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WP 3	Deliverable 3.2

RiCORE Project Novel Technology Selection

Deliverable 3.2

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RiCORE Project Synopsis

The aim of the RiCORE project (Risk based Consenting for Offshore Renewable Energy) is to establish a risk-based approach to consenting where the level of environmental survey required is based on the environmental sensitivity of the site, the risk profile of the technology and the scale of the proposed project. The project, which has received funding from the European Union's Horizon 2020 research and innovation programme, will run between January 1st 2015 and June 30th 2016.

The consenting of offshore renewable energy is often cited as one of the main non-technical barriers to the development of this sector. A significant aspect of this is the uncertainty inherent in the potential environmental impacts of novel technology. To ensure consents are compliant with EU and national legislation, such as the Environmental Impact Assessment and Habitats Directive, costly and time consuming surveys are required even for perceived lower risk technologies in sites which may not be of highest environmental sensitivity.

The RiCORE project will study the legal framework in place in the partner Member States to ensure the framework developed will be applicable for roll out across these Member States and further afield. The next stage of the RiCORE project is to consider the practices, methodologies and implementation of pre-consent surveys, post consent and post-deployment monitoring. This will allow a feedback loop to inform the development of the risk-based framework for the environmental aspects of consent and provide best practice. The project will achieve these aims by engaging with the relevant stakeholders including regulators, industry, and EIA practitioners, through a series of expert workshops and developing their outcomes into guidance.

A key objective of the project is to improve consenting processes in line with the requirements of the Renewable Energy Directive (specifically Article 13-1) to ensure cost efficient delivery of the necessary surveys, clear and transparent reasoning for work undertaken, improving knowledge sharing and reducing the non-technical barriers to the development of the Offshore Renewable Energy sector so that it can deliver clean, secure energy.

Executive Summary

This report compiles an inventory of technology types (within the tidal, wave and offshore wind categories) that the RiCORE project considers when providing recommendations and guidelines in favour of implementing a risk based consenting approach.

RiCORE recommendations are expected to be applicable and fully relevant in the next 3 to 5 years, which represent 1 to 2 successive full average permitting cycles, ensuring that the application of RiCORE guidelines will not lead to regulatory instability.

The assumption is made that the return of experience – for those choosing to apply RiCORE's recommendations - will be rich enough after 5 years to justify a new set of adjustments.

Therefore technology types have been chosen and divided into 2 groups as follows:

- **The main focus area includes 11 novel technology types** as well as all developed bottom fixed offshore wind technology types. All of these technologies have already reached a level of maturity enabling them to immediately benefit from the risk-based approach proposed by the RiCORE project. Their Technology Readiness Level is situated between 7 and 9. Half of these, as well as the most advanced projects, are in the floating wind category. Policies and guidelines proposed by the project are designed to be applicable in this area.
- **In the secondary area, 8 technology types are considered**, with none of these being pure wind technology types. These technology *may* reach a sufficient level of maturity soon enough to be included in the initial deployment of the proposed risk based approach. The conditions for applying the policies proposed by the project to these technologies will be studied, and guidelines will encompass them if feasible without interference with main focus area. Their Technology Readiness Level is situated between 5 and 6.

Table 1 below provides information on the main focus area novel technology types (bold) – it should be noted that they come in addition to developed **bottom fixed offshore wind technology types.** Table 1 also lists secondary area technologies (*italics*).

Table 1. Main focus area: Novel technology types (TRL: Technology Readiness Level).

Technology category	Technology type	TRL	Comments
Tidal	**Tidal impoundment**	**9**	
Tidal	**Horizontal axis turbine**	**8**	**Several advanced projects**
Tidal	**Enclosed Tips (Venturi)**	**8**	**Advanced but with only one advanced family of products**
Wave	**Attenuator**	**8**	
Wave	**Point Absorber**	**7**	
Wave	**Oscillating Wave Surge Converter**	**8**	**Most advanced with the highest number of projects**
Wave	**Oscillating Water Column**	**7**	
Float. Wind	**Spar-horizontal axis WT**	**7-8**	
Float. Wind	**Semi-submersible platform - Horizontal axis WT**	**8-9**	**Most advanced with the highest number of projects**
Float. Wind	**Semi-submersible platform - Vertical axis WT**	**7**	
Float. Wind	**Tension leg - submerged platform**	**7**	
Tidal	*Vertical-axis (Cross Flow) turbine*	*5*	
Tidal	*Oscillating Hydrofoil*	*5*	
Tidal	*Archimedes Screw*	*5*	
Tidal	*Tidal Kite*	*5*	
Wave	*Submerged pressure differential*	*6*	
Wave	*Rotating Mass*	*6*	
Wave	*Over topping device*	*6*	
Float. Wind	*Hybrid*	*6*	*The most advanced hybrid system combines a vertical wind turbine and a tidal current generator*

1. INTRODUCTION

Building on the approach undertaken by the Scottish Government through the development of the **Survey, Deploy and Monitor (SDM) Policy** (The Scottish Government, Marine Scotland) for wave and tide harnessing projects (see Deliverable 3.1), the aim of the RiCORE project is to establish a risk-based approach to consenting where the level of environmental survey required is based on the environmental sensitivity of the site, the risk profile of the technology and the scale of the proposed project.

To determine the scope of offshore renewable energy (ORE) the project will address the following major points:

- The consenting procedure, applicable regulatory and legal frameworks, stakeholders to involve, established practices (even when not formally part a regulatory or legal framework) and guidelines to be proposed (which may differ greatly depending on the ORE technology they apply to).

- The administrative permitting procedure - including required Environmental Impact Assessments (EIA) and fulfilment of consenting processes, which have been measured at an average of 32 months for offshore projects in the EU (EWEA, The European Wind Energy Association). To avoid creating instability, guidelines proposed for the evolution of procedures should remain valid for a duration of one full permitting cycle (2 to 3 years), and ideally up to 2 cycles (5 years).

These considerations have led the RiCORE project to identify, in the scope of Tidal, Wave and Offshore wind energy, technologies that:

- Have already reached TRL 7 or above, as they are very likely to enter consenting procedures for large or full scale prototype and demonstration arrays within the next

2/3 years, could possibly enter a commercial deployment in that same 2/3 year time frame, and are likely to do so within a 5 years' time frame[1].

- Have reached TRL 5 to 6 and may enter a consenting procedure for large or full scale prototypes and demonstration arrays within 5 years[2].

The aim of this document is to establish which technology types should be included in the scope of the RiCORE project (based on a list of identified projects). Prior to this, the most appropriate TRL scales are examined and discussed.

[1] According to ESBI (WestWave), TRL 7 and 8 may be completed within 12 to 24 months each, TRL 9 within 24 months, so technologies today at TRL 7 and above may in a best case scenario grow fully mature and ready for commercial development before 3 years.

[2] The same source states that TRL 5 to 6 may be completed in 12 to 18 months each, so TRL 5 and above may have large or full scale prototypes entering consenting procedures within 3 years and in a best case scenario have demonstration arrays entering the procedure within 5 years.

2. OBJECTIVES

The main objective of the present deliverable is to conduct a review of the novel wave, tidal and wind energy technologies nearing a level of maturity allowing them to benefit from a risk-based consenting approach now or in the near future.

Two technology areas were identified:

- A first, main focus area includes technologies that have already reached a level of maturity enabling them to benefit from the risk-based approach proposed by the RiCORE project. The policies proposed by the project will be applicable in this area.

- A second area includes the next tranche of technologies, which *may* reach a sufficient level of maturity soon enough to be included in the initial deployment of the proposed risk-based approach. The conditions for applying the policies proposed by the project to these technologies will be systematically studied.

This deliverable may also serve as a referential for technology classification and terminology in the subsequent deliverables of the project.

3. TECHNOLOGY READINESS LEVEL (TRL)

3.1 Definition

Technology Readiness Levels are used to structure design development phases through various levels so that the required knowledge is obtained at different stages to enable progress along a path of increasing technical complexity and investment risk. The scale ranges from 1 (earliest stage of development) to 9 (most mature). In the case of ocean energy devices the TRL stages can be linked to different device scales by following Froude Similitude Laws and geometric similarity.

3.2 Choice of the TRL scale

Different TRL scales can be used in different industries and consequently there can be slight differences in the precise definition attributed to each TRL. The RiCORE project uses the general TRL definition put forward by the European Union in its Horizon 2020 programme. Whilst it is helpful as a starting point, the specific characteristics of marine renewable energy (wind, wave, tidal) have necessitated the development of TRLs specific to those sectors. Hence, the EU TRL definitions will be supplemented by sector specific guidance on this topic. This document therefore utilises four main TRL schedules as follows:

- The Horizon 2020 definition, used for Horizon 2020 funded projects - this scale is not specific to marine energy (European Commission - Horizon 2020).
- WestWave (UCC – ESBI) - Technology Readiness Levels for Supply Chain Study for WestWave, ESBIoe-WAV-11-027. (WestWave)
- OES-IEA scales for Tidal-current and Wave Energy Systems (K. Nielsen for IEA / OES).
- The International Renewable Energy Agency (IRENA) scale, recently used in the August 2014 analysis of Technology Readiness, patents, deployment status and outlook (IRENA - International Renewable Energy Agency).

Table 2 below indicates how the horizon 2020 scale is supplemented by the other scales used in the document. In the following assessment, the rating might encompass a range of TRL due to a lack of information. IEA – OES scale is the most adapted to the range of technologies evaluated herein, and will be preferred in case a similar system could be rated differently on the 2 other marine adapted scales. In particular, it encompasses results of extensive work on both wave *and* tidal concepts.

3.3 Minimum TRL to be considered

TRL 5 has been chosen as the minimum maturity level to consider in this deliverable and from which to further assess ORE technologies. The policy RiCORE aims at developing will be applicable to technologies ranging from TRL 7 to 9. However, technologies presently at TRL 5 can, in a best case scenario, reach TRL 7 and above within 2 to 3 years, and may therefore benefit from the first implementation of the risk-based approach proposed by the RiCORE project. Although not in the main focus of the project, these technologies may be taken into account by the project.

Technologies below TRL 5 will most probably not or very marginally benefit from the first implementation of a risk-based approach following the RiCORE project. Therefore the RiCORE project has decided not to include Technologies below TRL 5 in the project scope.

Table 2. Definition of each TRL scale level in the main scales used in this document.

TRL	HORIZON 2020	IEA-OES	WestWave (UCC – ESBI)	IRENA
1	Basic principles observed	**Analytical numerical model, fundamental operation**	Basic principles observed and reported - Purpose(s) of technology identified	Basic principles observed and reported
2	Technology concept formulated	**Small scale laboratory setup and ideal concept tests**	Technology concept and/or application formulated - Market Identified	Technology concept and/or application formulated
3	Experimental proof of concept	**Small scale laboratory testing full suite of tests cross validated with numerical models, bench testing of components**	Analytical and experimental critical function and/or characteristic proof-of-concept - Initial capital cost and power production estimates / targets established	Analytical and experimental critical function and/or proof of concept
4	Technology validated in laboratory	**Larger scale DRY laboratory testing, bench testing of components and systems**	Technology component and/or basic technology subsystem validation in a laboratory environment – Preliminary Lifecycle design	Technology (system or components) validated in a laboratory experiment
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	**Medium scale component testing in WET lab marine environment. E.g. ¼ scale wave in Galway Bay or 1/10th scale tidal Strangford Lough**	Technology component and/or basic technology subsystem validation in a relevant environment – Supply-chain Mobilisation	Laboratory scale, with similar system validation in a realistic working environment
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	**Medium scale full system testing in ocean environment. E.g. ¼scale wave in Galway Bay or Nissum Breding or 1/10th scale tidal Strangford Lough**	Technology system model or prototype demonstration in a relevant environment – Customer interaction	Engineering/ pilot-scale, with prototype system or model demonstrated in an actual working environment
7	System prototype demonstration in operational environment	**Full Scale prototype testing at open ocean test site**	Technology system prototype demonstration in an operational environment - Ocean Experience	Full scale or prototype technology demonstration in an actual working environment

Table 2. (Continuation). Definition of each TRL scale level in the main scales used in this document.

TRL	HORIZON 2020	IEA-OES	WestWave (UCC – ESBI)	IRENA
8	System complete and qualified	**Full scale pre-commercial unit complying with MRLs**	Actual Technology system completed and qualified through test and demonstration - Actual Marine Operations completed and qualified through test and demonstration.	Actual system completed and qualified ready for deployment through test and demonstration
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)	**Full scale small array**	Operational performance and reliability of an array Demonstrated - Fully de-risked business plan for utility scale deployment of arrays	Technology operational, over full range of expected lifetime conditions

4. TECHNOLOGY INVENTORY AND ASSESSEMENT

The technologies assessed in this report can be classified into the following 3 categories:

1. **Tidal energy technologies:** these technologies transform the kinetic energy of tidal streams and also the potential energy of heads of water trapped in basins into power.

2. **Wave energy technologies**: convert the energy of waves into power. This can be achieved offshore, nearshore or onshore.

3. **Wind energy technologies:** convert the kinetic energy of wind into power. They can be bottom fixed off-shore devices or floating off-shore devices. Unlike bottom fixed off-shore wind, floating devices use a combination of mooring and buoyancy capability to stabilize themselves, instead of being fixed to the seabed using rigid foundations. Hence they can harness wind resources in deeper waters.
   High altitude devices - generally using kite like designs, are not considered in the scope of the project and therefore not listed in the present document.

4.1 Tidal energy

4.1.1 Energy resource and location

A major study by the European Commission evaluating the tidal current resource for 106 locations around Europe, with predefined characteristics making them suitable for tidal stream energy exploitation, estimated an exploitable resource from those sites of 48 TWh a year (European Commission). The aggregate capacity of this selection of sites amounted to an installed capacity of marine current turbines of more than 12,000 MW. A more recent study by Black & Veatch (Black & Veatch for Carbon Trust) suggests an estimated UK extractable resource of 22 TWh for tidal stream, using a modified and more accurate methodology. Other countries with an exceptionally high resource include Ireland, Italy, the Philippines and Japan. The following figure shows the mean tidal amplitude for 237 locations along the European coastline. These locations are situated 50 to 100 km away from the shoreline, and the distance from one location to another is approximately 100 km.

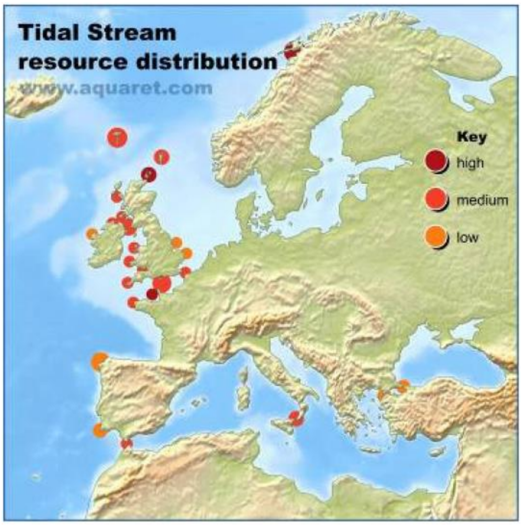

Figure 1. Tidal stream resource distribution. Source: www.aquaret.com.

4.1.2 Technology type

a) Tidal impoundment

Tidal impoundment technologies use the potential energy of heads of water trapped in basins to generate power with low head hydro-electric turbines as the tides rise or fall. Preferably located in places were the tidal range is high and waters shallow, basins can be barrages on estuaries, bounded tidal lagoons constructed against the bank without obstructing an estuary, or offshore artificial lagoons.

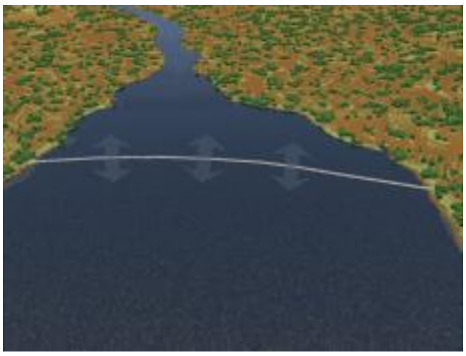

Figure 2. Tidal impoundment scheme. Source: http://www.aquaret.com/.

b) Tidal stream

Tidal stream technologies transform the kinetic energy of tidal streams into power. They are best placed where the tidal range is high and tidal streams are amplified by funnelling effects of the coastline and seabed.

Tidal stream technologies encompass 6 different types:

1. **Horizontal axis turbine:** these devices work in the same way as conventional wind turbines, and some look very similar in design. A turbine is placed in the tidal stream, which causes the turbine to rotate about an horizontal axis (Figure 3).

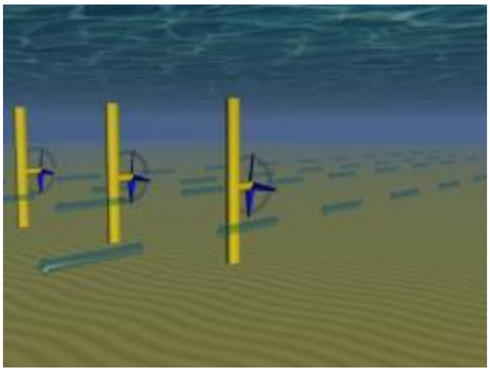

Figure 3. Horizontal axis turbine scheme. Source: http://www.aquaret.com/.

2. **Vertical-axis (Cross Flow) turbine:** these devices use the same principal as horizontal axis turbines, but have a vertical axis of rotation (Figure 4).

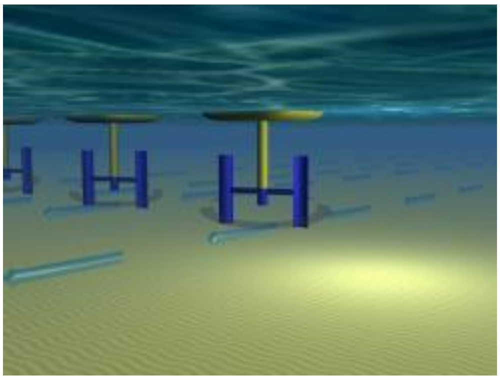

Figure 4. Vertical axis turbine scheme. Source: http://www.aquaret.com/.

3. **Oscillating Hydrofoil –** These devices use wing shaped hydrofoils attached do an oscillating arm. The resulting oscillation is converted to power (Figure 5).

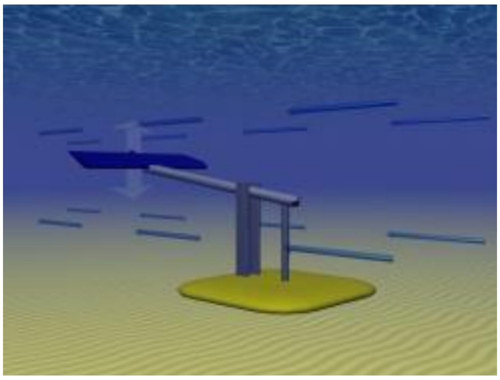

Figure 5. Oscillating hydrofoil scheme. Source: http://www.aquaret.com/.

4. **Enclosed Tips (Venturi) –** These systems increase the velocity and decrease the pressure of the flow by using funnel like devices. Power is then generated directly by a turbine, or in some cases by an air turbine taking advantage of the pressure differential (Figure 6).

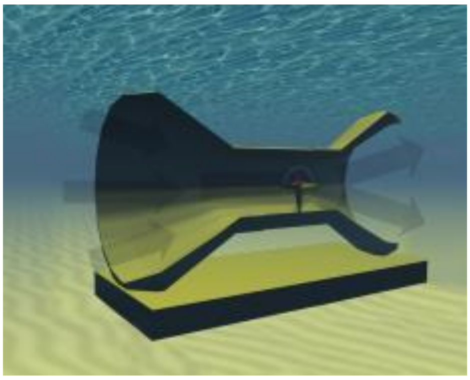

Figure 6. Venturi Effect scheme. Source: http://www.aquaret.com/.

5. **Archimedes Screw**: a helical corkscrew-shaped device (a helical surface surrounding a central cylindrical shaft) that draws power from the tidal stream as the water moves up/through the spiral, turning the turbines (Figure 7).

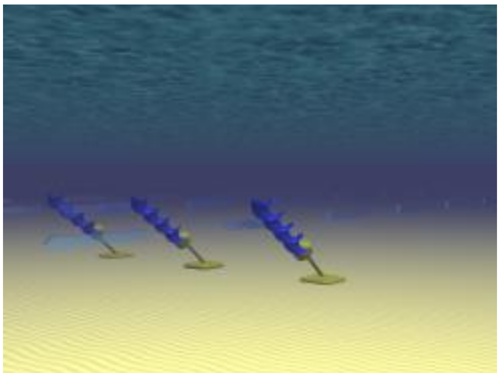

Figure 7. Archimedes screw scheme. Source: http://www.aquaret.com/.

6. **Tidal Kite**: these systems use horizontal axis turbines attached to an underwater kite. The movement of the kite is used to accelerate the apparent velocity of the flow passing through the turbine and generate power (Figure 8).

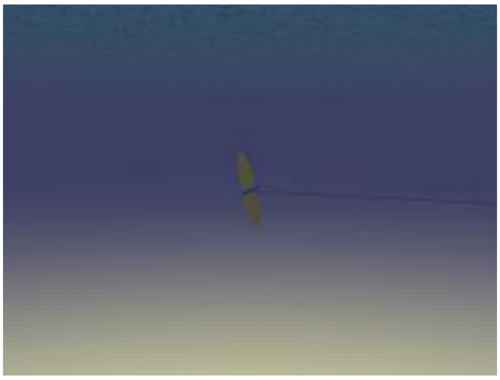

Figure 8. Tidal kite scheme. Source: http://www.aquaret.com/.

A detailed evaluation of TRL levels, updated regularly, by technology type has been undertaken by WavEC using the ESBI TRL classification since it was considered the most appropriate for wave and tidal energy technologies (Table 3).

Tidal impoundment and lagoon technologies are rated TRL 9 although they do not have demonstrators yet- as they are very close to estuary barrages that have full scale commercial plants in operation for more than 40 years. Hence they are not considered in the following novel technologies case studies.

Table 3. Maximum TRL of tidal stream technologies achieved by type. Source: WavEC, 2015, The ESBI TRL classification.

Tidal technology type	TRL
Tidal impoundment	9
Horizontal axis turbine	8
Vertical-axis (Cross Flow) turbine	5
Oscillating Hydrofoil	5
Enclosed Tips (Venturi)	8
Archimedes Screw	5
Tidal Kite	5

4.1.3 Case studies and TRL

Table 4 reviews existing tidal technologies with a TRL between 5 and 9. The total number of technologies is 62, but only 14 of them have confirmed TRL above 5 (Table 9). Most of them (10) are horizontal axis turbines, 2 are enclosed tips (Venturi) and only one belongs to hydrofoil oscillating technology and tidal kite.

The only two tidal energy projects with TRL 7-9 are the EMEC Andritz Hydro Hammerfest project (Table 5 and Figure 9) and the Seagen Strangford Lough project (Table 6 and Figure 10).

Table 4. Tidal energy technologies and associated TRL. Source: WavEC, 2015, using ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
ALSTOM Holdings SA	DeepGen 1MW	A: Horizontal axis turbine	7	Maybe
ALSTOM Holdings SA	DeepGen 500	A: Horizontal axis turbine	7	Maybe
Andritz Hydro Hammerfest	HS1000	A: Horizontal axis turbine	7	Yes
Andritz Hydro Hammerfest	HS300	A: Horizontal axis turbine	6	Yes
Atlantis Resource Ltd.	AK1000	A: Horizontal axis turbine	5	No
Atlantis Resource Ltd.	AR1000	A: Horizontal axis turbine	5	Maybe
Atlantis Resource Ltd.	AR-1500	A: Horizontal axis turbine	6	Not Tested
Hydra Tidal Straum AS	Morild II	A: Horizontal axis turbine	5	No Data
Hyundai Heavy Industries	HHI Tidal Prototype 500	A: Horizontal axis turbine	5	No Data
Kawasaki Heavy Industries, Ltd	KHI Tidal Turbine	A: Horizontal axis turbine	6	Not Tested
Marine Current Turbines Ltd.	SeaFlow	A: Horizontal axis turbine	6	Yes
SeaGeneration (Kyle Rea) Ltd - Marine Current Turbines Ltd.	SeaGen S 1.2 MW	A: Horizontal axis turbine	8	Yes
Marine Current Turbines Ltd.	SeaGen S 2 MW	A: Horizontal axis turbine	7	Not Tested

Table 4. (Continuation). Tidal energy technologies and associated TRL. Source: WavEC, 2015, using ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
Scotrenewables Tidal Power Ltd.	SR 1/5th Scale	A: Horizontal axis turbine	5	Yes
Nautricity Ltd.	CorMat	A: Horizontal axis turbine	5	Maybe
Nautricity Ltd.	CoRMaT 1/7 scale	A: Horizontal axis turbine	5	Maybe
Nova Innovation Ltd.	NOVA 30	A: Horizontal axis turbine	5	No Data
Nova Innovation Ltd.	Nova M100	A: Horizontal axis turbine	7	Not Tested
Ocean Renewable Power Company	TidGen 001 - Prototype TidGen TGU	A: Horizontal axis turbine	5	No Data
Ocean Renewable Power Company	Prototype OCGen TGU	A: Horizontal axis turbine	5	No
Ocean Renewable Power Company	Beta TidGen TGU	A: Horizontal axis turbine	5	Maybe
Oceanflow Energy Ltd.	Evopod E1 1:10	A: Horizontal axis turbine	5	Maybe
Oceanflow Energy Ltd.	Evopod E35	A: Horizontal axis turbine	5	Not Tested
Scotrenewables Tidal Power Ltd.	SR 250	A: Horizontal axis turbine	6	Yes
Tocardo International BV	T100 smart reverse prototype	A: Horizontal axis turbine	6	Yes
Tocardo International BV	T100 U Prototype	A: Horizontal axis turbine	6	Yes
SABELLA SAS	Sabella D10	A: Horizontal axis turbine	7	Being Tested
SABELLA SAS	Sabella D03	A: Horizontal axis turbine	5	Maybe
Tocardo International BV	T50 - 2800	A: Horizontal axis turbine	6	Yes
Scotrenewables Tidal Power Ltd.	SR 2000	A: Horizontal axis turbine	7	Not Tested
Verdant Power Inc.	KHPS Gen4	A: Horizontal axis turbine	6	Yes

Table 4. (Continuation). Tidal energy technologies and associated TRL. Source: WavEC, 2015, using ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
Tocardo International BV	T100 DD700	A: Horizontal axis turbine	6	Maybe
Swanturbines	Cygnus Inshore Tidal Turbine	A: Horizontal axis turbine	5	Not Tested
Tidal Energy Ltd	DeltaStream prototype	A: Horizontal axis turbine	5	No Data
Tocardo International BV	T200 DD1000	A: Horizontal axis turbine	6	Not Tested
Tocardo International BV	T500 DD1600	A: Horizontal axis turbine	6	Not Tested
Verdant Power Inc.	KHPS Gen3	A: Horizontal axis turbine	5	No
Verdant Power Inc.	KHPS Gen5	A: Horizontal axis turbine	6	No
Voith Hydro Ocean Current Technologies GmbH & Co. KG	HyTide	A: Horizontal axis turbine	7	No
Voith Hydro Ocean Current Technologies GmbH & Co. KG	HyTide 1:3 scale	A: Horizontal axis turbine	5	No
IHC Tidal Energy B.V	OceanMill 30 kW	B: Vertical-axis (Cross Flow) turbine	5	Maybe
Neptune Renewable Energy	Proteus 1:10 Scale Prototype	B: Vertical-axis (Cross Flow) turbine	5	Maybe
New Energy Corporation Inc.	ENC-025	B: Vertical-axis (Cross Flow) turbine	5	Maybe
New Energy Corporation Inc.	ENC-250	B: Vertical-axis (Cross Flow) turbine	5	Not Tested
BioPower System Pty Ltd	bioSTREAM 250	C: Oscillating Hydrofoil	5	Not Tested
Pulse Tidal	Pulse-Stream 100	C: Oscillating Hydrofoil	5	Yes
Clean Current Power Systems	CC025A	D: Enclosed Tips (Venturi)	5	Maybe

Table 4. (Continuation). Tidal energy technologies and associated TRL. Source: WavEC, 2015, using ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
Clean Current Power Systems	CC3P5	D: Enclosed Tips (Venturi)	5	Maybe
Clean Current Power Systems	CC050A	D: Enclosed Tips (Venturi)	6	Maybe
Clean Current Power Systems	CC015A	D: Enclosed Tips (Venturi)	6	No
Deepwater Energy BV	Oryon Watermill pilot	D: Enclosed Tips (Venturi)	5	No Data
OpenHydro Group Ltd.	Open-Centre Turbine 16	D: Enclosed Tips (Venturi)	8	Not Tested
OpenHydro Group Ltd.	Open-Centre Turbine 10	D: Enclosed Tips (Venturi)	5	No
OpenHydro Group Ltd.	L'Arcouest	D: Enclosed Tips (Venturi)	5	Yes
OpenHydro Group Ltd.	Open-Centre Turbine 6	D: Enclosed Tips (Venturi)	5	Yes
Flumill AS	Flumill F2 part scale model	E: Arquimedes Screw	5	No
Minesto AB	Deep Green 1/4 scale prototype	F: Tidal Kite	5	Maybe
Minesto AB	Deep Green full scale	F: Tidal Kite	5	Not Tested
Minesto AB	Deep Green 1:10 Prototype	F: Tidal Kite	5	Yes
Atlantis Resource Ltd.	AN-400 Nereus II	G: Other	5	No Data
Atlantis Resource Ltd.	AN-150 Nereus I	G: Other	5	No Data
Atlantis Resource Ltd.	Aquanator	G: Other	5	Maybe

Table 5. EMEC Andritz Hydro Hammerfest project description.

PROJECT NAME	EMEC Andritz Hydro Hammerfest
COUNTRY	Scotland
LOCATION	Fall of Warness Tidal Energy Test Site (Orkney)
LATITUDE	59,132
LONGITUDE	-2,77500
DEVELOPER	Andritz Hydro Hammerfest
TECHNOLOGY	Horizontal axis turbine
DEVICE MODEL	Andritz Hydro Hammerfest: HS1000
DEVICE/PROJECT_NAME	Andritz EMEC test
SEABED FIXATION	Seabed mounted/gravity base
START YEAR	2011
END YEAR	2016
PROJECT SCALE	Pre-commercial
DEVICE SCALE	Large scale prototype
ENVIRONMENT APPRAISAL	August 2014
ENVIRONMENT STATEMENT	December 2014
STATUS	Project complete
PROJECT CAPACITY (KW)	1000
WEBSITE	http://www.hammerfeststrom.com
	Source: http://www.emec.org.uk/

Figure 9. EMEC Andritz Hydro Hammerfest project.

Table 6. Seagen Strangford Lough project description

PROJECT NAME	Seagen Strangford Lough
COUNTRY	Northern Ireland
LOCATION	Strangford Lough (near Portaferry)
LATITUDE	54,365
LONGITUDE	-5,544
DEVELOPER	Marine Current Turbines
TECHNOLOGY	Horizontal axis turbine
DEVICE MODEL	Siemens MCT: SeaGenU
SEABED FIXATION	Pile mounted
START YEAR	2008
END YEAR	N/A
PROJECT SCALE	Commercial
DEVICE SCALE	Large scale prototype
ENVIRONMENT STATEMENT	2005
STATUS	Operational
PROJECT CAPACITY (KW)	1200
WEB SITE	http://www.seageneration.co.uk/
	Source: http://www.seageneration.co.uk/

Figure 10. Seagen Strangford Lough project.

4.2 Wave energy technologies

4.2.1 Energy resource and location

According to WEC (World Energy Council), the global wave power resource in deep water (i.e. 100 m or more) has been estimated between 1 and 10 TW, while the economically exploitable resource ranges from 140-750 TWh·yr^{-1} for current designs of devices when fully mature and could rise as high as 2,000 TWh·yr^{-1}, if all the potential improvements to existing devices are realised.

Depending on the coastline's orientation towards the open ocean and the latitude, certain countries are well suited for ocean wave energy conversion, while others almost have no potential in the initial phase (Figure 11). Countries best suited for ocean wave energy conversion are the UK, Ireland, Norway, New Zealand, Southern Australia and Chile, followed by Northern Spain, France, Portugal, North American and South American coasts and South Africa.

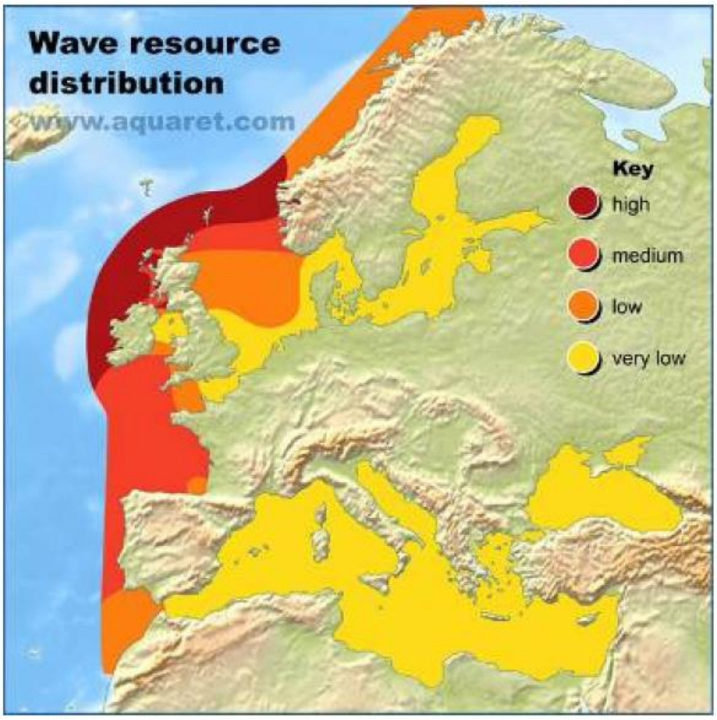

Figure 11. Wave resource distribution. Source: www.aquaret.com.

4.2.2 Technology types

As stated above, wave energy technologies convert the energy of waves into power. This can be achieved in offshore, nearshore and onshore deployments. We can identify 7 main technologies:

1. **Attenuators** are long devices aligned perpendicular to the wave front. As the wave passes by it, it deforms the device and the resulting constrains are transformed into power (Figure 12).

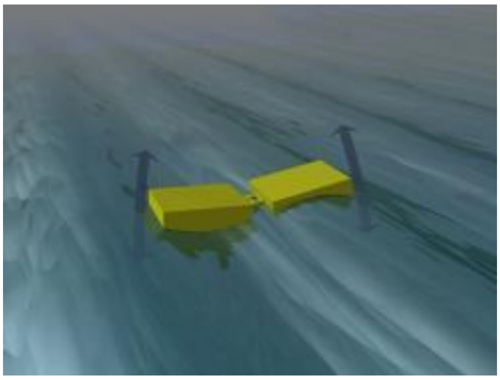

Figure 12. Wave attenuator scheme. Source: http://www.aquaret.com/.

2. **Point absorbers** are small floating devices (they are smaller than the typical wavelength) that transform their movement, caused by the waves at or near the surface, into power (Figure 13).

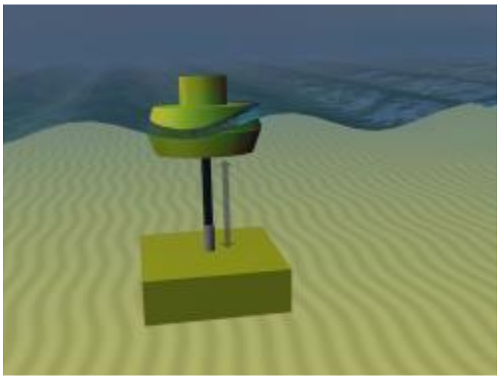

Figure 13. Point absorber scheme. Source: http://www.aquaret.com/.

3. **Oscillating Wave Surge Converters** are near surface collectors, mounted on a pivot arm resting on the seabed. They oscillate as the wave passes by, and generate power (Figure 14).

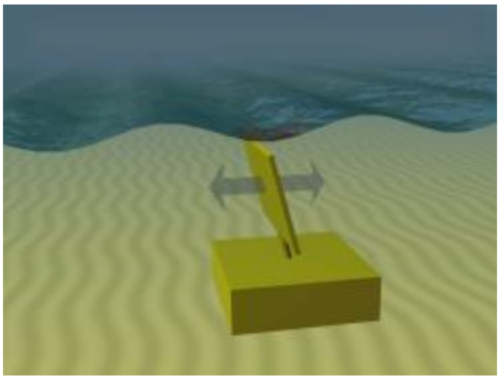

Figure 14. Oscillating wave surge converter scheme. Source: http://www.aquaret.com/.

4. **Oscillating Water Columns** are partially submerged, hollow structures. They are opened to the sea below the surface so that they contain air trapped above the water column. Waves cause the column to rise and fall, acting like a piston compressing and decompressing the air, channelled through an air turbine to generate power (Figure 15).

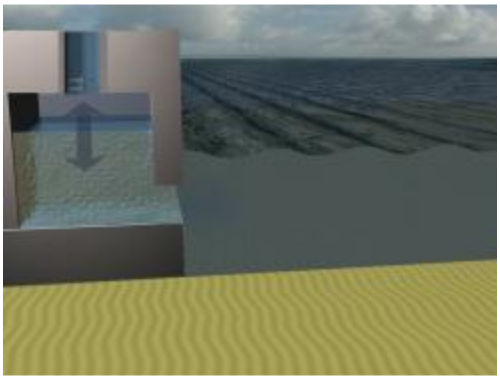

Figure 15. Oscillating water column converter scheme. Source: http://www.aquaret.com/.

5. **Submerged Pressure Differential Devices** are submerged, typical nearshore devises. The motion of the waves causes the sea-level to rise and fall, inducing a pressure differential which causes the device to rise and fall: this movement is used to generate power (Figure 16).

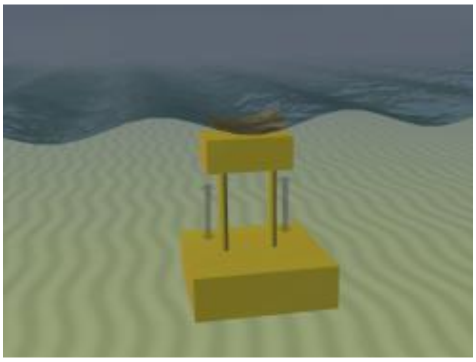

Figure 16. Submerged pressure differential devices scheme. Source: http://www.aquaret.com/.

6. **Rotating mass:** two forms of rotation are used to capture energy by the movement of the device heaving and swaying in the waves. This motion drives either an eccentric weight or a gyroscope causes precession. In both cases the movement is attached to an electric generator inside the device (Figure 17).

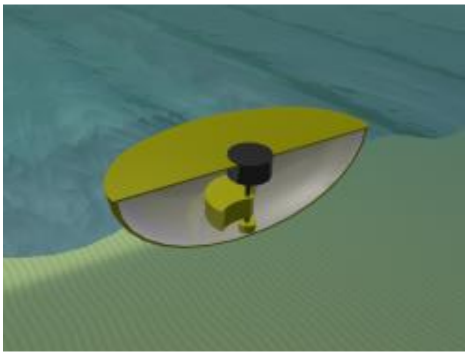

Figure 17. Rotating mass device scheme. Source: http://www.aquaret.com/.

7. **Overtopping devices** have walls over which the water washes, creating a water front turned into power through a low head turbine. Collectors may be used to concentrate the flow (Figure 18).

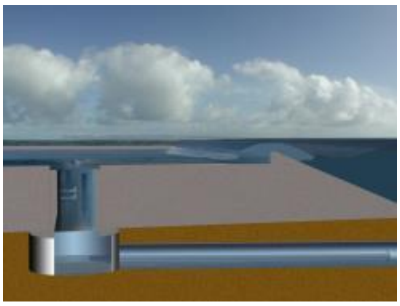

Figure 18. Overtopping device scheme. Source: http://www.aquaret.com/.

A detailed evaluation of TRLs, updated regularly, has been undertaken by WavEC using the ESBI TRL classification (since it was considered the most appropriate for wave and tidal energy technologies). The following table gives the maximum TRL achieved in each technology type.

Table 7. Maximum TRL level of Wave converter achieved by type – Source: WavEC

Wave converter technology type	TRL
Attenuator	8
Point Absorber	7
Oscillating Wave Surge Converter	8
Oscillating Water Column	7
Submerged pressure differential	6
Rotating Mass	6
Over topping device	6

4.2.3 Case studies and TRL

In Table 8 a review of the existing wave technologies with a TRL between 5 and 9 is shown. The total number of technologies is 94, but only 30 of them have confirmed TRL above 5 (Table 9). Most of them (17) are point absorbers, 4 are attenuators, 3 belong to oscillating wave surge, 4 to oscillating water column and only one to overtopping terminator and rotating mass. Only 6 projects present a mature TRL 7-9. These are the following:

a) EMEC Pelamis Wave Power (Table 10 and Figure 19).
b) EMEC Seatricity (Table 11 and Figure 20).
c) Mutriku Wave Power Plant (Table 12 and Figure 21).
d) LIMPET OWC (Table 13 and Figure 22).
e) PICO OWC (Table 14 and Figure 23).
f) Penguin (Table 15 and Figure 24).

Table 8. Wave energy technologies and associated TRL. Source: WavEC, 2015 using the ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
Dexawave A/S	DexaWave 1:10	A: Attenuator	5	Maybe
Dexawave A/S	DexaWave 1:5	A: Attenuator	5	Yes
Floating Power Plant AS	Poseidon 37	A: Attenuator	6	Yes
Pelamis Wave Power Ltd.	Pelamis P1	A: Attenuator	8	No
E. ON & Scottish Power Renewables - Pelamis Wave Power Ltd	Pelamis P2	A: Attenuator	7	Yes
Pelamis Wave Power Ltd.	Pelamis 1:7 prototype	A: Attenuator	5	Yes
40South Energy Srl	D100t	B: Point Absorber	6	No
40South Energy Srl	H24	B: Point Absorber	6	Not Tested
40South Energy Srl	R115	B: Point Absorber	6	Not Tested
40South Energy Srl	Y25t	B: Point Absorber	5	No
40South Energy Srl	R115 prototype	B: Point Absorber	6	Yes
Albatern Wave Energy Ltd.	SQUID/WaveNET - Series 6	B: Point Absorber	5	Yes
Albatern Wave Energy Ltd.	WaveNET 1:7	B: Point Absorber	5	Yes
AquaGen Technologies Pty Ltd	SurgeDrive Prototype	B: Point Absorber	5	Maybe
AWS Ocean Energy	Archimedes Wave Swing (AWS)	B: Point Absorber	7	No
Carnegie Wave Energy Ltd	CETO 3	B: Point Absorber	6	Maybe
Carnegie Wave Energy Ltd	CETO 2 pilot	B: Point Absorber	5	No
Carnegie Wave Energy Ltd	CETO 5	B: Point Absorber	7	No
Columbia Power Technologies Inc.	SeaRay Gen 3.1	B: Point Absorber	5	Maybe

Table 8. (Continuation). Wave energy technologies and associated TRL. Source: WavEC, 2015 using the ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
COPPE Subsea Technology Laboratory	COPPE Pecém	B: Point Absorber	6	Maybe
Carnegie Wave Energy Ltd	CETO 4	B: Point Absorber	6	No
Eco Wave Power	WaveClapper	B: Point Absorber	6	No
Eco Wave Power	PowerWing	B: Point Absorber	6	No
Fred.Olsen Renewables	BOLT 2	B: Point Absorber	7	Not Tested
Fred.Olsen Renewables	BOLT 2 lifesaver	B: Point Absorber	6	Yes
Fred.Olsen Renewables	B22	B: Point Absorber	5	Maybe
Fred.Olsen Renewables	BOLT 1	B: Point Absorber	6	Yes
Fred.Olsen Renewables	Buldra - FO3	B: Point Absorber	6	Yes
Fred.Olsen Renewables	B33	B: Point Absorber	5	No
Ocean Power Technologies, Inc.	PB40	B: Point Absorber	6	Yes
Ocean Power Technologies, Inc.	PB150 - Mark 3	B: Point Absorber	6	No
Oregon State University	OSU L10	B: Point Absorber	5	Yes
Oscilla Power, Inc.	OPI TDU2	B: Point Absorber	6	Maybe
Oscilla Power, Inc.	OPI Gen 1	B: Point Absorber	5	Maybe
Perpetuwave Power	Wave Harvester 1:4	B: Point Absorber	5	Maybe
RESEN Energy	LOPF-06-70W	B: Point Absorber	5	No Data
Seabased AB	Seabased 25	B: Point Absorber	6	No
Seabased AB	Seabased - Maren	B: Point Absorber	6	No
Seabased AB	Seabased Lysekill	B: Point Absorber	6	Yes

Table 8. (Continuation). Wave energy technologies and associated TRL. Source: WavEC, 2015 using the ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
Seatricity Ltd.	Oceanus 1	B: Point Absorber	7	Yes
Seatricity Ltd.	Oceanus Prototype	B: Point Absorber	5	Yes
Resolute Marine Energy Inc	AirWEC prototype	B: Point Absorber	5	No Data
Seatricity Ltd.	Oceanus 2	B: Point Absorber	7	No
Spindrift Energy	Spindrift Energy Device prototype	B: Point Absorber	5	No
Trident Energy Ltd	Trident Energy 5	B: Point Absorber	7	No
Trident Energy Ltd	Trident LG WEC	B: Point Absorber	6	Not Tested
Wave Energy Technology New Zealand	WET-NZ MDEF 1/2 NZ	B: Point Absorber	6	Yes
Wave Energy Technology New Zealand	WET-NZ PoC - Goalpost model	B: Point Absorber	5	Yes
Wave Energy Technology New Zealand	WET-NZ PSAF 1/4	B: Point Absorber	5	Yes
Wave Energy Technology New Zealand	WET-NZ MDEF 1/2 US	B: Point Absorber	6	Maybe
Wave Rider Energy Pty Ltd.	Wave Rider Pilot	B: Point Absorber	6	Maybe
Wave Star Energy A/S	WaveStar 1:10	B: Point Absorber	5	Yes
Wave Star Energy A/S	WaveStar 1:2 - 2 floaters	B: Point Absorber	6	Yes
Wavebob Ltd.	Wavebob 1:17th scale model	B: Point Absorber	5	No Data
Wavebob Ltd.	Wavebob ADM	B: Point Absorber	6	Yes
Wedge Global	W200	B: Point Absorber	6	Maybe
Aquamarine Power Ltd.	Oyster 800	C: Oscillating Wave Surge Converter	8	No
Aquamarine Power Ltd.	Oyster 315	C: Oscillating Wave Surge Converter	7	Maybe
AW-Energy Oy	WaveRoller WR1	C: Oscillating Wave Surge Converter	6	Yes

Table 8. (Continuation). Wave energy technologies and associated TRL. Source: WavEC, 2015 using the ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
AW-Energy Oy	WaveRoller 3x100	C: Oscillating Wave Surge Converter	7	Maybe
AW-Energy Oy	WaveRoller WR2	C: Oscillating Wave Surge Converter	6	Yes
BioPower System Pty Ltd	bioWave 250	C: Oscillating Wave Surge Converter	6	Not Tested
Langlee Wave Power AS	Langlee Robusto	C: Oscillating Wave Surge Converter	6	Not Tested
AW-Energy Oy	WaveRoller 1:3 prototype	C: Oscillating Wave Surge Converter	5	No Data
Resolute Marine Energy Inc	SurgeWEC 30kW	C: Oscillating Wave Surge Converter	5	Not Tested
Resolute Marine Energy Inc	SurgeWEC 17,5m2 Prototype	C: Oscillating Wave Surge Converter	5	Yes
Resolute Marine Energy Inc	SurgeWEC	C: Oscillating Wave Surge Converter	7	Not Tested
Resolute Marine Energy Inc	SurgeWEC 3,8m2 Prototype	C: Oscillating Wave Surge Converter	5	Maybe
WERPO wave energy	SDE 150 WEC	C: Oscillating Wave Surge Converter	6	No Data
WERPO wave energy	SDE 100 WEC	C: Oscillating Wave Surge Converter	6	No Data
WERPO wave energy	SDE 60 WEC	C: Oscillating Wave Surge Converter	6	No Data
WERPO wave energy	SDE 40 WEC	C: Oscillating Wave Surge Converter	6	No Data
LEANCON Wave Energy	LEANCON 1:10 Prototype	D: Oscillating Water Column	5	Not Tested
Ocean Energy Ltd	OE Buoy 1:4	D: Oscillating Water Column	6	Yes
Ocean Energy Ltd	OE Buoy Full Scale	D: Oscillating Water Column	7	Not Tested
Oceanlinx Limited	ogWave MK2	D: Oscillating Water Column	5	No
Oceanlinx Limited	blueWave MK3 PC	D: Oscillating Water Column	6	No
Oceanlinx Limited	greenWave	D: Oscillating Water Column	7	No
Oceanlinx Limited	greenWave MK1	D: Oscillating Water Column	7	Maybe

Table 8. (Continuation). Wave energy technologies and associated TRL. Source: WavEC, 2015 using the ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
Voith Hydro Wavegen Limited	Mutriku OWC	D: Oscillating Water Column	8	Yes
Voith Hydro Wavegen Limited	LIMPET OWC	D: Oscillating Water Column	7	Yes
WavEC Offshore Renewables	PICO OWC	D: Oscillating Water Column	7	Yes
WaveDragon ApS	WaveDragon 1:4.5	E: Overtopping/Terminator device	5	Yes
Bombora WavePower	Bombora WEC	F: Submerged pressure differential	6	Not Tested
Offshore Wave Energy Ltd	OWEL WEC 350kW	D: Oscillating Water Column	6	Not Tested
Bombora WavePower	Bombora WEC prototype	F: Submerged pressure differential	5	Not Tested
M3 Wave Energy Systems LLC	APEX wave energy device	F: Submerged pressure differential	5	Maybe
Neptune Wave Power LLC	Neptune WECD Model 3.1	H: Rotating Mass	5	No Data
Oceantec Energías Marinas, S.L.	Oceantec Rotating Mass WEC 1:4 prototype	H: Rotating Mass	6	Maybe
Wello OY	Penguin	H: Rotating Mass	7	Yes
Wello OY	Baby Penguin	H: Rotating Mass	5	No Data
AWS Ocean Energy	AWS-III 1:9	I: Other	5	Maybe
AWS Ocean Energy	AWS-III 1:2	I: Other	6	No
Ocean Harvesting Technologies AB	OHT (Full-scale)	I: Other	5	Not Tested

Table 9. Confirmed TRL for wave energy technologies. Source: WavEC, 2015 using the ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
Dexawave A/S	DexaWave 1:5	A: Attenuator	5	Yes
Floating Power Plant AS	Poseidon 37	A: Attenuator	6	Yes
E. ON & Scottish Power Renewables - Pelamis Wave Power Ltd.	Pelamis P2	A: Attenuator	7	Yes
Pelamis Wave Power Ltd.	Pelamis 1:7 prototype	A: Attenuator	5	Yes
40South Energy Srl	R115 prototype	B: Point Absorber	6	Yes
Albatern Wave Energy Ltd.	SQUID/WaveNET - Series 6	B: Point Absorber	5	Yes
Albatern Wave Energy Ltd.	WaveNET 1:7	B: Point Absorber	5	Yes
Fred.Olsen Renewables	BOLT 2 lifesaver	B: Point Absorber	6	Yes
Fred.Olsen Renewables	BOLT 1	B: Point Absorber	6	Yes
Fred.Olsen Renewables	Buldra - FO3	B: Point Absorber	6	Yes
Ocean Power Technologies, Inc.	PB40	B: Point Absorber	6	Yes
Oregon State University	OSU L10	B: Point Absorber	5	Yes
Seabased AB	Seabased Lysekill	B: Point Absorber	6	Yes
Seatricity Ltd.	Oceanus 1	B: Point Absorber	7	Yes
Seatricity Ltd.	Oceanus Prototype	B: Point Absorber	5	Yes
Wave Energy Technology New Zealand	WET-NZ MDEF 1/2 NZ	B: Point Absorber	6	Yes
Wave Energy Technology New Zealand	WET-NZ PoC - Goalpost model	B: Point Absorber	5	Yes
Wave Energy Technology New Zealand	WET-NZ PSAF 1/4	B: Point Absorber	5	Yes
Wave Star Energy A/S	WaveStar 1:10	B: Point Absorber	5	Yes
Wave Star Energy A/S	WaveStar 1:2 - 2 floaters	B: Point Absorber	6	Yes

Table 9. (Continuation). Confirmed TRL for wave energy technologies. Source: WavEC, 2015 using the ESBI TRL classification.

Developer	Name	Classification	TRL	Achieved TRL
Wavebob Ltd.	Wavebob ADM	B: Point Absorber	6	Yes
AW-Energy Oy	WaveRoller WR1	C: Oscillating Wave Surge Converter	6	Yes
AW-Energy Oy	WaveRoller WR2	C: Oscillating Wave Surge Converter	6	Yes
Resolute Marine Energy Inc	SurgeWEC 17,5m2 Prototype	C: Oscillating Wave Surge Converter	5	Yes
Ocean Energy Ltd	OE Buoy 1:4	D: Oscillating Water Column	6	Yes
Voith Hydro Wavegen Limited	Mutriku OWC	D: Oscillating Water Column	8	Yes
Voith Hydro Wavegen Limited	LIMPET OWC	D: Oscillating Water Column	7	Yes
WavEC Offshore Renewables	PICO OWC	D: Oscillating Water Column	7	Yes
WaveDragon ApS	WaveDragon 1:4.5	E: Overtopping/Terminator device	5	Yes
Wello OY	Penguin	H: Rotating Mass	7	Yes

Table 10. EMEC Pelamis Wave Power project description.

PROJECT NAME	EMEC Pelamis Wave Power[3]
COUNTRY	Scotland
LOCATION	Billia Croo wave test site 2 km off the Orkney coast
LATITUDE	58,9772
LONGITUDE	-3,38710
PROJECT DEVELOPER	E. ON and Scottish Power Renewables
TECHNOLOGY DEVELOPER	Pelamis Wave Power
TECHNOLOGY	Attenuator
DEVICE MODEL	Pelamis: P2
START YEAR	E.ON installed in 2010; Scottish Power Renewables installed in 2012
END YEAR	2014
PROJECT SCALE	Pre-commercial
DEVICE SCALE	Large scale prototype
STATUS	Project complete
PROJECT CAPACITY (KW)	1500 (0.75 x 2 full-scale devices)
WEB SITE	http://www.emec.org.uk/marine-energy/wave-and-tidal-projects/
Source: http://www.emec.org.uk/about-us/media-centre/gallery/	

Figure 19. EMEC Pelamis Wave Power project.

[3]http://tethys.pnnl.gov/sites/default/files/sites/Annex%20IV%20Metadata%20%20Orkney%20Pelamis_0.pdf

Table 11. EMEC Seatricity project description.

PROJECT NAME	EMEC Seatricity
COUNTRY	Scotland
LOCATION	Billia Croo wave test site 2 km off the Orkney coast
LATITUDE	58,9772
LONGITUDE	-3,3871
PROJECT DEVELOPER	Seatricity Ltd.
TECHNOLOGY	Point absorber
DEVICE MODEL	Oceanus
START YEAR	2013
END YEAR	2014
PROJECT SCALE	Pre-commercial
DEVICE SCALE	Large scale prototype
STATUS	Project complete
PROJECT CAPACITY (KW)	1000
WEB SITE	http://seatricity.com/
Source: http://seatricity.com/gallery/	

Figure 20. EMEC Seatricity project.

Table 12. Mutriku Wave Power Plant project description.

PROJECT NAME	Mutriku Wave Power Plant4
COUNTRY	Spain
LOCATION	Mutriku, Gipuzkoa (Basque Country)
LATITUDE	43,312
LONGITUDE	-2,377
PROJECT DEVELOPER	Ente Vasco de la Energia (EVE)
TECHNOLOGY DEVELOPER	Voith Hydro Wavegen Ltd.
TECHNOLOGY	Oscillating Water Column
START YEAR	2011
END YEAR	N/A
PROJECT SCALE	Commercial
DEVICE SCALE	Full scale
STATUS	Operational
PROJECT CAPACITY (KW)	296 kW (16 turbines)
WEB SITE	http://www.eve.es
	Source: Ente Vasco de la Energia (EVE)

Figure 21. Mutriku Wave Power Plant project

[4] http://tethys.pnnl.gov/sites/default/files/sites/Annex%20IV%20Metadata%20-%20Mutriku.pdf

Table 13. LIMPET OWC project description.

PROJECT NAME	Portnahaven, Islay[5]
COUNTRY	United kingdom
LOCATION	Portnahaven, Islay
LATITUDE	55,69
LONGITUDE	-6,522
TECHNOLOGY DEVELOPER	Voith Hydro Wavegen Limited
TECHNOLOGY	Oscillating Water Column
DEVICE MODEL	Wavegen: LIMPET
START YEAR	2010
END YEAR	N/A
PROJECT SCALE	Commercial
DEVICE SCALE	Part-scale / part-function prototype
STATUS	Operational
PROJECT CAPACITY (KW)	250
WEB SITE	http://voith.com
Source: https://commons.wikimedia.org/wiki/File:Wave_energy_power_plant,_Islay_-_geograph.org.uk_-_273216.jpg#/media/File:Wave_energy_power_plant,_Islay_-_geograph.org.uk_-_273216.jpg	

Figure 22. LIMPET OWC project

[5] http://tethys.pnnl.gov/sites/default/files/publications/Islay_LIMPET_Report.pdf

Table 14. PICO OWC project description.

PROJECT NAME	PICO OWC[6]
COUNTRY	Portugal
LOCATION	Pico Island, Azores
LATITUDE	38,557
LONGITUDE	-28,446
PROJECT DEVELOPER	WavEC Offshore Renewables
TECHNOLOGY	Oscillating Water Column
START YEAR	1999
END YEAR	N/A
PROJECT SCALE	Commercial
DEVICE SCALE	Full scale
STATUS	Operational
PROJECT CAPACITY (KW)	400
WEB SITE	http://www.pico-owc.net/

Source: http://www.pico-owc.net/

Figure 23. PICO OWC project.

[6] http://mhk.pnnl.gov/sites/default/files/sites/Annex%20IV%20Metadata%20-%20Pico%20OWC_0.pdf

Table 15. Penguin project description.

PROJECT NAME	Penguin
COUNTRY	Scotland
LOCATION	Billia Croo wave test site 2 km off the Orkney coast
LATITUDE	58,9772
LONGITUDE	-3,3871
TECHNOLOGY DEVELOPER	Wello OY
TECHNOLOGY	Rotating Mass
DEVICE MODEL	Penguin
SEABED FIXATION	Floating (flexible mooring)
START YEAR	2013
END YEAR	-
PROJECT SCALE	Pre-commercial
DEVICE SCALE	Large scale prototype
STATUS	Operational
PROJECT CAPACITY (KW)	500
WEB SITE	http://www.wello.eu/en/penguin
Source: http://www.wello.eu/en/penguin	

Figure 24. Penguin project.

4.3 Offshore wind technologies

4.3.1 Energy resource and location

In 2014, Europe fully grid connected 408 offshore wind turbines in nine wind farms and one demonstration project with a combined capacity totalling 1,483 MW. 536 turbines were erected during 2014. 2,488 turbines are now installed and grid connected, making a cumulative total of 8,045.3 MW in 74 wind farms in 11 European countries. Once completed, the 12 offshore projects currently under construction will increase installed capacity by a further 2.9 GW, bringing the cumulative capacity in Europe to 10.9 GW (EWEA, The European Wind Energy Association). The total wind power capacity installed by the end of 2014 would, in a normal wind year, produce 284 TWh of electricity, enough to cover 10.2% of the EU's electricity consumption – offshore wind power capacity alone being able to produce 29.6 TWh of electricity, covering 1.1% of the EU’s electricity consumption (EWEA, The European Wind Energy Association). According to Petersen and Malm (Petersen and Malm), the planned development in the European Atlantic coast would be of about 50 GW by the year 2030. The UK has the largest number of turbines (1,301) and capacity (4,494 MW) connected, representing over half of all installed offshore wind capacity in Europe. Denmark follows with 1,271 MW (16%), then Germany (1,049 MW, 13%). Norway and Portugal both have a full-scale floating turbine (2.3 MW and 2 MW respectively).

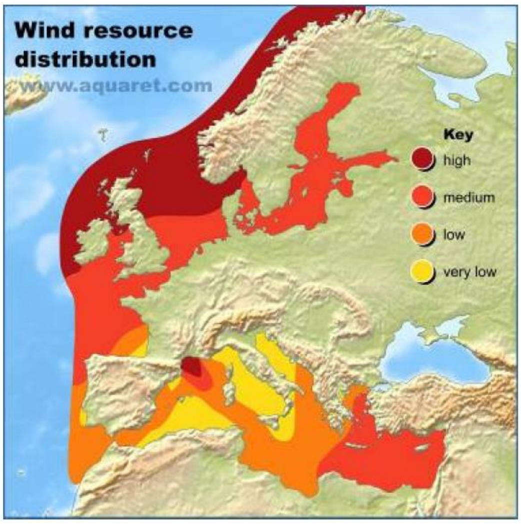

Figure 25. Wind resource distribution. Source: www.aquaret.com.

4.3.2 Technology types

a) Horizontal axis wind turbines

These systems are by far the most common form of wind turbine in use around the world today. The majority of modern onshore wind turbines are three-bladed, horizontal axis designs and these are the types that have so far been employed offshore (Figure 26). Modern horizontal axis wind turbines also include single, twin and multi-bladed designs (Figure 27).

Figure 26. Horizontal three bladed axis wind turbine scheme. Source: www.aquaret.com.

Figure 27. Horizontal two bladed bladed axis wind turbine scheme. Source: www.aquaret.com.

b) Vertical axis wind turbines

Vertical axis wind turbines can be further differentiated into drag-type devices, lift-type devices and devices that employ a combination of the two. Each of these device types come in various different configurations and unlike the horizontal axis wind turbines, can harness winds from any direction without needing to reposition the rotor (Figure 28).

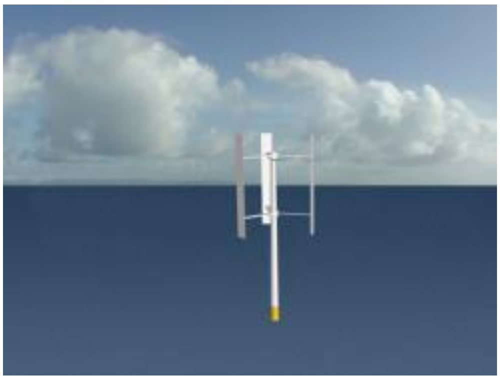

Figure 28. Vertical axis wind turbine scheme. Source: www.aquaret.com.

c) Other turbine types and hybrid systems

Projects in development include other innovative concepts.

- **Innovative wind energy convertors** are currently being explored. These include, enclosed tips concepts, which increase productivity of the turbine for a given diameter, and reduce noise levels, (e.g. Wind Lens project, Japan).

Figure 29. Enclosed tip / Wind lens turbine. Source: https://commons.wikimedia.org/wiki/File:Wind_lens_pinwheel_A.jpg

- **Hybrid systems** are also being developed, combining several sources of energy. For example, the MODEC system, in Japan, combines a vertical wind axis wind turbine and a vertical axis current energy converter.

d) Foundations and water depth

So far, installations of offshore wind turbines have been limited to relatively shallow waters and have been using bottom fixed foundations, however with increased experience and recent developments – noticeably towards floating foundations, deeper water installations offer new potential opportunity. These will be able to utilize stronger winds further out to sea and provide the opportunity for more areas to be developed whilst minimising the visual impact onshore.

Many types of fixed foundations have reached full maturity. In Europe as of the end of 2014, according to EWEA (EWEA, The European Wind Energy Association), there were 2,486 bottom fixed offshore turbines using as substructure: Monopile (79% of turbines), Gravity foundations (10%), Jackets / Truss (5%), Tripods (4%), Tripiles (2%).
An evaluation of TRLs of the most relevant projects has been undertaken by E-CUBE Strategy consultants:

- For bottom-fixed projects, a remainder of a selection of existing projects has been drawn: bottom fixed turbines on Monopole, Gravity base, Jacket/Truss, tripile have all been in use in large scale commercial projects for more than 2 years (and sometimes up to 20 years) – placing all this technologies at the highest TRL level.

- For floating devices, the Table 16 gives the maximum TRL achieved in each technology type.

Table 16. Maximum TRL of wave converter achieved by type – Source: Developer public communication, analysis E-CUBE.

Wave converter technology type	TRL
A:Spar-horizontal axis WT	7-8
B: Semi-submersible platform - Horizontal axis WT	8-9
C: Semi-submersible platform - Vertical axis WT	7
C: Tension leg - submerged platform	7
D: Hybrid	7

4.3.3 Case studies and TRL: bottom fixed offshore turbines

Bottom fixed offshore turbines have been deployed since 1991 in commercial arrays, and benefit an extensive return of experience on a wide range of models, type of foundation, and range of power and depth - as illustrated in Table 17 below, which documents a selection of projects in operation for more than 2 years (partially for BARD Offshore I) – and for some of them more than 20 years (the oldest offshore park being Vindeby Offshore Wind Park in Denmark, commissioned in 1991). All of them can be considered TRL 9 and above.

4.3.4 Case studies and TRL: floating offshore technologies

Table 18 displays a review of existing floating wind technologies with a TRL between 5 and 9. Twenty three technologies were analysed and sixteen were rated above a TRL of 5:

- 3 have spar based technologies, with catenary mooring or tension leg.
- 9 have semi-submersible platforms with catenary mooring, including 8 horizontal axis turbines and 1 vertical axis turbines.
- 2 have tension leg submerged platforms.
- 2 are hybrid systems.

The following projects have TRL between 7 and 9:

- Hywind Pilot (Table 19 and Figure 30).
- Demowfloat project (Table 20 and Figure 31).
- Vertiwind Project (Table 21 and Figure 32).
- FORWARD Phase I project (Table 22).
- FORWARD Phase II project (Table 23).
- Goto FOWT (Table 24).
- SWAY (Table 25).
- VolturnUS (Table 26 and Figure 33).
- Modec SKWID (Table 27).

Table 17. Selection of existing commercial projects (source: Marina Platform - www.marina-platform.info).

Wind Farm	Location	Turbine Model	Turbine Rating (MW)	# of Turbines	Water Depth (m)	Foundation type
Alpha Ventus	DE	Multibrid M5000 RE Power 5M	5	66	30	Tripods Truss
Arklow Bank	IE	GE Energy 3.6	3.6	7	25	Monopile
BARD Offshore 1	DE	Bard 5.0	5	80	40	Tripile
Barrow Offshore Wind	UK	Vestas V90	3	30	20	Monopile
Beatrice	UK	RE Power 5M	5	2	45	Truss
Burbo	UK	Siemens	3.6	25	8	Monopile
Horns Rev I	DK	Vestas V80	2	80	14	Monopile
Horns Rev II	DK	Siemens	2.3	91	17	Monopile
Kentish Flats	UK	Vestas V90	3	30	5	Monopile
Nysted	DK	Siemens	2.3	72	10	Gravity based
Thornton Bank	BE	RE Power 5m	5	60	10	Gravity based
Lilligrund	SE	Siemens	2.3	48	10	Gravity based
Lynn and Inner Dowsing	UK	Siemens	3.6	54		Monopile
Princess Amalia	NL	Vestas V80	2	60	24	Monopile
Rhyll Flats	UK	Siemens	3.6	25		Monopile
Vindeby	DK	Initially Bonus 450	0.45	11	4	Gravity based

Table 18. Offshore wind innovative projects and associated TRL.

Developer	Name	Classification	TRL	Achieved TRL
SWAY (/Statoil)	SWAY	A:Spar-horizontal axis WT	6	May-be
Hywind	Hywind Pilot	A:Spar-horizontal axis WT	7-8	Yes
TODA Corp.	Goto FOWT	A:Spar-horizontal axis WT	7-8	Yes
Principal Power - EDP	Demowfloat project (WindFloat)	B:Semi-submersible platform - Horizontal axis WT	7-8	Yes
Marubeni Corp.	FORWARD Phase I	B:Semi-submersible platform - Horizontal axis WT	7-8	Yes
Marubeni Corp.	FORWARD Phase II	B:Semi-submersible platform - Horizontal axis WT	8-9	No
University of Maine / DeepCwind	VolturnUS	B:Semi-submersible platform - Horizontal axis WT	6	yes
Nass et Wind / DCNS	WINFLO	B:Semi-submersible platform - Horizontal axis WT	7	No
IDEOL - GAMESA	FLOATGEN	B:Semi-submersible platform - Horizontal axis WT	7	No (planned for 2015-19)
Glosten Associates	PelaStar	B:Semi-submersible platform - Horizontal axis WT	5	May be
IWES	HiPRWind	B:Semi-submersible platform - Horizontal axis WT	7	No
Nenuphar Wind	Vertiwind	C:Semi-submersible platform - Vertical axis WT	7	No
DCNS	SEA REED	C:Tension leg - submerged platform	5-7	No (planned for 2016)
Blue H Engineering	Submerged Deepwater Platform	C:Tension leg - submerged platform	5	May be
Modec	SKWID (Wind and Current)	D:Hybrid	6	No
Kyushu University	Wind Lens floater (Wind and Solar)	D:Hybrid	5	May be

Table 19. Hywind Pilot (source: Statoil, Siemens).

PROJECT NAME	Hywind Pilot
COUNTRY	Norway
LOCATION	Skudeneshavn
TECHNOLOGY DEVELOPER	Hywind
AXIS	Horizontal
TECHNOLOGY	Ballasted Spar
DEVICE MODEL	Siemens SWT-2.3 MW
SEABED FIXATION	3 line Mooring
START YEAR	2010
END YEAR	N/A
PROJECT SCALE	Full scale demonstrator
DEVICE SCALE	1:1
STATUS	Operational
PROJECT CAPACITY (MW)	2.3 MW
WEB SITE	www.statoil.com
COMMENTS	
Source	https://commons.wikimedia.org/wiki/File:Hywind_havvindm%C3%B8lle.JPG (License: Creative Commons Attribution-Share Alike 3.0)

Figure 30. Hywind Pilot - Photo: Jarle Vines (Creative Commons Attribution Sharealike 3.0)

Table 20. Demowfloat project (WindFloat).

PROJECT NAME	Demowfloat project (WindFloat)
COUNTRY	Portugal
LOCATION	Aguçadoura
TECHNOLOGY DEVELOPER	Principal Power
AXIS	Horizontal
TECHNOLOGY	Semi-submersible with heave plates and active ballast
DEVICE MODEL	Vestas v80 2.0 MW turbine
SEABED FIXATION	Catenary mooring with drag embedment anchors
START YEAR	2011
END YEAR	N/A
PROJECT SCALE	Full scale demonstrator
DEVICE SCALE	1:1
STATUS	Operational
PROJECT CAPACITY (MW)	2 MW
WEB SITE	www.demowfloat.eu
COMMENTS	
Source	https://commons.wikimedia.org/wiki/File:Agucadoura_WindFloat_Prototype.jpg (License: Creative Commons Attribution-Share Alike 3.0)

Figure 31. Demowfloat project (WindFloat).

Table 21. Vertiwind project.

PROJECT NAME	Vertiwind
COUNTRY	France
LOCATION	Fos-sur-Mer
TECHNOLOGY DEVELOPER	Nenuphar Wind
AXIS	Vertical
TECHNOLOGY	Semi-submersible
DEVICE MODEL	
SEABED FIXATION	Catenary mooring
START YEAR	2018 (delayed)
END YEAR	N/A
PROJECT SCALE	Full scale demonstrator
DEVICE SCALE	
STATUS	Partly build turbine - onshore testing
PROJECT CAPACITY (MW)	2 MW
WEB SITE	www.nenuphar-wind.com
COMMENTS	
Source	Nenuphar Wind

Figure 32. Vertiwind – Copyright © : Nenuphar Wind [2015]

Table 22. FORWARD Phase I project.

PROJECT NAME	FORWARD Phase I
COUNTRY	Japan
LOCATION	Fukushima
TECHNOLOGY DEVELOPER	11 consortium members among which Mitsubishi Heavy Industry - Mitsui Shipyard - Hitachi - Japan Marine United
AXIS	Horizontal - downwind - 3 blades
TECHNOLOGY	Semi-submersible
DEVICE MODEL	2MW downwind Hitachi turbine
SEABED FIXATION	Catenary mooring
START YEAR	2013
END YEAR	N/A
PROJECT SCALE	Full scale demonstrator
DEVICE SCALE	Full scale
STATUS	Operational
PROJECT CAPACITY (MW)	2 MW
WEB SITE	www.fukushima-forward.jp/english/index.html
COMMENTS	
Photo available at	www.fukushima-forward.jp/english/photo/img048.html

Table 23. FORWARD Phase II project (Source: developer site and communication).

PROJECT NAME	FORWARD Phase II
COUNTRY	Japan
LOCATION	Fukushima
TECHNOLOGY DEVELOPER	11 consortium members among which Mitsubishi Heavy Industry - Mitsui Shipyard - Hitachi - Japan Marine United
AXIS	Horizontal - upwind and downwind
TECHNOLOGY	1 Semi-submersible and 1 advanced spar
DEVICE MODEL	Sea Angel / HTW5.0
SEABED FIXATION	Catenary mooring
START YEAR	2015
END YEAR	
PROJECT SCALE	Full scale small array
DEVICE SCALE	Full scale
STATUS	Assembled (for the 7MW turbine) - procurement for the 5 MW
PROJECT CAPACITY (MW)	7MW+5MW=12 MW
WEB SITE	www.fukushima-forward.jp/english/index.html
COMMENTS	
Photo available at	www.fukushima-forward.jp/english/photo/images/index_ph057.jpg

Table 24. Goto FOWT (Source: developer site and communication).

PROJECT NAME	Goto FOWT
COUNTRY	Japan
LOCATION	Kabashima Island
TECHNOLOGY DEVELOPER	5 consortium members among which TODA Corp., Hitachi, Fuji Heavy Industries
AXIS	Horizontal
TECHNOLOGY	Spar
DEVICE MODEL	2 MW Hitachi (ex FHI)
SEABED FIXATION	2013
START YEAR	2013
END YEAR	N/A
PROJECT SCALE	Full scale demonstrator
DEVICE SCALE	Full scale
STATUS	Operational
PROJECT CAPACITY (MW)	2 MW
WEB SITE	www.goto-fowt.go.jp/english/home
COMMENTS	This prototype was preceded by a 100 kW demonstrator. It does not appear to be planned to be extended in the immediate future.

Table 25. SWAY (source: Sway public communication).

PROJECT NAME	SWAY
COUNTRY	Norway
LOCATION	Bergen
TECHNOLOGY DEVELOPER	SWAY
AXIS	Horizontal
TECHNOLOGY	Floating spar down wind turbine with tension rod system
DEVICE MODEL	1:6 scale turbine
SEABED FIXATION	1 Tension Leg Mooring
START YEAR	2011
END YEAR	2014 ?
PROJECT SCALE	Small scale prototype
DEVICE SCALE	One 1/6th model
STATUS	Tested in actual environment
PROJECT CAPACITY (MW)	0.015 ?
WEB SITE	www.sway.no
COMMENTS	Major stakeholders in the project are Statoil, Statkraft, Norwind, Lyse Produksjon AS

Table 26. VolturnUS (source: Umaine public communication).

PROJECT NAME	VolturnUS
COUNTRY	USA
LOCATION	Castine
TECHNOLOGY DEVELOPER	University of Maine
AXIS	Horizontal
TECHNOLOGY	Semi-submersible
DEVICE MODEL	Renewegy VP-20
SEABED FIXATION	
START YEAR	2013
END YEAR	N/A
PROJECT SCALE	Small scale prototype
DEVICE SCALE	Small scale prototype
STATUS	Ongoing tests
PROJECT CAPACITY (MW)	0.020 MW
WEB SITE	www.umaine.edu
COMMENTS	
Source	University of Maine Advanced Structures and Composites Center

Figure 33. VolturnUS turbine – Copyright © : University of Maine Advanced Structures and Composites Center [2013]

Table 27. Modec SKWID (source: Modec public communication).

PROJECT NAME	SKWID
COUNTRY	Japan
LOCATION	Karatsu City
TECHNOLOGY DEVELOPER	Modec Inc
AXIS	Vertical, combined with Tidal generator
TECHNOLOGY	Hybrid
DEVICE MODEL	Skwid
SEABED FIXATION	Catenary mooring
START YEAR	2014
END YEAR	2014
PROJECT SCALE	Medium scale demonstrator
DEVICE SCALE	Medium scale
STATUS	Sank in December 2014 during installation process at sea – project does not seem to have been pursued further
PROJECT CAPACITY (MW)	0.5 MW
WEB SITE	www.modec.com
COMMENTS	
Sketch available at	www.modec.com/fps/skwid/images/skwid_ph01.jpg

5. CONCLUSIONS

Besides bottom fixed offshore wind technologies, the RiCORE project will need to integrate 19 technology types across all 3 technology categories.

The main focus area includes 11 technology types that have already reached a level of maturity enabling them to immediately benefit from the risk-based approach proposed by the RiCORE project. Half of them, as well as the most advanced projects, are in the floating wind category (Table 28).

Table 28. Main focus area.

Technology category	Technology type	TRL	Comments
Tidal	Tidal impoundment	9	
Tidal	Horizontal axis turbine	8	Several advanced projects
Tidal	Enclosed Tips (Venturi)	8	Advanced but with only one advanced family of products
Wave	Attenuator	8	
Wave	Point Absorber	7	
Wave	Oscillating Wave Surge Converter	8	Most advanced with the highest number of projects
Wave	Oscillating Water Column	7	
Flot. Wind	Spar-horizontal axis WT	7-8	
Flot. Wind	Semi-submersible platform - Horizontal axis WT	8-9	Most advanced with the highest number of projects
Flot. Wind	Semi-submersible platform - Vertical axis WT	7	
Flot. Wind	Tension leg - submerged platform	7	

Policies and guidelines proposed by the project are designed to be applicable in this area.

In the second area, 8 technology types are considered, none of them being pure wind technology types (Table 29). These technology types *may* reach a sufficient level of maturity soon enough to be included in the initial deployment of the proposed risk-based approach. The conditions for applying the policies proposed by the project to these technologies will be studied, and guidelines will encompass them only if feasible without interference with main focus area technologies.

Table 29. Secondary focus area

Technology category	Technology type	TRL	Comments
Tidal	Vertical-axis (Cross Flow) turbine	5	
Tidal	Oscillating Hydrofoil	5	
Tidal	Archimedes Screw	5	
Tidal	Tidal Kite	5	
Wave	Submerged pressure differential	6	
Wave	Rotating Mass	6	
Wave	Over topping device	6	
Flot. Wind	Hybrid	6	The most advanced hybrid system combines a vertical wind turbine and a current generator, but sank during installation and does not seem to be pursued

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7. LIST OF ABBREVIATIONS

EMEC: European Marine Energy Centre

EIA: Environmental Impact Assessment

H2020: Horizon 2020

IEA-OES: International Energy Agency's Ocean Energy Systems Implementing Agreement

kW / kWh: Kilowatt / Kilowatt-hour

MRL: Manufacturing Readiness Level

MW / MWh: Megawatt / Megawatt-hour

ORE: Offshore renewable energy

TRL: Technology readiness level

TW/TWh: Terawatt / Terawatt-hours

WEC: Wave energy converter

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