioned	9-Sep-12	288	SWT-3.6-120 (Siemens)	Grounded: Monopile	EUR 1200m	27	
Butendiek	Germany	Fully Commissioned	31-Mar-14	288	SWT-3.6-120 (Siemens)	Grounded: Monopile	EUR 1300m	21	
Global Tech I	Germany	Fully Commissioned	6-Aug-12	400	M5000-116 (Areva Wind), Now known as AD 5-116 (Adwen)	Grounded: Tripod	EUR 1800m	41	

Continued-

Trianel Windpark Borkum II	Germany	Pre-Construction	31-May-18	203	6.2M152 (Senvion)	Grounded: Monopile	EUR 800m	33	25
Hohe See	Germany	Under Construction	16-Apr-18	497	SWT-7.0-154 (Siemens Gamesa)	Grounded: Monopile	EUR 1800m	40	
Sandbank	Germany	Fully Commissioned	6-Jul-15	288	SWT-4.0-130 (Siemens)	Grounded: Monopile	EUR 1200m	29	
Gode Wind 1 and 2	Germany	Fully Commissioned	14-Apr-15	582	SWT-6.0-154 (Siemens)	Grounded: Monopile	EUR 2200m	34	25
Nordergründe	Germany	Fully Commissioned	3-May-16	110.7	6.2M126 (Senvion)	Grounded: Monopile	EUR 410m	11	
Riffgat	Germany	Fully Commissioned	14-Jun-12	108	SWT-3.6-120 (Siemens)	Grounded: Monopile	EUR 480m	23	
BARD Offshore 1	Germany	Fully Commissioned	27-Mar-10	400	Bard 5.0 (Bard)	Grounded: Tripile	EUR 2900m	41	
Deutsche Bucht	Germany	Pre-Construction	1-Sep-18	252	V164-8.0 MW (MHI Vestas Offshore Wind)	Grounded: Monopile	EUR 1300m	40	
Merkur	Germany	Under Construction	20-Apr-17	396	Haliade 150-6MW (GE Energy)	Grounded: Monopile	EUR 1600m	33	25
Trianel Windpark Borkum I	Germany	Fully Commissioned	1-Sep-11	200	M5000-116 (Areva Wind), Now known as AD 5-116 (Adwen)	Grounded: Tripod	EUR 900m	33	25
Nordsee One	Germany	Fully Commissioned	14-Dec-15	332.1	6.2M126 (Senvion)	Grounded: Monopile	EUR 1200m	29	25
Borkum Riffgrund 2	Germany	Under Construction	14-Jul-17	450	V164-8.0 MW (MHI Vestas Offshore Wind)	Various	EUR 1300m	29	
Veja Mate	Germany	Fully Commissioned	6-Apr-16	402	SWT-6.0-154 (Siemens)	Grounded: Monopile	EUR 1900m	41	
Arkona	Germany	Under Construction	15-Jul-17	385	SWT-6.0-154 (Siemens)	Grounded: Monopile	EUR 1200m	27.5	
Wikinger	Germany	Fully Commissioned	4-Apr-16	350	AD 5-135 (Adwen)	Grounded: Jacket (Piled)	EUR 1350m	40	
Arcadis Ost 1	Germany	Consent Authorised	1-Jan-20	247.3	Haliade 150-6MW (GE Energy)	Grounded: Jacket (Piled)	EUR 1400m	45	25
EnBW Baltic 2	Germany	Fully Commissioned	16-Aug-13	288	SWT-3.6-120 (Siemens)	Various	EUR 1250m	42	
EnBW Baltic 1	Germany	Fully Commissioned	1-May-10	48.3	SWT-2.3-93 (Siemens)	Grounded: Monopile	EUR 200m	19	20
Anholt	Denmark	Fully Commissioned	30-Dec-11	399.6	SWT-3.6-120 (Siemens)	Grounded: Monopile	DKK 9000m	19.4	
Horns Rev 3	Denmark	Under Construction	10-Apr-16	406.7	V164-8.0 MW (MHI Vestas Offshore Wind)	Grounded: Monopile	EUR 1000m	20	25
Kriegers Flak	Denmark	Under Construction	16-Feb-18	605	SG 8.0-167 DD (Siemens Gamesa)	Grounded:	EUR 1300m	30	

Continued-

Nissum Bredning Vind	Denmark	Fully Commissioned	10-May-17	28	SWT-7.0-154 (Siemens Gamesa)	Grounded: Jacket	DKK 300m	6	
ELISA/ELICAN - Mario Luis Romero Torrent (PLOCAN site)	Spain	Pre-Construction	30-Jun-18	5	AD 5-132 (Adwen)	Floating:	EUR 14.8m	30	
Reposaaren tuulipuisto	Finland	Fully Commissioned	21-Jul-10	2.3	SWT-2.3-101 (Siemens)	Grounded: Gravity-Base	EUR 8.5m	19	
Tahkoluoto Offshore Wind Power Project	Finland	Fully Commissioned	24-May-17	42	SWT-4.0-130 (Siemens)	Grounded: Gravity-Base	EUR 120m	26	20
Parc éolien en mer de Dieppe - Le Tréport	France	Consent Application Submitted	1-Jan-21	496	SG 8.0-167 DD (Siemens Gamesa)	Grounded: Jacket	EUR 2500m	24.5	
Parc éolien en mer de Fécamp	France	Consent Application Submitted	1-Mar-19	498	Haliade 150-6MW (GE Energy)	Grounded: Gravity-Base	EUR 2000m	31	20
Eoliennes Offshore du Calvados project	France	Consent Application Submitted	1-Mar-20	450	Haliade 150-6MW (GE Energy)	Grounded: Monopile	EUR 1800m	30	25
Projet éolien en mer de la Baie de Saint-Brieuc	France	Consent Authorised	1-Jun-20	496	SG 8.0-167 DD (Siemens Gamesa)	Grounded: Jacket	EUR 2500m	36	20
Projet de parc éolien en mer de Saint-Nazaire	France	Consent Application Submitted	1-Mar-21	480	Haliade 150-6MW (GE Energy)	Grounded: Monopile	EUR 2000m	20.8	25
Floatgen Project	France	Under Construction	25-Aug-17	2	V80-2.0 MW (Vestas)	Floating: Semi-Submersible Platform	EUR 21.5m	30	
Les éoliennes flottantes de Groix & Belle-Île	France	Consent Application Submitted	1-Jun-21	24	Haliade 150-6MW (GE Energy)	Floating: Semi-Submersible Platform	EUR 200m	71	
Les éoliennes flottantes du Golfe du Lion	France	Concept/Early Planning	1-Jan-20	24	Haliade 150-6MW (GE Energy)	Floating: Semi-Submersible Platform	EUR 180m	82	20
EolMed	France	Concept/Early Planning	1-Jan-20	24.6	6.2M152 (Senvion)	Floating: Semi-Submersible Platform	EUR 175m	72	20
Les éoliennes flottantes de Provence Grand Large	France	Concept/Early Planning	1-Jan-20	24	SWT-8.0-154 (Siemens Gamesa)	Floating: Tension Leg Platform	EUR 200m	99	20
Parco eolico nella rada esterna del porto di Taranto	Italy	Consent Authorised	1-Jan-19	30	3.0M122 (Senvion)	Grounded: Monopile	EUR 63m	13.5	
Gemini	Netherlands	Fully Commissioned	1-Jul-15	600	SWT-4.0-130 (Siemens)	Grounded: Monopile	EUR 2800m	34	20
Eneco Luchterduinen	Netherlands	Fully Commissioned	23-Jul-14	129	V112-3.0 MW Offshore (MHI Vestas Offshore Wind)	Grounded: Monopile	EUR 450m	22	25
Westermeerwind	Netherlands	Fully Commissioned	10-Mar-15	144	SWT-3.0-108 (Siemens)	Grounded: Monopile	EUR 400m	7	
Olav Olsen and Seawind Systems Demonstator – Metcentre	Norway	Consent Authorised	31-Dec-18	6.2	Seawind 6.2MW	Grounded: Gravity-Base	EUR 20m	31	
WindFloat 1 Prototype (WF1)	Portugal	Decommissioned	10-Jan-11	2	V80-2.0 MW (Vestas)	Floating: Semi-Submersible Platform	EUR 19m	50	3

Continued-

WindFloat Atlantic (WFA)	Portugal	Consent Authorised	1-Jul-19	25	V164-8.0 MW (MHI Vestas Offshore Wind)	Floating: Semi-Submersible Platform	EUR 125m	100	25
Kårehamn	Sweden	Fully Commissioned	1-Jun-12	48	V112-3.0 MW Offshore (MHI Vestas Offshore Wind)	Grounded: Gravity-Base	EUR 120m	20	25
SeaTwirl S2	Sweden	Concept/Early Planning	1-Jan-20	1	SeaTwirl 1MW (SeaTwirl)	Floating: Spar Floater	SEK 70m		
Dudgeon	United Kingdom	Fully Commissioned	20-Mar-16	402	SWT-6.0-154 (Siemens)	Grounded: Monopile	GBP 1500m	23.5	25
Gwynt y Môr	United Kingdom	Fully Commissioned	8-May-12	576	SWT-3.6-107 (Siemens)	Grounded: Monopile	EUR 2700m	32	
Humber Gateway	United Kingdom	Fully Commissioned	19-Jul-13	219	V112-3.0 MW Offshore (MHI Vestas Offshore Wind)	Grounded: Monopile	GBP 736m	16.2	25
Lincs	United Kingdom	Fully Commissioned	10-Mar-11	270	SWT-3.6-120 (Siemens)	Grounded: Monopile	GBP 1000m	16.4	20
London Array	United Kingdom	Fully Commissioned	2-Jan-11	630	SWT-3.6-120 (Siemens)	Grounded: Monopile	EUR 2420m	23	
Ormonde	United Kingdom	Fully Commissioned	29-Jul-10	150	5M (Senvion)	Grounded: Jacket (Piled)	EUR 552m	21	25
Race Bank	United Kingdom	Fully Commissioned	29-Jun-16	573.3	SWT-6.0-154 (Siemens), Power mode enables capacity of 6.3MW	Grounded: Monopile	GBP 1700m	23	24
Teesside	United Kingdom	Fully Commissioned	6-Feb-12	62.1	SWT-2.3-93 (Siemens)	Grounded: Monopile	GBP 200m	18	
Kincardine Offshore Windfarm Project	United Kingdom	Consent Authorised	1-May-18	50	1 x V80-2MW 6 x upto 8.4MW	Various	GBP 250m	62	
East Anglia ONE North	United Kingdom	Concept/Early Planning	1-Jan-25	800	Up to 67 turbines. The range of wind turbines currently being considered is 12MW – 19MW.	Grounded:	GBP 2000m	59	
Dounreay Trì	United Kingdom	Consent Authorised	1-Jun-18	10	H 151-5MW (CSIC Haizhuang Windpower Equipment)	Floating: Semi-Submersible Platform	GBP 42.7m	76	

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Triton Knoll	United Kingdom	Consent Authorised	31-Dec-19	860	V164-9.5 MW (MHI Vestas Offshore Wind)	Grounded: Monopile	GBP 2000m	30	
Walney Phase 1	United Kingdom	Fully Commissioned	10-Mar-10	183.6	SWT-3.6-107 (Siemens)	Grounded: Monopile	GBP 630m	23	20
Walney Phase 2	United Kingdom	Fully Commissioned	9-Apr-11	183.6	SWT-3.6-120 (Siemens)	Grounded: Monopile	GBP 630m	30	25
West of Duddon Sands	United Kingdom	Fully Commissioned	3-May-13	389	SWT-3.6-120 (Siemens)	Grounded: Monopile	GBP 1254m	21	
Westermost Rough	United Kingdom	Fully Commissioned	21-Jan-14	210	SWT-6.0-154 (Siemens)	Grounded: Monopile	EUR 870m	22	25
Rampion	United Kingdom	Partial Generation/Under Construction	25-Jan-16	400.2	V112-3.45 MW Offshore (MHI Vestas Offshore Wind)	Grounded: Monopile	EUR 1900m	39	25
East Anglia TWO	United Kingdom	Concept/Early Planning	1-Jun-24	800	Up to 75 turbines-exact number. The range of wind turbines currently being considered is 12MW – 19MW	Grounded:	GBP 2000m	73	
Moray East	United Kingdom	Consent Authorised	1-Mar-19	950	V164-9.5 MW (MHI Vestas Offshore Wind)	Grounded: Jacket (Piled)	GBP 1800m	50	
Aberdeen Offshore Wind Farm (EOWDC)	United Kingdom	Under Construction	25-Mar-18	93.2	MHI Vestas specially designed 9 V164-8.4 MW turbines and two V164-8.8 MW turbines.	Grounded: Jacket (Suction Bucket)	GBP 335m	30	20
Beatrice	United Kingdom	Under Construction	27-Mar-17	588	SWT-7.0-154 (Siemens Gamesa)	Grounded: Jacket (Piled)	GBP 2600m	50	25
Inch Cape	United Kingdom	Consent Authorised	10-Oct-21	784	At least 7MW turbines	Grounded:	GBP 3000m	54	25
Neart na Gaoithe	United Kingdom	Consent Authorised	1-Jan-20	448	Estimate: SG 8.0-167 DD (Siemens Gamesa)	Grounded: Jacket	GBP 1614m	56	
Burbo Bank Extension	United Kingdom	Fully Commissioned	6-Jun-16	254.2	V164-8.0 MW (MHI Vestas Offshore Wind)	Grounded: Monopile	GBP 800m	13.9	25

Continued-

Kentish Flats Extension	United Kingdom	Fully Commissioned	25-Apr-15	49.5	V112-3.3 MW Offshore (MHI Vestas Offshore Wind)	Grounded: Monopile	GBP 150m	4	20
Galloper	United Kingdom	Partial Generation/Under Construction	28-Dec-16	353	SWT-6.0-154 (Siemens, each turbine from 6MW to 6.3MW)	Grounded: Monopile	GBP 1500m	50	23
East Anglia ONE	United Kingdom	Under Construction	11-Apr-18	714	SWT-7.0-154 (Siemens Gamesa)	Grounded: Jacket (Piled)	GBP 2600m	41	30
Blyth Offshore Demonstrator Project - Array 2	United Kingdom	Fully Commissioned	11-Jul-17	41.5	V164-8.0 MW (MHI Vestas Offshore Wind)	Grounded: Gravity-Base	GBP 145m	39	22
Gunfleet Sands 3 - Demonstration Project	United Kingdom	Fully Commissioned	7-Jul-12	12	SWT-6.0-120 (Siemens), Also will fit a 154m rotor later on.	Grounded: Monopile	GBP 51m	11.9	
Hywind Scotland Pilot Park	United Kingdom	Fully Commissioned	22-Apr-17	30	SWT-6.0-154 (Siemens)	Floating: Spar Floater	GBP 210m	110	20
Hornsea Project One	United Kingdom	Under Construction	11-Jan-18	1218	SWT-7.0-154 (Siemens Gamesa)	Grounded: Monopile	EUR 3360m	37	
Hunterston Test Centre (onshore)	United Kingdom	Fully Commissioned	2-Jul-13	11	7MW Offshore Hydraulic Drive Turbine Formerly SeaAngel 7 MW (Mitsubishi Power Systems Europe), Siemens 6MW	Grounded: Onshore Concrete	GBP 20m	0	5

Table 6 Windfarm Status Definitions

Development Zone	This refers to an area or zone that the government has identified as being suitable for development for offshore wind. Normally developers are then invited to submit project proposals falling within area
Concept/Early Planning	The early stages of a wind farm. At this pre-application stage tasks are undertaken to establish the feasibility and design of project
Consent Application Submitted	The formal application has been officially submitted and is awaiting a decision from the authorities
Consent Authorised	Approval has been granted by the authorities and construction can begin assuming the developer wishes to invest
Pre Construction	The project has reached financial close/ made a final investment decision and is moving towards offshore construction
Under Construction	The offshore construction is in progress. No turbines are yet energised
Partial Generation/ Under Construction	At least one turbine has been energised and is feeding power to the grid. Part of the project is still under construction
Fully Commissioned	All turbines energised and feeding power to the grid
Dormant	The planning process for a country is moving forward but the wind farm I not explicitly include in plans. However the windfarm has not formally been declined by the authorities or cancelled by the developer
Decommissioned	The project has come to the end of its lifecycle. The turbines and foundations are removed.

The two different charts (Figs. 14 and 15) are clearly highlighting 3 major areas of development of offshore wind farms (4COffshore). All of them are not at the same stage but North America, Asia and Europe are pushing towards this technology (Tables 4 and 5). Europe was the first to step into this technology at a large scale (about 100 projects today) but Asia and America are quickly bridging the gap with very ambitious projects (with more than 50 wind turbines on a single farm). The reason of this fast development can be identified by crossing the data with the global average wind speed chart (Global Wind Atlas 2017). In each high potential region, the average wind speed (at 100 m-high: the mean altitude of wind turbines) is above 7.5 m/s. As it can be observed, many other spots on Earth are offering the same parameters (Argentina, Somalia, Sakhalin or Newfoundland in Canada for example). Nevertheless these locations are very remote and would need a very complex system of cables going through pristine and uninhabited areas (transmission loss is a main issue as well as the cost of maintenance, installation and energy transmission). Today, it seems more reasonable to exploit offshore wind next to areas with high energy demand.

From the study of wind turbine generators, we can get many clues to deduce what is very important for the design. Horizontal axis three-bladed systems seem to be very performant (6 to 8 MW for the most recent turbines) and are the favorite choice of most companies (Salvatore and Greco 2008). But something must be done to reduce the construction cost. This issue is to be solved by preferring floating solutions. Companies are trying to reach high sea to get more wind power and find more steady winds. Nonetheless, this leads to many other issues; going further offshore makes it harder for inspection and maintenance (time, cost, performance at work, cables, etc.). A good balance must be found between pushing further offshore and the cost of related installations.

Afterwards, the CAPEX study (Capital Expenditure) puts into perspective the cost reduction of projects throughout the years. In approximately 10 years the CAPEX for a 50 MW installation (with monopiles) has been divided by two (from about $4.8 m to $2.4 m per MW).

Finally, to get precise idea of Offshore Wind Farm development, a more accurate benchmark is presented on France in APPENDIX A. France has been selected among other countries in Europe for the vast number of projects in development, the number of foundation solutions under test and the high level of renewable energy integration into the local economy as well as in the environmental policy.

2.2 Wave energy converters

2.2.1 Overview

Wave energy distributes extensively in oceans. According to the Bureau of Ocean Energy Management, the recoverable wave energy resource in the U.S. is capable of powering more than 100 million homes annually. In terms of energy density, the wave power is in a higher order of magnitude compared to solar and wind power. Wave power is produced in coastal area near to where 50% of the world's population resides, therefore it can save additional construction for transmission. The wave power is greatest in winter, when electrical demand is also highest. In some areas 40 kW per meter of crest-length can be extracted from waves (mainly between 30-60 degrees North and South). In addition, the electricity supply from wave energy can be accurately forecast days in advance and it is available all days and nights (Columbia Power Technologies, 2017).

The PTO (Power Take Off) is really the key of each WEC. It is converting the undulating motion of waves to electricity. In other words, these PTOs are converting kinetic and potential energy into electricity. This one is then brought to the grid through subsea cables. According to the linear theory of wave formation

$$E = E_k + E_P = \frac{1}{8}\rho g H^2 \tag{3}$$

E (J): wave energy;

E_k (J): kinetic energy;

E_p(J): potential energy;

ρ (kg/m^3): specific density of salt water;

H (m): wave height;

g (m/s^2): free fall acceleration;

In deep water (where the water depth is greater than the wave crest-length), the wave power formula is given by the equation

$$P = \frac{\rho g^2}{64\pi} H^2 T \tag{4}$$

P (W/m): wave power per unit of wave crest-length;

ρ (kg/m^3): specific density of salt water;

H (m): wave height;

g (m/s^2): free fall acceleration;

T (s): wave energy period;

During major storms (15 m wave height with 15s wave period) each meter of wave front is developing up to 1.7 MW. It is to be noticed that this power is not in any case fully extracted by WECs. A good performance for today's WECs would be 14.5 kW per unit of wave crest-length (Babarit *et al.* 2012).

WECs must cope with the assault of seawater. They must be protected against corrosion (sacrificial anodes), fatigue (permanent motion), trawlers, collision, located not too far from the cost to allow a connection with the power grid and watertight. Collison is a major concern: to be very efficient, the closer to the sea surface the turbine is, the better it is (as shown by the calculation of water particle motion in deep and shallow water). Waves are creating more motions on the surface than deeper (Fig. 16) (Khrisanov and Dmitrev 2016).

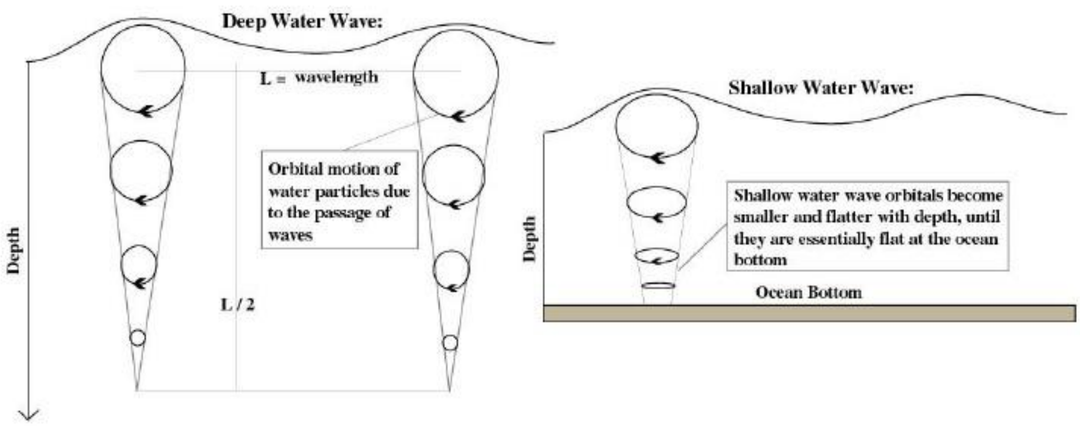

Fig. 16 Wave particle motion (State of New South Wales, 1990)

Table 7 WEC Designs

Oscillating Water Columns (OWC)
Oscillating Wave Surge Converters (OWSC)
Surface Attenuator (SA)
Overtopping Devices (OD)
Rotating Mass (RM)
Heaving Buoy (HB)
Surface Pressure Differential (SPD)
Bulge Wave (BW)

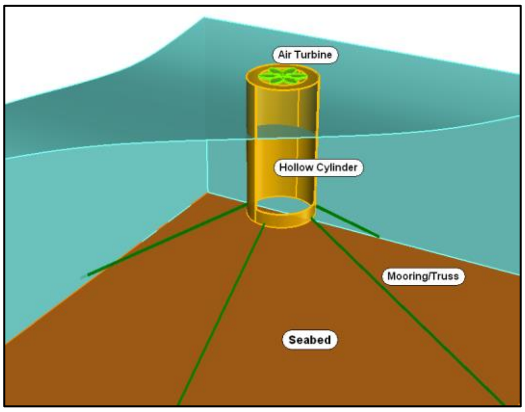

Fig. 17 Oscillating Water Column Principle (Wang and Falzarano 2017)

Fig. 18 Oscillating Water Column System, (Ocean Energy Limited, NREL 2005)

Table 8 Ocean Energy Buoy Rated Weight/Power (Ocean Energy Limited 2017)

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
Ocean Energy Buoy	1800	2.8	643

2.2.2 Current generation systems

Oscillating Water Columns (OWCs) are mastering the air pressure differential created by wave motions in a funnel (Wang and Falzarano 2013). This pressure differential is driven to a generator to create electricity (Figs. 17 and 18). This system can be set offshore on floating modules or even on the coastline. In this way, it is very easy to have access to it (Lye *et al.* 2008).

The Oscillating Wave Surge Converter (OWSC) is designed to convert the surging mode of waves into electricity (Whitter and Folley 2012). OWSC uses buoyant flap hinged at the seabed and the movement of water particle drives the OWSC to oscillate back and forth. This motion drives a piston to pull/push water through a hydraulic turbine to generate electricity (Fig. 19). Usually OWSC are deployed nearshore with shallow water depths.

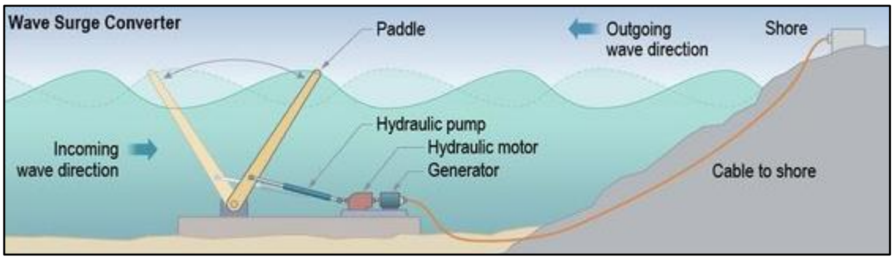

Fig. 19 Oscillating Wave Surge Converter, (OpenEI, NREL 2013)

The Surface Attenuator (SA) (Syndicat des Energies Renouvelables, 2015) is a long floating device ‘riding’ on waves. It is generally made of two or several floating pipes tightened together by hydraulic pistons converting mechanical stress in electricity (Fig. 20). This technology needs a large area to be operated and is very sensitive to storms (important fatigue). It is also very difficult to make maintenance offshore and to tow as well. On top of that, the boating collision hazard is high.

The Overtopping Device (OD) consists of a storage reservoir where waves break in. Then, water is driven in a pipe to a water turbine. This technology has already been tested but to be efficient it requires a lot of surface and a lot of steel (Fig. 21).

Table 9 Oyster 2 Rated Weight/Power (Lorenzo Sáenz M. 2018)

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
Oyster 2	5233	0.8	6541

Table 10 Pelamis Wave Power P2 Rated Weight/Power (Pelamis Wave Power 2007)

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
Pelamis Wave Power P2	1350	0.82	1646

Fig. 20 Attenuator Pelamis P2, (Pelamis Wave Power 2007)

Fig. 21 Overtopping devices, (Wave Dragon 2009)

Table 11 Wave Dragon Rated Weight/Power (Wave Dragon 2009)

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
Wave Dragon	237	0.1	2370

The Rotating Mass (RM) is a buoyant electric converter using the oscillating effect of a mass following the wave motions to create electricity by the same process of the point absorber (stator-rotor) (Drew *et al*. 2009). A magnetic shaft and an electric coil convert mechanical energy (Fig. 22).

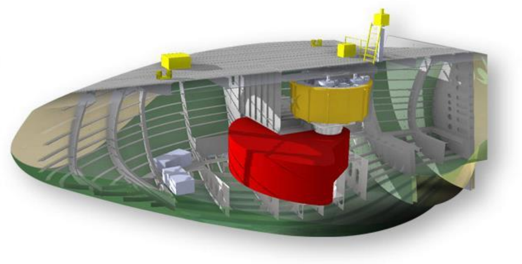

Fig. 22 Rotating Mass (Wello Penguin 2017)

Table 12 Wello Penguin Rated Weight/Power (Wello Penguin 2017)

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
Wello Penguin	260	0.60	433

Fig. 23 OPT Power Buoy off the coast of Scotland (Ocean Power Technologies 2017)

The Heaving Buoy (HB) is a floating system (Fig. 23), which absorbs energy from wave motion in any direction (Wang *et al*. 2017). It is made of a reactor and a displacer (Syndicat des Energies Renouvelables, 2015). One part is moving around a static other (Wang *et al*. 2017). The buoyant part (moving) is following the wave motion and the mechanical motion is converted to electricity by a magnetic shaft (static) and an electric coil (moving with the buoy). This system is more efficient as the wave frequency is high and the amplitude is not too high (< 3 m). Up to now, it seems to be the most commercialized type of WECs.
The Submerged Pressure Differential (SPD) device is a submerged body deployed below the sea surface with its base fixed onto the seabed. The pressure differential induced by the travelling waves pushes/pulls the submerged body to heave which drives the generator (see Fig. 24). The advantage of the SPD is that it can survive many extreme sea states, while other WECs (like OWCs and PAs) usually need to get into survival mode (Lehmann *et al.* 2014).

Table 13 Ocean Power Technologies Rated Weight/Power (Lorenzo Sáenz 2018)

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
OPT PB40	114	0.04	2850

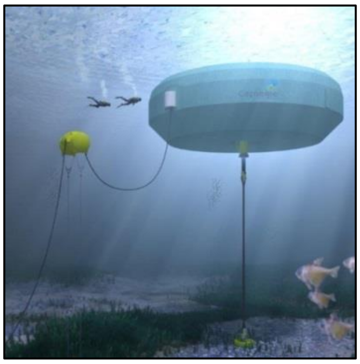

Fig. 24 SPD (Carnegie Clean Energy 2017)

Table 14 Carnegie CETO 6 Rated Weight/Power (Lorenzo Sáenz 2018)

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
Carnegie CETO 6	550	1.0	550

One important issue for the WECs is the control, which is essential in almost all advanced modern mechanical systems. The application of advanced hydrodynamic control is likely to become a game-changer in not only promoting the WECs conversion efficiency but also in improving motions that helps the WECs in overcoming variability and seasonality of the environment as well as surviving extreme sea state.
Salter *et al*. (2002) have reviewed different control strategies in detail. In general, the most common control mechanisms include latching control and reactive loading control, while other control mechanisms include unlatching control, porcupine control and full complex-conjugate control.
From the study of WECs, we can observe that reducing the number of moving parts is always a key factor. Each generator needs a constant monitoring system and many maintenance operations. Moreover, most solutions are located close to the sea surface so the impact on shipping routes and fishing must be quantified. And then, it is imperative that the system be retrievable to facilitate heavy maintenance operations and protect the system against rough sea states in case of a hurricane for example. Some new ideas have come up and are presented in the next section.

2.2.3 New generation systems

The Bulge Wave (BW) device is designed as a distensible tube filled with water. A bulge of water will form inside the tube under pressure variations (due to waves) along the length of the tube. The bulge of water will propagate through the tube and return back to the sea. The bulge of water flow can drive a low-head turbine to generate electricity (see Fig. 25).

Table 15 Anaconda Rated Weight/Power (Lorenzo Sáenz 2018)

	Estimated Weight (tons)	Rated Power (MW)	Rated Weight/MW (tons/MW)
Anaconda	500	1.0	500

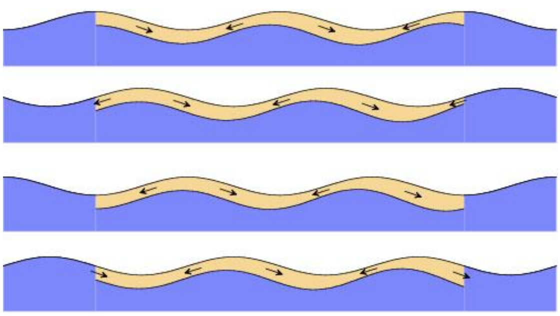

Fig. 25 Bulge wave (Anaconda 2012)

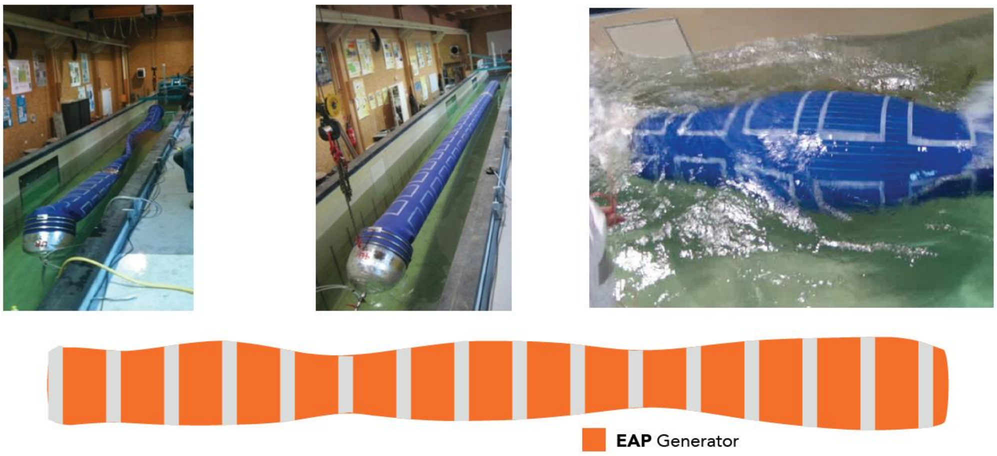

Fig. 26 EAP (S3, SBM Offshore 2014)

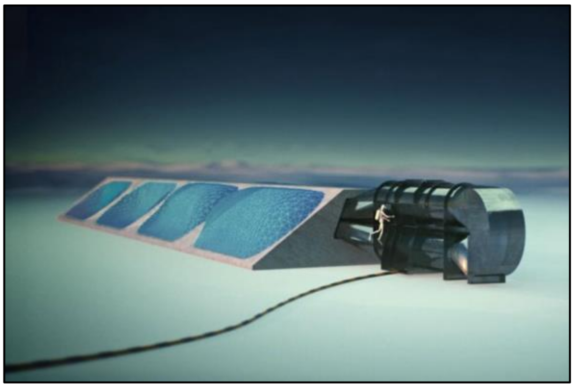

Fig. 27 Bombora mWave 2017

The Electro-Active Polymer (EAP) is a more extreme version of the bulge wave device (Fig. 26). Instead of using a water turbine at the end of a tube, the membrane is closed at both ends. Electricity is created by the relative motion of cylindrical electro-active polymer. The membrane is built with these coils, not as a structure but as the PTO system. The membrane gives flexibility and lightness to the design which can go through heavy weather. The PTO contains no mechanical part which makes it more sustainable (not rust, lightness, less fatigue). Another interesting technology is to be noticed. This project is supposed to be installed in shallow water and in the same axis of the propagating waves. It is using inflated membranes embedded on a concrete structure and undulating with wave motions. The internal circuit of pipes is leading the generated airflow to an air turbine set underwater (as shown Fig. 27).

2.2.4 Design & Power Take Off (PTO)

Table 16 Design & PTO (A. Babarit et al. 2011)

Design	PTO								
	Membrane	**Air Turbine**	**Hydraulic Pump**	**Belt & Pulley**	**Winch & Gear Box**	**Linear Electric Generator**	**Water Turbine**	**Pneu-Mechanical Drive Train**	**Electro Active Polymer**
Oscillating Water Column		X							
Oscillating Wave Surge Converter			X					X	
Surface Attenuator			X					X	
Overtopping Device							X		
Rotating Mass		X						X	
Heaving Buoy			X	X	X	X		X	
Submerged Pressure Differential		X			X	X			
Bulge Wave	X	X					X		X

2.2.5 Benchmark WEC

Table 17 Worldwide WEC Benchmark

DEVELOPER	NAME	COUNTRY	PRINCIPLE	PTO	RATED POWER (kW)	PERIOD	PROJECT OUTCOME	STILL ACTIVE
Pico-OWC, WavEC	**Pico**	Portugal	OWC (fixed)	Air Turbine	500	1999, 2006-2016	Turbine default (1999), Operational (2006-2016), Stopped	Yes
WaveGen & Queen's University Belfast	**LIMPET**	UK	OWC (fixed)	Air Turbine	500	2000-2012	Stopped	No
EVE	**Mutriku**	Spain	OWC (fixed)	Air Turbine (VOITH Siemens)	259	2011-?	Operating	Yes

Continued-

Japan Marine Science & Technology Center	**Mighty Whale**	Japan	OWC (floating)	Air Turbines (x3)	110	1998-2000	Decommissioned	No
Embley Energy	**Sperboy**	UK	OWC (floating)	Air Turbine		1999-2001 (1/5th)	Decommissioned	No
Oceanlinx	**Oceanlinx Mk1**	Australia	OWC	Air Turbine	500	2005-2009	PTO failure, Prototype abandonned	No
	Oceanlinx Mk2	Australia	OWC	Air Turbine		2007 (1/3rd)	Decommissioned	No
	Oceanlinx Mk3	Australia	OWC	Air Turbine		2010	Lost after rupture of the mooring system	No
Eco Wave Power	**Eco Wave Power**	Israel	HB (@ shoreline, Wave Claper and Power Wing)	Hydraulic Pump	10	2012-?	Operating	Yes
Finavera	**AquaBuoy**	US	HB	Direct Drive Generator		2007	Lost after breakdown of a pump	No
OceanPowerTechnology	**PB3**	US	HB	Direct Drive Generator	3	2016-?	Operating	Yes
	PB37	Denmark	OWSC	Hydraulic Pump	50	2008; 2010; 2012-2013	Decommissioned	Yes
	PB40	Spain	HB	Direct Drive Generator	40	2008	Decommissioned	Yes
	PB150	UK	HB	Direct Drive Generator	150	2011	Decommissioned	Yes
AWS Ocean Energy	**WaveSwing**	Portugal	SPD	Direct Drive Generator	1000	2001; 2002; 2004;2015-?	Lost following a pump breakdown	Yes
SeaBased	**SeaBased**	Sweden	HB	Linear Electric Generator		2006-?	Operating	Yes
	SeaBased (x36)	Sweden	HB	Linear Electric Generator	30	2016-?	Pilot farm	Yes
AquaMarine Power, ABB	**Oyster 1**	UK	OWSC	Hydro-electric Water Turbine	315	2009	Decommissioned	No
	Oyster 2	UK	OWSC	Hydro-electric Water Turbine	800	2011-2015	Hydraulic circuit breakdown. Still intalled, folded flap.	No
Waves4Power	**WavEL-Buoy**	SWEDEN	HB	Hydraulic Conversion System		2010	Decommissioned	Yes
Seatricity	**Oceanus 1 (x3)**	UK	HB	Hydro Electric Turbine		2011; 2012-2013	Decommissioned	No
	Oceanus 2	UK	HB	Hydro Electric Turbine	162	2014-2015; 2016-?	Operating	No
Fred. Olsen	**Bolt Lifesaver**	Norway	HB	Winch, gear box, electric generator	400	2009; 2010	Decommissioned	Yes
	Bolt Lifesaver	US	HB	Winch, gear box, electric generator	400	2016-?	PTO failures repaired as they occurred	Yes
	Bolt Lifesaver	UK	HB	Winch, gear box, electric generator	400	2012-2013	Decommissioned	Yes
WaveEnergy.it	**REWEC 3**	Italy	OWC	Air Turbine		2016-?	In Operation?	?

Continued-

Albatern	**SQUID**	UK	OWSC	Hydraulic Pump	7.5	2012	Decommissioned	Yes
	SQUID (x3)	UK	OWSC	Hydraulic Pump	7.5	2014	Decommissioned	Yes
	SQUID (x6)	UK	OWSC	Hydraulic Pump	7.5	2015; 2016-?	PTO failure	Yes
Dimemo	**OBREC**	Italy	OD	Water Turbine	2.5	2015-?	Operating	Yes
Chinese Academy of Sciences	**Sharp Eagle**	China	OWSC	Hydraulic Pump	100	2015-?	In Operation?	?
BPS	**BioWave**	Australia	OWSC	Hydro-pneumatic System	250	2015-?	Electric cable breakdown repaired in 2016. Activation in progress	Yes
Wave For Energy	**ISWEC**	Italy	OWSC	Hydraulic Pump	100	2015-?	In Operation?	Yes
Korea Research Institute of Ships and Ocean Engineering	**Jeju Island**	Korea	OWC	Air Turbine	500	2015-?	Operating	Yes
40 South Energy	**R115**	Italy	HB	Hydraulic Pump	150	2013-2014	Decommissioned?	Yes
Carnegie	**CETO**	France	SPD	Hydraulic Pump		2014	Destroyed by a hurricane	Yes
	CETO 1	Australia	SPD	Hydraulic Pump		2006	Decommissioned	Yes
	CETO 2	Australia	SPD	Hydraulic Pump		2006; 2008	Decommissioned	Yes
	CETO 3	Australia	SPD	Hydraulic Pump	80	2011	Decommissioned	Yes
	CETO 5 (x3)	Australia	SPD	Hydraulic Pump	240	2014-2016	Decommissioned	Yes
	CETO 6	Australia	SPD	Hydraulic Pump	1000	2016-?	Development	Yes
Pelamis	**Pelamis P1**	UK	SA	Pneu-Mechanical Drive Train	750	2004-2007	Decommissioned	No
	Pelamis P1 (x3)	Portugal	SA	Pneu-Mechanical Drive Train	750	2007	Mooring System Failure	No
	Pelamis P2 (x2)	UK	SA	Pneu-Mechanical Drive Train	820	2010-2014	Decommissioned	No
OceanSwing	**SEAREV**	France	RM	Pneu-Mechanical Drive Train		2012-2013	Project	No
Wello	**Penguin**	Finland	RM	Mechanical Drive Train	600	2011; 2012; 2013; 2014-2016; 2017	Operating	Yes
Northwest Energy Innovations	**Azura**	US	OWSC	Hydraulic Pump	20	2012; 2015-?	Operating	No
OceanEnergy Group	**OceanEnergy Buoy**	Ireland / US	OWC (floating)	Air Turbine	2800	2005-?		Yes
Nemos	**Nemos**	Germany	HB (floating)	Belt and Pulley System			Test	Yes
Corepower	**Corepower**	Sweden	SPD	Pneu-Mechanical Drive Train		2008-	Test	Yes
Columbia Power Technology	**Sting RAY**	US	SA	Electric Generators	500 max, average: 100	2008-	Test	Yes
AW Energy	**WaveRoller**	Portugal	OWSC	Hydraulic Pump	300 max, average: 100	2012	Decommissioned	Yes
	WaveRoller	Finland	OWSC	Hydraulic Pump	300 max, average: 100	2006-2008	Decommissioned	Yes
WaveStar	**WaveStar**	Denmark	HB	Pneu-Mechanical Drive Train	110	2009; 2010-2013	Decommissioned	No
Bombora Wave Power	**mWave**	US	BW (shallow water, concrete structure)	Air-inflated rubber membranes mounted to a concrete structure on the sea floor, duct and air turbine.	1500 max	2012-	Project	Yes

Continued-

OceanTec Energias Marinas SL	**OceanTec**	Spain	SA	Bi-radial Turbine	10	2008-	Test	Yes
GreenWave Energy	**GreenWAVE**	Australia	OWC	Air Turbine	1000	2014	Lost during installation	No
WaveBob	**Wavebob**	Ireland	HB (floating)	Pneu-Mechanical Drive Train		1999-2013		No
Wave Dragon	**Wave Dragon**	Denmark	OD (floating)	Water Turbine	100	2003-2007		No
SBM Offshore	**S3**	Monaco	EAP	Electro Active Membrane	1000	2009-?	Test	Yes
Checkmate, SeaEnergy	**Anaconda**	UK	SA	Hydroelectric turbine	1000	2008		No

Dormant or cancelled
Active
Status Unknown

All these WECs designs have been studied and even model tested. However, the development of wave energy is to some extend lag behind compared to wind energy in that most designs remain to be commercialized (Table 17). On the other hand, though the basic ideas have been developed, the innovations for the designs, improvements and optimizations are consistent. It is also a good sign that in addition to the government, few private groups provide funding for research and development. Some companies are already on the verge of starting commercial deployment.

3. Key factors for a strong renewable energy industry

From the previous survey on current Marine Renewable Energy solutions, it occurred that the main concern to allow an expansion of the industry is to reduce the cost and all the risks linked with the entire process.

Thus, six key factors are set to improve Marine Renewable Energy development:

A. Technology Breakthrough
B. Knowledge of Offshore Resources
C. Operation, Installation, Maintenance and Supply Chain Optimization
D. Grid Integration
E. Environmental Impact and Human-use Concerns
F. Competitiveness

3.1 Technology breakthrough

This first key factor is about the production tool: turbine, moorings, platform, cables, weight, materials, durability, PTO, etc. Regarding WTG, the first breakthrough concerns the dimensions of the rotor (diameter and height). By upsizing them we will be able to reach greater power production at lower rotational speed regime and capture more energy because the wind is generally stronger higher up. In this case, the power generated by these turbines will grow from 6 MW (today) to up to 10 MW (by 2020). Second, the substructure and the location must be rethought. So far, the current wind farms are located below 40 km from shore and in less than 40 m water depth. Most generators are set on fixed-bottom structures, which account for up to 30 % of the global cost of the installation (Yasseri 2008), (SI Ocean 2014). A major advancement must be done in this field to export WTGs offshore and touch stronger and steadier winds or currents (SI Ocean 2014). However, this goes with switching to floating platform solutions (TLP, Semi-Submersible and Spar). Talking now about WEC, the current issues are much more numerous. So far, the technology that would allow a large commercial development has not been chosen. The current major problems are the weight/MW and the durability at sea. A very good indicator called capacity factor helps understanding the level of performance of a WTG or a WEC. Today the most reliant WTG has a capacity factor close to 50% whereas WECs remain around 5 to 10%. The capacity factor is basically the power effectively generated by the system over the maximum theoretical power. This is perfectly highlighting the performance gap between WTGs and WECs today. By reading articles and listening to the industry, capacity factors can reach up to 60 %. This data can be verified but during the perfect weather or sea state condition and remains stable over a very short period of time (about 24h). It cannot be taken as a general capacity factor as such. As long as this factor stays below 50 or 60% for WECs, only few can intend to start a commercial development and it is most likely that it will not go anywhere. A deep collaboration with Oil & Gas Industry must be done to adapt technologies and reduce costs. Then, the last point that must be overtaken is reliability. Generators must be able to handle rough sea states up to hurricanes.

Eventually, as soon as WTGs and WECs are mature technologies, it is likely that these two systems will be gathered into a multi-purposes system to reduce costs and significantly increase production. The goal to achieve and become a competitive energy source is $110 per MWh (Ocean Energy Forum 2014) (Fig. 28 and Table 18).

Table 18 Timeline for the development phase of Ocean Energy Systems

Offshore Systems	Prototype	Demonstration	Pre-commercial	Industrial Roll-out
WTGs (monopiles & jackets)	–	–	–	(approx. 2020)
WTGs (floating)	–	–	(approx. 2020)	(approx. 2025)
WECs	–	–	(approx. 2025)	(approx. 2030)

Fig. 28 Phases of Technology Readiness Level, (courtesy of Ocean Energy Europe. Generated through consultation with Ocean Energy Europe and the Ocean Energy Forum)

3.2 Knowledge of offshore resources

Both Governments and Private Companies agree on the fact that a great effort must be done to enhance the collection of data available to characterize the resources (U.S. Department of Energy, 2016). It includes meteorological, oceanographic and geologic data to make a precise and reliable pattern of the different flows surrounding our coasts. This data is crucial to set generators, predict production and even design the structure of each system. The methods to collect information must be standardized to reduce risks and uncertainty. Creating reliable current and wind charts is essential to optimize generators production. So far, the Ocean is the last big unknown in our planet so there is still a lot to discover and understand. As an example, the Gulf Stream can be highlighted: at first sight this warm northward current going along the east coast of the U.S. seems to be the perfect location to set WECs. The current seems to be steady and strong which is perfect for those kinds of systems. Nevertheless, oceanographers have shown that the Gulf Stream was in fact constantly moving back and forth along a zonal axis with the creation of eddies. This motion makes the Gulf Stream very difficult to harness. The solution brought from this data is that WECs must tend to be autonomous platforms constantly ‘chasing’ the Gulf Stream from one location to another. A various collection of data is though required.

3.3 Operation, installation, maintenance and supply chain optimization

To set a strong marine renewable energy industry, the entire chain must be reframed and built (Fig. 29). So far, shipyards from Oil & Gas Industry have been largely used to build early offshore renewable plants. However, this is not enough to reduce cost and time, it is necessary to set up serial production lines as close as possible to the future location of the farm. As an example, some of the plants in the Gulf of Mexico could easily switch to renewables. Moreover, the current trend is to increase the size and the height of turbines. Thus, vessels must be now purpose-built to handle the weight of heavier installations in rough sea. In the U.S., since the 1920s the Jones Act forces vessels operating between two points of the U.S. (from the coastline to 3 nautical miles offshore) to be U.S.-flagged with a U.S. crew and ownership. To navigate under this law, only three solutions can be found (U.S. Department of Energy, 2016). The first is to adapt current U.S. vessels to their new purpose. The second is to create from scratch a new U.S. fleet. Or, the last and current solution is to operate existing purpose-built European vessels from abroad only. But if we consider that the cost to mobilize one vessel for a single day is counted in millions of dollars, it is clear this is not a long-term solution. It is though neither reliable neither safe. To summarize, it is

imperative to reduce the distance between projects and maintenance facilities by building new facilities devoted exclusively to Renewables (Yasseri 2008).
The subsea cable is also a great challenge to be tackled. Due to the length of it, it is technologically difficult to avoid losses. The cost is also a great issue (about $3.5m per km). It is still not clear how a farm will be connected to shore and by who? The developer or the grid owner? It is assumed that this question will be solved first separately for each project. At the same time, farms must stay accessible at any time to assure maintenance by operators coming from helicopters or boats. A safe transport must be guaranteed to improve work quality and wellness of operators once on board the generator. Moreover, a global regulation of safety and management must be enforced to insure security and health of operators (Gatzert and Kosub 2016). Offshore Oil & Gas facilities safety regulations could easily be adapted to Offshore Renewables.

3.4 Grid integration

Before providing offshore energy, the level of penetration in the grid must be foreseen to prevent from major impacts on the cost of energy. By studying the European market, we can argue that the penetration of offshore energy is only restrained by economics and not by technical issues. Today, the production capacity of European offshore generators is about 15 GW but this figure could easily increase (Houghton *et al.* 2016). Surveys are trying to forecast electrical system impacts by making an analogy with land-based windmills. To be very efficient, the integration of offshore energy must penetrate a well prepared local grid (near coastal areas). Another factor is to consider the cost and efficiency of conventional high-voltage alternating-current cables. European operators are switching to direct-current technologies to overtake 100 km with a less significant energy-loss. Preparing the grid is though as important as creating offshore systems. Marine renewable energy must be integrated in short and long-term grid planning to avoid constraining ocean projects to connected areas.

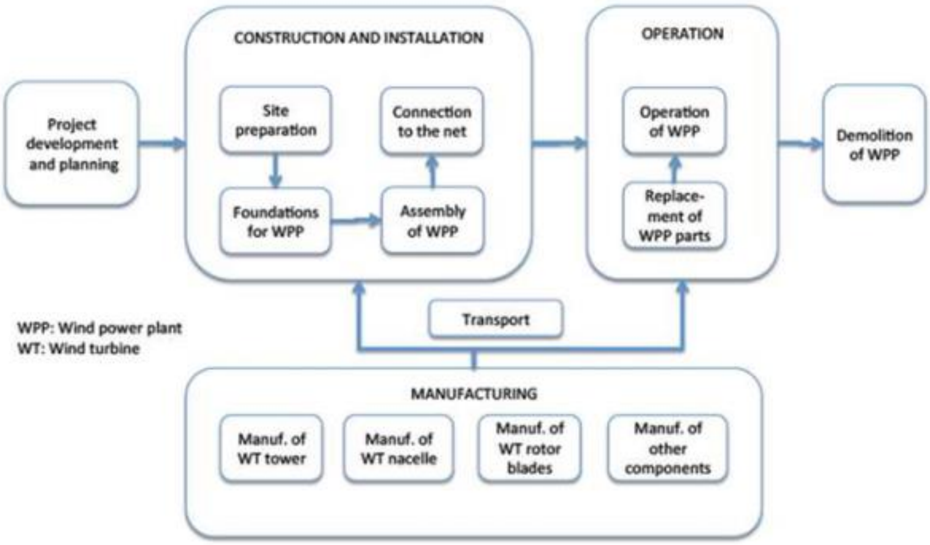

Fig. 29 Offshore Wind Supply Chain, (Breitschopf *et al.* 2011)

The grid must be also decentralized and allow interconnections between countries. All data coming from the supply capability of offshore systems, the demand in the grid and the current provider of energy must be completely known to create a smooth transition and a progressive integration of offshore energy. In that case, the size of the farm must first be adapted to a tiny local grid and then expanded with a progressive deeper integration in the regional and national grid going along with the changes in the consumers' habits and needs.

3.5 Environmental impact and human-use concerns

One concern in the development of offshore renewable energy is to generate a new type of sustainable energy. But generators are set in very sensitive areas where migratory birds, marine mammals and human communities are interacting. To keep a positive environmental benefit, it is imperative that we consider all external factors.

3.5.1 Birds and bats interactions

Due to the size of the windmills, studies must be made on the impact on migrating birds. It has been shown that in most coastal areas, seabirds are flying on average below the rotor swept area. But the statement of the Migratory Bird Treaty Act and the Endangered Species Act must be considered to avoid or minimize the impact of such installations on seabirds. But still, the risk of collision remains high as well as the risk of creating a barrier in the regular way of migratory birds. Studies have shown that among 10,000 birds killed every year by human activities, only 1 is due to wind farms (Erickson *et al.* 2016). On average, each wind farm accounts for a range from 0 to 50 birds or bat killed in a year. But all the studies must be treated with infinite caution because the results are dependent on the location and the habits of the local animals.

3.5.2 Marine mammals and fish interactions

In the same way, marine mammals and fish can be affected by offshore installations and their behavior can be drastically affected. Most of the marine mammals and fish are relying on their acoustic system to find their way, orientate and communicate. Construction and heavy underwater equipment are an important source of noise. As an example, we already know that pile-driving associated with a fixed-bottom structure is a major source of sound and this solution must be avoided in regions where mammals are living (Rodkin and Reyff 2004). At the same time, the operation and decommissioning stages are also disturbing the hearing system of the fauna. On the other hand, the reported noise level of the rotor of the system (in case of a rotating one) is unlikely to disturb mammals or fish even in a proximity to the generator (Nedwell *et al.* 2003).

But the noise is not the only one to be a vector of threat for marine fauna. Electromagnetic fields induced by submarine power cables and underwater generators are also a source of perturbation. So far, very few studies have been reported on this subject but we know that the type of transmission (AC/DC), the material and the conductivity of the water have an influence on the generated electromagnetic field (Westerberg and Langenfelt 2008).

Nevertheless, offshore systems have also one precious positive effect: they create an artificial reef which becomes the shelter of numerous species that colonize the structure and protect themselves from other animals.

The Marine Mammal Protection Act is gathering all the surveys and the establishment of species along our coasts and this act must also be considered before designing a farm (U.S. Department of Energy, 2016).

3.5.3 Human-use concerns

Human activities along the coastline such as historic fishing grounds, shipping routes, navigation, radar systems and air traffic control are parts of the coastal life. They should not be affected by the construction of offshore generators though.

Beyond all these concerns, two main sources of issues are reported by the population: visual and noise impacts. These two are mostly responsible of the *Not In My Back Yard* (NIMBY) syndrome. To win the support of the population it is important to have a look at it. To maintain the well-being of the local communities, systems cannot emit more than 45 dB in a daytime (Ocean Energy Forum 2014). This noise is created by the aerodynamic parts of WTGs. Moving them away offshore is a good thing to be at a distance superior to 400m from the inhabitants which is the new rule for modern WTGs. Then, visual impact is something that could be avoided with WECs but not with WTGs. Nevertheless, it is always possible to decrease the strong NIMBY effect. First, as we have seen it previously it is possible to use more compact systems like vertical axis WTGs or move further offshore. But the main solution for this problem would be to communicate with the local communities about renewable energy and the energetic mix.

3.6 Competitiveness

3.6.1 Financial support

The Levelised Costs Of Energy (LCOE) keeps falling since the last couple of years (ICF International for the European Commission 2014). Governments still account for the clear majority of the global investment in offshore renewable energy (Fig. 30). Companies receive a financial support per kW of capacity installed or kWh delivered to the grid (FIT: Feed-in-Tariff). Even though there is a great opportunity for new financing structures due to the elevated risk profile and the scale of financing, these structures are still afraid of the relative weakness of the industry and the uncertainty of the regulation. Thus, even in Europe where specialists agree on the high potential of the Marine Renewable Energy Industry, the market is unstable (Ocean Energy Forum 2014). The cost of offshore energy and grid connection must be divided by almost two to reach a competitive level.

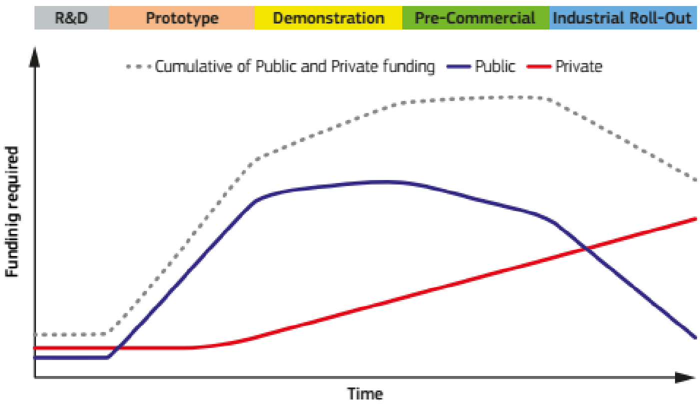

Fig. 30 Indicative share of private and public funding for an ocean energy concept per development phase (Ocean Energy Forum 2014)

3.6.2 Regulatory framework and administrative procedures

The use of marine space is a source of conflicts all over the world. Thus, it is extremely long and difficult to have a full access to a production area, especially in locations where many territorial waters are close to each other. This leads to a complicated process which could be reduced by an international collaboration for the exploitation of Marine Renewable Energy. As an example, in the North Sea Denmark and Scotland have already begun a process called the ‘one stop shop’ to simplify the development of Renewable Farms (Ocean Energy Forum 2014). The collateral effect would be to rethink the grid and decentralized it to allow interconnection between countries and areas with a different production potential.

3.6.3 Employment

With the development of Marine Renewable Energy, it estimated that by 2030 460,000 direct jobs will be created in Europe (300,000 in offshore wind and 160,000 in ocean energy) (ICF International for the European Commission 2014). It is allowed to believe that the same amount of jobs will also be created in the U.S. in about the same period. Nevertheless, it will require a great level of investment to qualify these people and increase their skills in Marine Renewable Energy. Not only companies but also University will have to adapt their academic programs. This is change has been triggered about ten years ago. Most European and American companies are now offering Renewable programs but not really devoted to Marine Renewable Energy.

A shortage in high-skilled workers in offshore and deep-water engineering as well as operation & maintenance engineering is already expected which will secure high wages on the long-term.

Eventually, we cannot stop our efforts to the design of turbines if we want to provide an energy reducing Green House Gas emission, air pollution and capable to bridge the future electricity demand gap. The entire industry must be started from scratch.

4. Conclusions

Marine renewable energy is a huge potential in fulfilling the growing world energy demand. On a large scale, close distribution to populated and industrial area, good consistency, high energy density, low pollution in manufacturing and little (if not zero) carbon emission all put it into place as a game changer for the next generation of energy supply.

On the other hand, switching to marine renewable energy is more about preparation and progressive integration than direct application of current technologies.

Technologies are for most part available, they only need to be gathered and adapted to today’s consumption. Forcing the installation of marine renewable energy systems would be a better way to grow the industry. Many improvements must be made in different domains such as oceanography, supply chain, production chain, human-use concerns, regulation, employment and consumption to optimize the production cost and the environmental impact of marine renewable energy. After these improvements, energy farms will be able to grow and penetrate deeper into the grids by slowly pushing out ‘traditional’ fossil fuels and assuring employments at the same time. So far, the biggest effort is still to be made by governments who account for most of the financial support but in the near future the industrial roll-out will arrive and go along with the competitiveness of the industry.

Table 19 Summary of the Marine Renewable Energy Industry

Opportunities	Threats
✓ Large areas available for development	✓ Offshore environment
✓ Technology available	✓ CAPEX, LCOE and Capacity factor
✓ Strong R&D	✓ Reduction of governments support
✓ Security of supply	✓ Overcapacity in early developed farms
✓ Patents	✓ Grid connection and capacity
✓ Employments and wages	✓ Lack of higher skilled people
✓ Popular backing of Renewable Energy	✓ Supply chain still not optimized
✓ Worldwide leading supply is still to take	✓ Administrative barriers
✓ Tackle Climate Change	✓ Human-use concerns (NIMBY symptom)
✓ Energy mix	✓ Lack of knowledge on the Ocean

Nevertheless, marine renewable energy must not be considered as the single solution to tackle energy prices and global warming. To solve the entire problem, marine renewable energy is only a part of the solution. Multiple efforts must be undertaken. Changing our consumption habits, reducing energy loss, switching to electric vehicles, developing new solutions such as LNG Power, adapting nuclear power, making oil & gas production greener and safer, increasing the energy efficiency or developing solar panels will be as effective as the marine renewable energy industry and must also be part of the global effort. This multi-faceted solution is well defined by a number of reports edited by both governments and major companies dealing with energy perspectives. They are all trying to predict energy perspectives for the years to come by presenting different scenarios such as: no Change, full Renewable and progressive integration of renewable with oil & gas or renewable as major provider. No one can predict the future shape of energy production but we can be sure that the best solution is to significantly improve the systems we currently have, reduce losses and use new technologies such as marine renewable energy to lead the change in the energy mix.

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APPENDIX A: Case in France

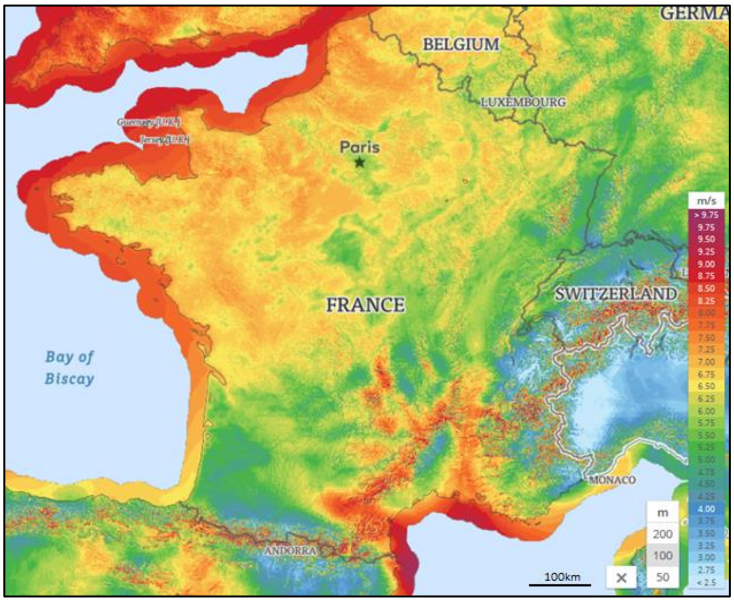

Fig. 31 Average Wind Speed Chart (Global Wind Atlas 2017)

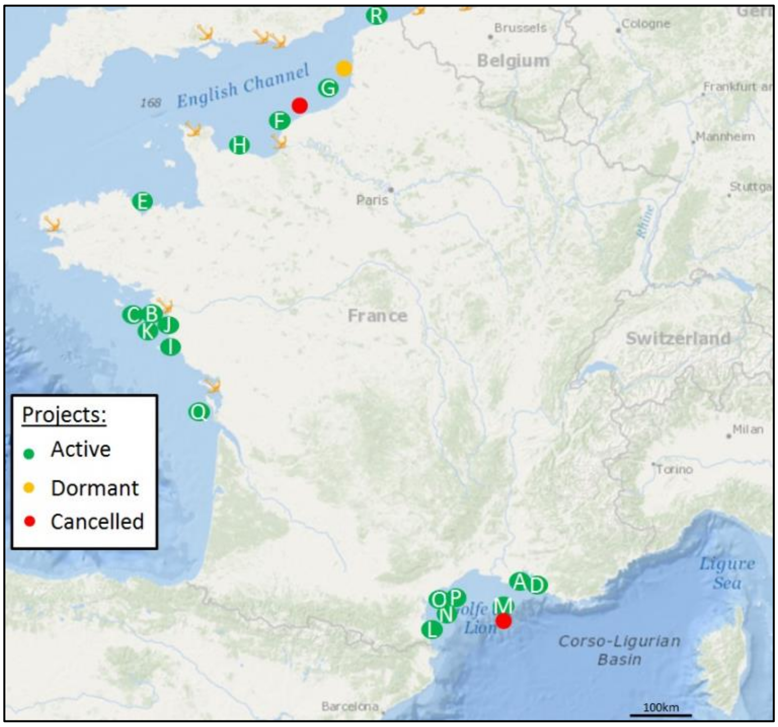

Fig. 32 Offshore Wind Projects Locations

Letter on Map	A	B	C
Name	Nénuphar VERTIWIND (onshore)	SEM-REV - SITE D'EXPERIMENTATION EN MER - MARINE TEST SITE	Floatgen Project
Developer	Technip S.A./EDF Energies Nouvelles Group (EDF SA)/NENUPHAR SA/France Energies Marines	SEM-REV	FLOATGEN
Development status	Decommissioned	Fully Commissioned	Under Construction
Fully Commissioned in	2015	2015	2018
Under Construction in	2015	2015	2016
Pre construction in	2015	2015	2016
Consent Authorized in	2014	2014	2014
Consent application Submitted	2013		
Project capacity (MW)	0.6	8	2
Turbine model			V80-2.0 MW (Vestas)
Turbine capacity	0.6 MW		2 MW
Number of turbines	1		1
Rotor diameter			80 m
Foundation	Grounded: Onshore Concrete	Floating: Semi-Submersible Platform	Floating: Semi-Submersible Platform (1 x OCEAGEN (Floating square concrete ring by IDEOL and the University of Stuttgart.))
Stated Cost/MW	$17,989,500		$12,892,475
Depth range	0 m - 0 m	35 m	33 m
Distance from shore	0.9 km	24 km	22 km

Fig. 33 Offshore Wind Projects in France in 2018 (1)

Letter on Map	D	E	F	G
Name	InFLOW (INdustrialization setup of a FLoating Offshore Wind turbine)	Projet éolien en mer de la Baie de Saint-Brieuc	Parc éolien en mer de Fécamp	Parc éolien en mer de Dieppe - Le Tréport
Developer	NENUPHAR SA/Fraunhofer Institute for Wind Energy and Energy Systems Technology (IWES)/EDF Energies Nouvelles Group (EDF SA)/Vicinay Cadenas S.A/Eiffage Construction Metallique SAS/DTU Wind Energy, Department of Wind Energy, Technical University of Denmark/Alstom Hydro Espana (Alstom Group)/DUCO Ltd (Technip S.A.)/France Energies Marines/Vryhof Anchors NV	Ailes Marines SAS	Eolien Maritime France	Les Eoliennes en mer de Dieppe-Le Tréport (EMDT)
Development status	Consent Authorized	Consent Authorized	Consent Application Submitted	Consent Application Submitted
Fully Commissioned in	2018	2021	2022	2022
Under Construction in		2020	2019	2021
Pre construction in		2020		2021
Consent Authorized in	2014	2017		2018
Consent application Submitted	2013	2012	2014	2017
Project capacity (MW)	1.2	496	498	496
Turbine model	Nénuphar 1MW two straight bladed vertical axis wind turbine	SG 8.0-167 DD (Siemens Gamesa)	Haliade 150-6MW (GE Energy)	SG 8.0-167 DD (Siemens Gamesa)
Turbine capacity	1 MW	8 MW	6 MW	8 MW
Number of turbines	1	62	83	62
Rotor diameter		167 m	150 m	167 m
Foundation	Floating: Semi-Submersible Platform (Tri-floater system)	Grounded: Jacket (4-piled jacket. A 30:34 ratio of driven piles (diameter 2m, depth 14m) and drill-drive-drill (diameter 2.5m, 45m) will be used.)	Grounded	Grounded: Jacket (Average weight 1000t, height 40-50m)
Stated Cost/MW	$16,790,200	$6,044,859	$4,816,466	$6,044,859
Depth range	52 m - 63 m	29 m - 42 m	24 m - 31 m	5 m - 25 m
Distance from shore	50 km	16.3 km	13 km	15 km

Fig. 34 Offshore Wind Projects in France in 2018 (2)

Letter on Map	H	I	J	K
Name	Eoliennes Offshore du Calvados project	Parc des Iles d'Yeu et de Noirmoutier	Projet de parc éolien en mer de Saint-Nazaire	Les éoliennes flottantes de Groix & Belle-Île
Developer	Eolien Maritime France	Les Eoliennes en mer de Vendée	Eolien Maritime France	EOLFI Offshore France
Development status	Consent Application Submitted	Consent Application Submitted	Consent Application Submitted	Concept/Early Planning
Fully Commissioned in	2022	2023	2023	2021
Under Construction in	2020	2021	2021	2021
Pre construction in	2020	2019		2021
Consent Authorized in				2018
Consent application Submitted	2014	2017	2014	2017
Project capacity (MW)	450	496	480	24
Turbine model	Haliade 150-6MW (GE Energy)	SG 8.0-167 DD (Siemens Gamesa)	Haliade 150-6MW (GE Energy)	Haliade 150-6MW (GE Energy)
Turbine capacity	6 MW	8 MW	6 MW	6 MW
Number of turbines		62		4
Rotor diameter	150 m	167 m	150 m	150 m
Foundation	Grounded: Monopile (Approximately 7m in diameter.)	Grounded: Jacket	Grounded: Monopile (The monopiles will have a diameter of approximately 7m and penetrate 20m into the seabed)	Floating: Semi-Submersible Platform (DCNS SEAReed)
Stated Cost/MW	$4,797,200		$4,997,083	$9,994,167
Depth range	21 m - 29 m	17 m - 35 m	12 m - 23 m	54 m - 71 m
Distance from shore	11 km	16.5 km	12 km	13 km

Fig. 35 Offshore Wind Projects in France in 2018 (3)

Letter on Map	L	M	N	O
Name	Les éoliennes flottantes du Golfe du Lion	Les éoliennes flottantes du Provence Grand Large	EolMed - Ideol & Quadran Commercial Scale Floating Project	EolMed
Developer	EDP Renewables (EDP - Energias de Portugal)	EDF Energies Nouvelles Group (EDF SA)	Quadran Energies Libres/IDEOL	EolMed SAS (Quadran Energies Libres)
Development status	Concept/Early Planning	Concept/Early Planning	Concept/Early Planning	Concept/Early Planning
Fully Commissioned in	2021	2020	2020	2020
Under Construction in	2020	2020		2020
Pre construction in	2020	2020		2020
Consent Authorized in	2019	2018		2018
Consent application Submitted	2018	2017	2013	2018
Project capacity (MW)	24	24	500	20
Turbine model	Haliade 150-6MW (GE Energy)	SWT-8.0-154 (Siemens Gamesa)		6.2M152 (Senvion)
Turbine capacity	6 MW	8 MW		6.15 MW
Number of turbines	4	3		4
Rotor diameter	150 m	154 m		152 m
Foundation	Floating: Semi-Submersible Platform (Windfloat foundation with 3 catenary mooring and classic anchors.)	Floating: Tension Leg Platform (SBM/IFPEN concept)	Floating: Semi-Submersible Platform (Ideol floating platform)	Floating: Semi-Submersible Platform (Ideol Damping Pool)
Stated Cost/MW	$8,994,750	$9,994,167		$10,493,875
Depth range	60 m - 82 m	94 m - 104 m		50 m - 74 m
Distance from shore	57 m - 84 m	17 km		15 km

Fig. 36 Offshore Wind Projects in France in 2018 (4)

Letter on Map	P	Q	R
Name	Spinfloat Demonstrator	Parc éolien en mer d'Oléron	L'éolien en mer région Dunkerque (troisième appel d'offres)
Developer	EOLFI		
Development status	Concept/Early Planning	Development Zone	Development Zone
Fully Commissioned in	2020		
Under Construction in	2019	2023	2022
Pre construction in			
Consent Authorized in			
Consent application Submitted			
Project capacity (MW)	6	500	250 - 750
Turbine model	Spinfloat		
Turbine capacity	6MW		
Number of turbines	1	60 - 80	
Rotor diameter			
Foundation	Floating: Semi-Submersible Platform	Grounded:	Grounded:
Stated Cost/MW		$4,797,200	
Depth range		24 m - 38 m	0 m - 23 m
Distance from shore		15 km	5 km

Fig. 37 Offshore Wind Projects in France in 2018 (5)

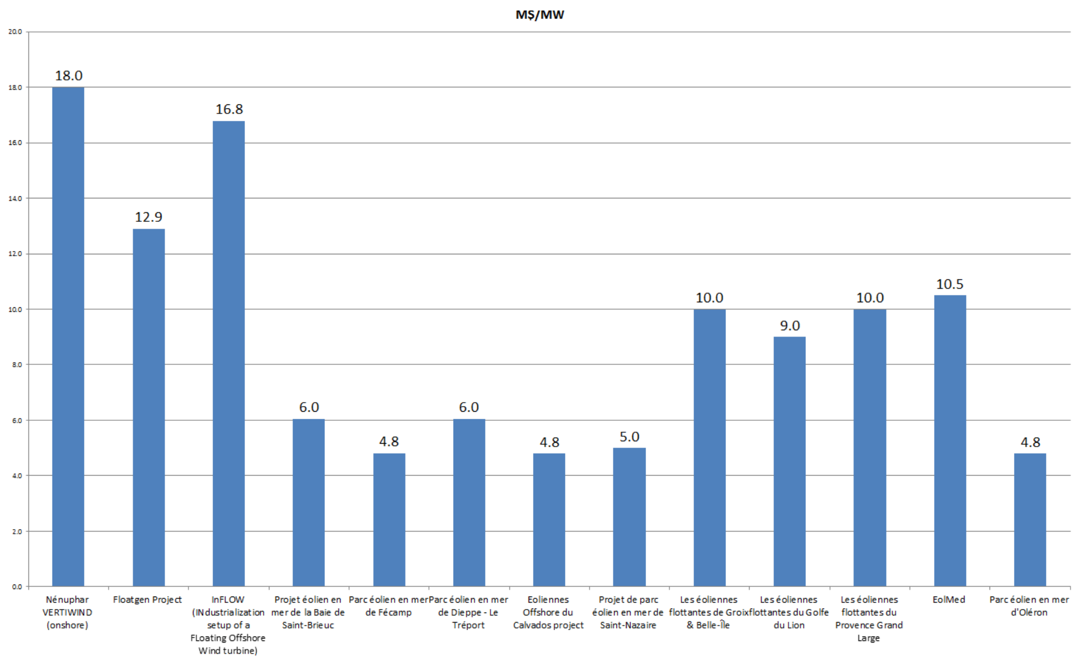

Fig. 38 Offshore Wind Projects in France over 10 years (2018), Cost/MW

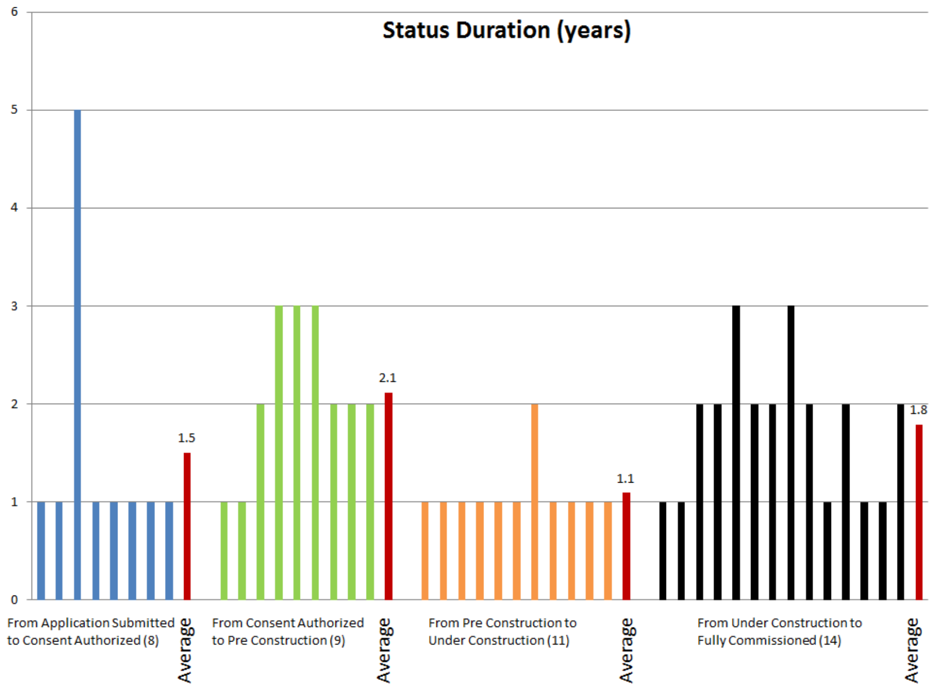

Fig. 39 Status Duration (Permitting Process, France)

From the benchmark in France, it appears that areas with more than 8.5 m.s^{-1} average wind speed are under prospect for offshore farms (English Channel & Mediterranean Sea for most, Figs. 31 and 32). The average cost/MW is greatly reducing from about $18m per MW in 2015 to about $5 m per MW expected at the turn of 2025 (Figs. 33-38). Eighteen projects are under development and at different stages in the permitting process. It is widely recognized that floating offshore wind below 50 m water depth and beyond 100km from shore cannot be profitable at the current stage. Finally, the permitting process seems to be relatively long (about 6 to 7 years) from the application to first electricity (fully commissioned, Fig. 39).