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OFFSHORE RENEWABLE ENERGY

CURRENT STATUS-FUTURE PERSPECTIVES FOR PORTUGAL

OTEO

OBSERVATÓRIO TECNOLÓGICO PARA AS ENERGIAS *OFFSHORE*

OFFSHORE RENEWABLE ENERGY

CURRENT STATUS-FUTURE PERSPECTIVES FOR PORTUGAL

OFFSHORE RENEWABLE ENERGY CURRENT STATUS-FUTURE PERSPECTIVES FOR PORTUGAL:

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PREFACE

OFFSHORE RENEWABLE ENERGY – CURRENT STATUS

Future Perspectives for Portugal

Portugal and its regions have a strong connection to the Sea. The sea is a place of discovery, work, business and leisure. Sea exploration has interests in the areas of health, fisheries, marine industries, shipping and energy.

Portugal is a pioneer country in the exploitation of offshore renewable energy, particularly in harnessing wave energy, for which have already witnessed several experimental achievements on its territory (Pico, AWS, Pelamis, Wave Roller) and more recently in "offshore" wind energy with the installation of the first floating wind turbine in open Atlantic waters (WindFloat). These forms of energy are thus the batch of offshore renewable energies which, in short and medium term, predictably constitute the largest contribution to the national goals of using offshore renewables.

The use of offshore renewable energy is likely to have a great impact for Portugal and for its national industry in the level of job creation, innovation and exportation of goods and services. Our comparative advantages result from our coastal characteristics (high average energy use, relatively deep water near the coast), the availability of infrastructural support along the coast (ports, ship repair yards and the national grid) and relevant technical and scientific knowledge in this area which in most situations do not receive the recognition it deserves.

The challenge of availing commercial form the enormous potential of energy resource in the oceans, in order to meet the energy needs on the ground, has a long history. However, the discovery of large resources (with high energy densities and relatively simple for commercial exploitation) like coal, gas, oil and nuclear elements, of which Europe is an heavily dependent importer, leading to a delay in the maturity of offshore renewable energy technologies.

Recently, the growing rise in the price of fossil fuels and the increased discussion on the use of nuclear energy, in parallel with the growth of environmental awareness, has given rise to a new breath in the sector of offshore renewable energy.

In this context, the OTEO project (Observatório Tecnológico para as Energias Offshore) arises, an initiative led by the Institute of Mechanical Engineering and Industrial Management (INEGI), in partnership with the Wave Energy Center (WavEC - Offshore Renewables) and the Competitiveness and Technology Pole (ENERGYIN).

INEGI is an interface Institution between University and Industry, oriented to the activities of Research and Development, Innovation and Technology and contributes to the increase of the competitiveness of the national industry, through Research and Development, Technology Transfer and Training, in the fields of engineering design, materials, production technology, energy and environment and industrial management.

The Wave Energy Centre (WavEC - Offshore Renewables) is a non-profit organization dedicated to the promotion and development of ocean wave energy, offshore wind and other marine forms of energy (seaweed and tidal currents, salinity, thermal, etc.) through technical and strategic support to companies, R&D institutions and public entities.

ENERGYIN - the Competitiveness Cluster for Energy and Technology strives to enhance the competitiveness of Portuguese companies operating in the Energy sector. The offshore energies subsector, with the current deployment of conversion technologies, the development of service providers and associated research activities, provide opportunities for a massive presence of Portuguese companies in the global markets of the future.

The OTEO project – "Offshore Energy Technology Observatory" establishes as a strategy the Portuguese and the international knowledge of offshore energy technologies as well as support technologies in order to increase the competitiveness and the entrepreneurship in this sector.

After more than two years since the OTEO project began (Year 2011) we present the Book "OFFSHORE RENEWABLE ENERGY - CURRENT STATUS, Future Perspectives for Portugal". This book provide the reader with a global perspective on the state of national and international development of offshore renewable energy technologies as well as support technologies, whose authors are recognized researchers, technologists, developers and associations involved in promoting entrepreneurship and competitiveness in offshore renewable energy sector. Topics such as the state of the art of offshore renewable energies, market development, value chain, future prospects and a technological roadmap are presented in this issue.

I leave with acknowledgement to all those who directly or indirectly contributed to the achievement of this book, in particular to Professor Augusto Barata da Rocha and Professor António Sarmento, as editors of this book, and to all authors to whom all the credit is given and without your input the realization of this book would not have been possible.

I say farewell, but not before presenting the following question to the readers:

- Can Portugal aspire to own an offshore renewable industrial sector, in the development of floating technologies (wind and waves) for deep water systems, with predictable positive impacts in the national's marine industry and metalworking?

Tiago Morais

Editor- in- chief

PREVIEW NOTE

This book is the work of a vast network of experts and some of the chapters are based on texts produced by the coordinators of the areas covered by the OTEO Project and therefore, should be considered the following authors:

1. Offshore Renewable Energy Systems History

Author: Augusto Barata da Rocha, FEUP

2. Offshore Renewable Energy

Author: Ana Brito e Melo, IEA- OES

3. State-of-the-art renewable energy technologies

3.1. Offshore Wind Energy

Author: José Carlos Matos, INEGI

3.2. Wave Energy

Author: António Falcão, IST

3.3. Tidal Current Energy and Ocean Energy

Author: Peter Scheijgrond, MET–support

3.4. Ocean Thermal Energy

Author: Luis Vega

3.5. Offshore Algae Cultivation for Biofuels

Author: Frank Neumann, Seaweed Energy Solutions

4. Enabling technologies for offshore renewable energy – Review

Author: Karl C. Strømsem, Offtek AS

5. Market Development

Author: Alex Raventós, WavEC Offshore Renewables

6. Offshore Renewable Energy Supply Chain

Author: David Krohn, RenewableUK

7. Portuguese productive capacity: Current Situation and Prospects

Author: António Sá da Costa, APREN

8. Road Map

Author: Nuno Matos, WavEC Offshore Renewables

9. Conclusions

Author: Prof. António Sarmento, WavEC Offshore Renewables

This book also benefited from valuable suggestions and contributions made throughout its development, particularly by the consultation of FEUP, INEGI, WavEC and ENERGYIN employees, of which I should highlight: Rui Teixeira, Rui Sá, Alcibiades Paulo Guedes, Jorge Seabra, Manuela Nogueira, Paulo Chainho, Soraya Hamawi, Miguel Lopes, Mariana Abecassis, Teresa Bertrand and Custódio Miguens.

I should also mention that the project on which this book is based upon was co-financed by “Support system for collective actions (SIAC) - Strategies collective efficiency - Typology clusters and dynamic network” of COMPETE, Operational Programme for Competitiveness Factors, NSRF, the National Strategic Reference.

Finally I express my appreciation for the graphic designing and word processing performed by João Pedro Ferreira, Nelson Pereira and Jorge Correia from INEGI.

Tiago Morais

OTEO Project Coordinator

CONTENTS

INTRODUCTION

1

AUGUSTO BARATA DA ROCHA

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Augusto Duarte Campos Barata da Rocha is a Professor of Mechanical Engineering at the Faculty of Engineering of the University of Porto, Portugal.

He obtained his first degree from the Faculty of Engineering of the University of Porto, Portugal, a Master's Thesis from the Université de Metz, France and a Ph.D. from the Institut National Polytechnique de Grenoble, France.

He is a Professor of Mechanical Engineering at the Faculty of Engineering of the University of Porto and has been active in R&D in Manufacturing Processes. He is the founder and a member of the IDDRG – International Deep Drawing Research Group.

He has been the President of INEGI – Institute of Mechanical Engineering and Industrial Management of the University of Porto for the last 12 years. During this period he was the leader and coordinator of many Industrial Research Projects with National and European companies.

He is a member of the Advisory Council of AEP, Portuguese Enterprise Association.

He is a member of the CESM – Conselho do Ensino Superior Militar, by invitation of the Minister of Defence of Portugal.

He is a founding member and Director of IDCEM – Institute for the Development of Knowledge and Economy of the Oceans and founder and member of the board of Directors of the Portuguese Sea Cluster, OCEANO XXI.

In 2014, he was invited to be the CEO of the Ocean Research & Innovation Centre of the University of Porto, Portugal.

The surface of the planet earth is composed by 29,2% of Land and about 70,8% of water [1], [2]. Only 2,6% of this area is freshwater, the remaining area (97,4%) is salt water of the Oceans (96,5%) and Seas (0,9%).

The Ocean is one of the less explored resources of the Planet. It has a vast offer of natural resources to explore, in particular energy resources of different types. This enormous surface receives the largest amount of energy emitted by the Sun.

The oceans contain a huge amount of energy and solar energy is the main source of energy received by the earth. The dynamics of the planet, related to sun radiation, earth rotation, rate of spinning and interaction among gravitational forces, cause winds, ocean waves, tidal currents, changes in salinity, thermal gradients. These natural phenomena can generate electricity using a range of different technologies. In the future, these technologies could provide reliable, sustainable and cost-competitive energy.

Capturing ocean energy will have substantial benefits. Renewable ocean energy is fundamental in the future to solve the problems related to the intense use of fossil fuels and its growing price, greenhouse gases, climate changes, pollution and global warming.

The oldest known use of renewable energy, in the form of traditional biomass to fuel fires, dates from 790,000 years ago. The primary sources of traditional renewable energy were human labour, animal power, waterpower, wind, and firewood.

Probably the second oldest usage of renewable energy is sailing. This practice can be traced back some 7000 years, to sailing ships on the Nile.

In the Age of Discovery, starting in the early 15th century and continuing to the 17th century, Europeans explored Africa, the Americas, Asia and Oceania and humanity assisted the first era of globalization.

Portuguese and Spanish pioneer navigators used wind in the Age of Discovery as energy source for long-distance maritime travels, in search of alternative trade routes to "the East Indies", moved by the trade of gold, silver and spices.

These discovery vessels (caravels) were probably the first commercial and global use of marine renewable energy (wind energy) for international trade and globalization.

The Age of Discovery changed our perception of the world and allowed for the beginning of the Modern Era. This period represents one of the most significant global events concerning our history. Global exploration using sailing vessels powered by Wind Renewable Energy in offshore environment allowed the global mapping of the world, resulting in a new worldview.

Today, more than 20% of the global final energy consumption comes from renewable energy. Figure 1.1 shows the Renewable Energy share of global final energy consumption in 2008[3].

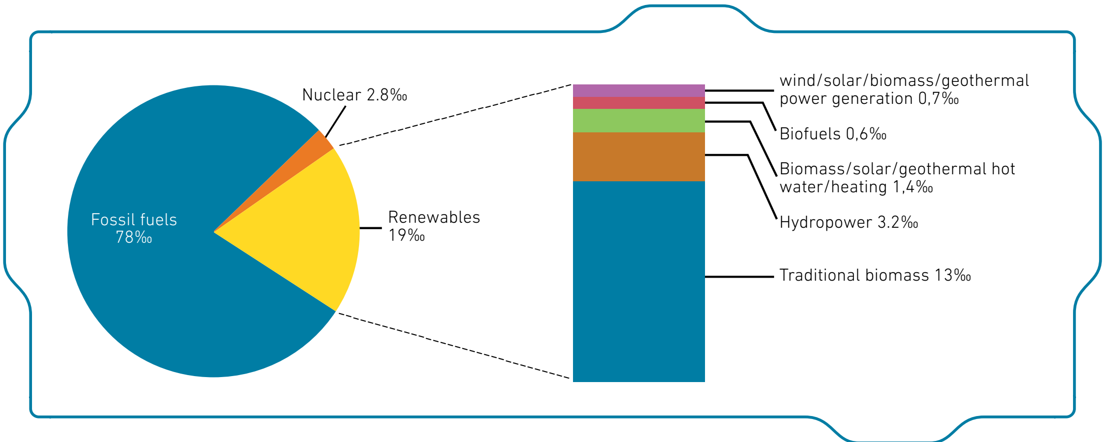


Figure 1.1 - Renewable Energy Share of Global Final Energy Consumption, 2008 [3].

In the electricity generation, renewables have a share of around 18%, with 15% of global electricity coming from hydroelectricity and 3% from new renewables [3], [4].

Worldwide renewable energy capacity grew, during a 5 years period, between 2004 and 2009, at rates between 10 and 60% annually. Wind Power, for example, grew 32% in 2009 (see Figure 1.2), with a worldwide installed capacity of 158 gigawatts (GW) by the end of 2009 [3].

Renewable power capacity worldwide reached 1,230 gigawatts (GW) in 2009. This production represents about a quarter of the global power-generating capacity (estimated at 4,800 GW in 2009) and supplies 18 % of global electricity production.

Most countries worldwide have defined ambitious policy targets for renewable energy production, for 2020. The 27 EU countries confirmed, in 2008, national targets for 2020, following a 2007 EU-wide target of 20 percent of final energy by 2020 (see Figure 1.3) [3].

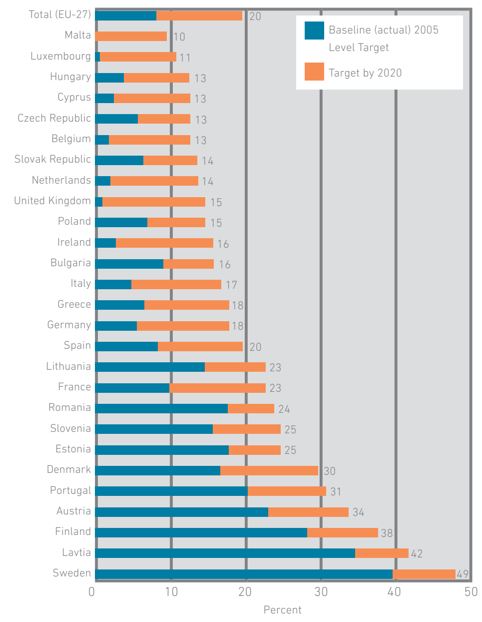


Figure 1.3 – Examples of national targets among EU developed countries [3].

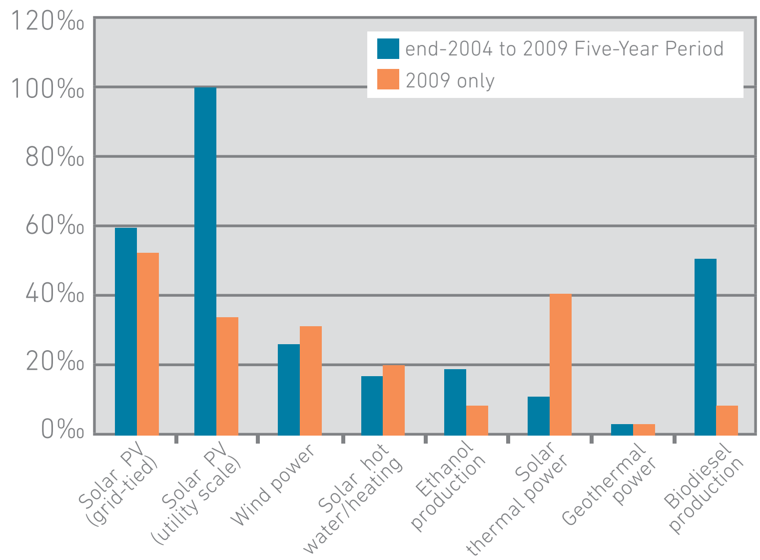


Figure 1.2 – Average Annual Growth Rates of Renewable Energy Capacity, from 2004 to 2009 [3].

The Vision of the Marine Board of the European Science Foundation stated in 2010 [1] predicted that by 2050 Europe could source up to 50% of its electricity needs from Marine Renewable Energy. This would have a profound impact on the European economy and European citizens.

It would contribute to energy supply and security, reduce CO2 emissions and their impact on the oceans, improve the overall state of the environment, improve quality of life, create jobs in a range of innovative sectors and herald a new era of environmentally sustainable development.

This vision is achievable and the potential rewards are considerable. It will rely on political commitment, public support, the establishment of a European offshore energy grid and a supportive fiscal and planning regime. Crucially, it will also require sustained research to feed both innovation and concept demonstration and to develop appropriate environmental monitoring protocols [1].

Marine Renewable Energy can be a significant contributor to energy needs in Europe.

In the next decade, this will require research efforts in Europe to be intensified and better coordinated across relevant sectors, disciplines and regional, national and European programmes, with particular attention to developing cost-efficient energy production technologies and appropriate environmental monitoring protocols [1].

These ambitious targets need improved coordination between industry needs and research efforts, through the joint development of a Strategic Research Agenda for Marine Renewable Energy and the development of collaborative networks of researchers and technology developers.

A pro-active, visionary and supportive European policy on Marine Renewable Energy will be the key to achieve a 100% renewable energy future [1].

Offshore Renewable Energy is a great challenge for the future. Oceans can be used to produce clean energy and reduce carbon emissions. These natural resources can provide renewable sourced energy. Using adequate and modern technologies, oceans are important sources of available energy:

- Offshore Wind Energy
- Wave Energy
- Tidal Energy (Tidal Marine Current Energy or Tidal Barrage Energy)
- Thermal Gradient Energy
- Salinity Gradient Energy

The World Energy Council [5], [6] estimated a value of available power greater than 2TW for energy production. From the different ocean energy resources, wave energy is the largest of the sources of the oceans, and is far from commercial exploitation.

Table 1.1 presents the estimated available energy for production, by the different types of conversion mechanisms.

Type of source	Anual theoretical Energy
Thermal Gradient	10.000 TWh/year
Tidal (Marine) Current	+800 TWh/ year
Tides	+300 TWh/ year
Waves	8000 to 80.000 TWh/year

"Table 1.1 - Estimated global resources for different technologies (TWh/year) [5], [6].

1.1. OFFSHORE RENEWABLE ENERGY SYSTEMS HISTORY

1.1.1. OFFSHORE WIND ENERGY

Offshore Wind Energy is a key to achieve the world's future energy demands, to avoid environmental and climate changes, to develop a new worldwide leading technology and to create a new renewable energy economy. With adequate political strategies, Europe has the opportunity to be a world leader in offshore wind power technology. Figure 1.4 displays an offshore wind farm.

Offshore Wind Energy is an unlimited energy resource, which, for electricity production purposes, does not emit greenhouse gases, enables reduction of fuel imports and can create thousands of new jobs in offshore advanced technologies. Europe's offshore wind potential is enormous and over 100 GW of offshore wind projects are currently under development.

As it has been said before, wind energy powered pioneer sailors that discovered new continents.

Sailing ships have been using wind power for thousands of years, and new continents and cultures were discovered by explorers from all over the world, using wind as the main source of energy for transportation.

The wind wheel of the Greek engineer Heron of Alexandria in the 1st century AD is the earliest known device of using a wind-driven mill to power a machine [8].

The first windmills were in use in Persia at least by the 9th century and possibly as early as the 7th century [8]. The use of windmills became widespread across the Middle East and Central Asia, and later spread to China and India.

In July 1887, Professor James Blyth, in Marykirk, Scotland built a cloth-sailed wind turbine and used the electricity it produced to power the lights in his cottage. His experiments culminated in a UK patent in 1891.

Figure 1.4 – Example of an offshore wind farm [7].

Wind turbines to generate electricity and pump water were widely used since the Industrial Revolution. Figure 1.5 shows an advertisement of a commercial windmill for pumping and electricity generation.

In 1956 Johannes Juul, built a three-bladed turbine (200 kW), at Gedser in Denmark, which influenced the design of the contemporary wind turbines.

Wind turbine production has expanded all over the world and wind power is expected to grow worldwide in this century, mainly in offshore wind plants.

The first offshore wind farm opened in 1991 in Vindeby, 2.5 km from the Danish coast. Developed by DONG Energy, the park consists of 11 turbines of 450 kW (4.95 MW of total capacity) [9].

The largest offshore wind farm is the "London Array 1 Offshore Wind Farm" with a total capacity of 630 MW (date of commissioning: April 2013) [10].

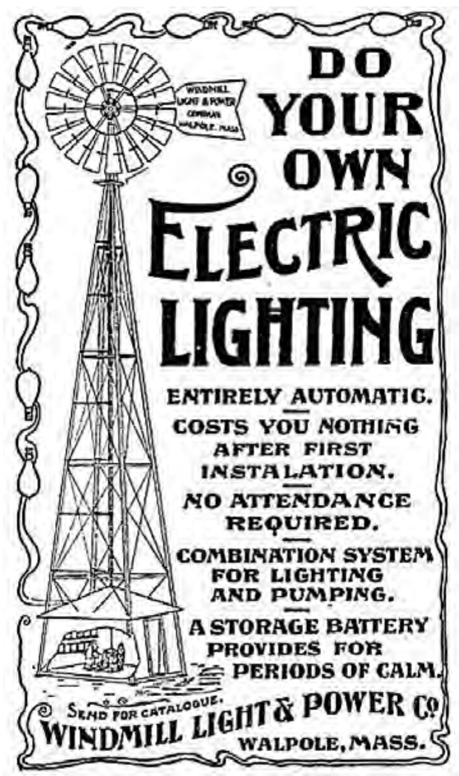


Figure 1.5 – Example of an advertisement for a win-powered electric lightning system, 1987 [8].

For coastlines with deep coasts, new Floating Structures are being developed today, for future offshore wind farms. It is the case of the full scale prototypes in operation SPAR, established in 2009, in Karmøy, Norway, with a 2.3 MW turbine from Siemens or the semi-submersible project Windfloat in Portugal, Aguçadoura, installed in 2011 with a turbine of 2 MW Vestas [11].

For offshore wind energy large turbines have been developed and are ready for commercial use like REpower 6M - 6 MW [12], rotor diameter of 126 m and Samsung S7.0171 - 7 MW [13], 196 m height, in Scotland.

Currently there is not yet any commercial version of vertical axis turbines for offshore environment. However, VertAx Wind Ltd., a company created in 2007 is dedicated to the development of these devices for large production capacity [14]. It is expected that in 2014 its 10 MW product will be commercially available [14].

Innovative solutions are also being developed for wind energy production capable of harnessing the energy potential of high altitude wind using aerodynamic lift. The absence of an "equivalent" wind tower or elevated nacelle renders installation and functioning much simpler and dramatically reduces cost. The Boreas, developed by Omnidea, is a device for the harnessing of wind power at high altitude, with high potential for use in the offshore environment. It was patented in 2007 [15] and the testing of its first prototype took place in 2011.

Many other innovative projects are being developed like the Altaeros project, a horizontal axis turbine for use at high altitude wind and also for the potential use in offshore environment. This device was tested for the first time in 2012 [16].

The progress of Wind Energy in the last 10 years has been impressive.

The EU had 9.6 GW of onshore installed power in 1999. By the end of 2009, 72GW were reached. According to the European Commission's "New Energy Policy" projections for electricity demand in 2020, wind energy would meet 16.9 % of the EU electricity demand, including 4.3 % being met by offshore wind farms.

Figure 1.6 displays the growth rate expected for the wind energy capacity and the growing importance of the offshore contribution [7], [17].

Offshore Wind Energy production is growing consistently and reached 1471 MW in 2008 in 8 EU member states. In 2009, 2000 MW were reached and it is expected to achieve 3000 MW by the end of 2010, with 11 TWh of electricity production, and 0,3% of total EU electricity demand, avoiding 7 million tons of CO2 emissions.

The EWEA – European Wind Energy Association has a target of 230 GW of Wind Power capacity in the EU by 2020, including 40 GW of offshore wind installed power, with an average annual market growth of 28% over the next twelve years [17]. With this target, 148TWh of electricity would be produced in 2020, representing 4% of EU electricity demand. For 2030 the offshore target is of 150 GW, with an impressive annual growth of installed capacity [7], [17], reflecting an annual production of electricity reaching 580 TWh in 2030.

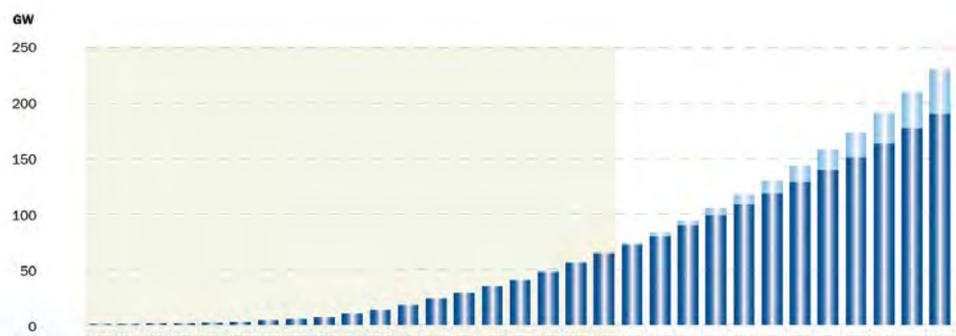
Offshore Wind Potential is enormous. The winds are stronger and more constant; the turbines can generate electricity 70% to 90% of the time. The available area for wind farms is much larger than in land and the wind resource is also more interesting [1].

The offshore wind energy farms will go in the future beyond the classical 20:20 (20 meter depth, 20 km from shore), up to 350 m depth and up to 140Km from shore, with new technological solutions, new substructures, new support ships for maintenance and construction and even new offshore artificial harbours [1].

Especially for countries with steep shores and that rapidly reach depths in which existing offshore installation is not possible, offshore wind energy development will surely follow this path. Figure 1.7 presents the prototype of WindFloat installed in the north of Portugal.

1.1.2. WAVE ENERGY

The origin of wave energy, created by the effect of the wind on the ocean surface, is the result of the redistribution of solar radiation in the atmosphere.



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Offshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.5	0.6	0.7
Onshore	0.4	0.6	0.8	1.2	1.7	2.5	3.4	4.7	6.4	9.6	12.9	17.2	22.8	28.0	33.8	39.8
TOTAL	0.4	0.6	0.8	1.2	1.7	2.5	3.5	4.8	6.5	9.7	12.9	17.3	23.1	28.5	34.4	40.5

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Offshore	0.9	1.1	1.5	1.9	3.0	4.5	6.5	8.9	11.6	14.7	18.3	22.4	27.2	33.1	40.0
Onshore	47.1	55.4	63.5	71.6	79.5	88.9	98.3	107.9	117.9	128.3	139.2	150.8	163.3	176.4	190.0
TOTAL	48.0	56.5	64.9	73.5	82.5	93.4	104.7	116.7	129.4	142.9	157.5	173.2	190.5	209.5	230.0

Source: EWEA

Figure 1.6 – Cumulative EU wind power capacity (1990 – 2020) [7], [17].

Typically, the power carried by the waves is measured in kilowatts per meter of wave front (kW/m). Figure 1.8 shows the distribution of the potential energy in the planet attributed to ocean waves. The highest values occur in the same regions of the globe, especially in both southern and northern Atlantic and Pacific Ocean.

The earth's temperature variation due to solar heating, combined with several atmospheric phenomena, generate wind currents in a global scale. The energy of the ocean waves is created through complex wind-ocean surface interactions.

Ocean waves' origin, propagation and direction are directly related to global wind dynamics. Wave energy is the largest of the energy sources of the oceans, and is far from commercial exploitation. Kinetic and potential energy associated with ocean waves can be harnessed using modern technologies.

It is estimated [19] that the power resource available in surface waves on a global level would be approximately 10 to 100 TW for depths greater than or equal to 100 m.

The conversion of wave energy seems simple and has motivated more than 1000 patents registered by 1980 [20], [21], [22], [23], [24]. Nevertheless, today, the challenge is far from being solved and future developments are needed to achieve a commercial stage of wave exploitation.

The first registered patent for wave energy conversion dates from Girard, in 1799 [25].

In 1910, the French Praceique-Bochaux developed a home device in Royan, based on a Oscillating Water Column (OWC) device to produce electricity [20].

In 1940, Yoshio Masuda, a former Japanese naval officer developed a navigation buoy powered by wave energy, equipped with an air turbine, which was later named a (floating) oscillating water column (OWC) device [20].

Following his research, Masuda promoted in 1976 the construction of a larger unit, called Kaimei, used as a floating testing platform, housing several OWCs [20]. Unfortunately, the power output levels of this unit were under the expectations.

Michael E. McCormick, of the U.S. Naval Academy, was another pioneer who did important research in OWC systems in the early seventies. McCormick was the author of the first book devoted to this subject [26].

Figure 1.7 - WindFloat Project in the Northern Coast of Portugal.

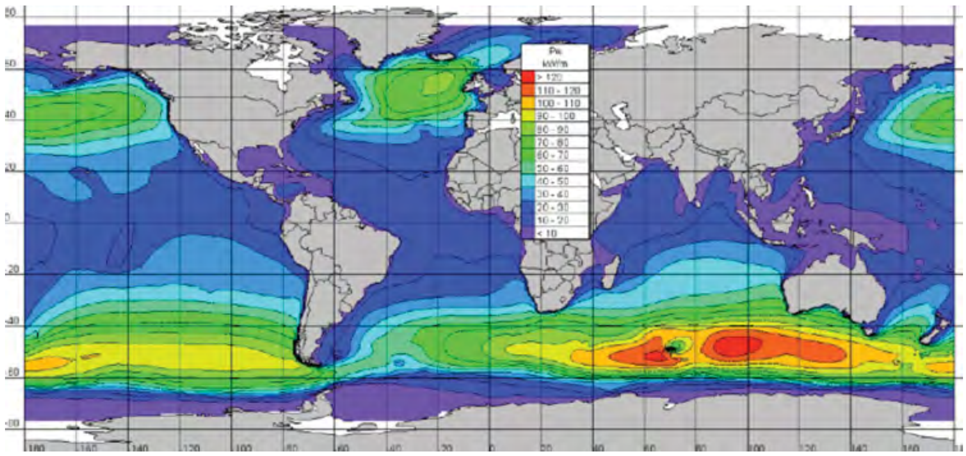


Figure 1.8 – World distribution of mean annual wave energy potential [18].

During this period, Stephen Salter, of the University of Edinburgh, proposed a different principle for Wave Energy Conversion, known as the Duck [20].

The oil crisis of 1973 induced an enhanced interest in wave energy conversion systems and in 1975, the British and Norwegian Government started an important research and development program in wave energy conversion systems [20].

In the 80s, new research and investments lead to the construction of IPS buoy, in Scandinavia, Hose pump device, in Sweden (1982), and Heaving buoy, in Norway (1983) [20].

In 1985, the Norwegian government constructed a large-scale wave conversion unit at Toftestallen. The TAPCHAN ocean wave power plant at Toftestallen in Øygarden, outside Bergen, was finished in 1985, with 350kW. The installation was built by Norwave, which was started by Even Mehlum, amongst others, as a result of the wave activity at SI/SINTEF [27].

In 1990, a 60kW wave power generating system was installed by the First District Port Construction Bureau and Costal Development Institute of Technology in Japan, in a breakwater at Sakata port in front of the Sea of Japan. The system is composed of an air-chamber, a turbine-generator, and a safety system [28].

In the same year, the Indian wave energy plant at Vizhinjam was constructed to demonstrate wave energy conversion into electrical energy using the Oscillating Water Column (OWC) principle [29].

The wave energy conversion is a hydrodynamic process of considerable complexity and this explains most of the failures of many inventors.

Due to its enormous potential, the European Commission included wave energy in their R&D program on renewable energies. The first projects started in 1992 and since then, the European Union has granted many projects on wave energy conversion.

The International Energy Agency (IEA-OES) established, in 2001, an Implementing Agreement on Ocean Energy Systems whose mission is to facilitate and coordinate ocean energy research, development, and demonstration through international cooperation and information exchange [5], [6].

Figure 1.9 – OWC Pico Power Plant, Ilha do Pico, Azores, Portugal [30].

In 1999 researchers from Instituto Superior Técnico, Lisbon, Portugal, built a wave energy converter on the coast of Island of Pico, Azores, (400 kW) [20], [30] (see Figure 1.9).

This unit is one of the first and few world wave energy production units in actual production on the Ilha do Pico, Azores, Portugal [20], [22], [30].

Portugal is located in an oceanic region with a medium-high potential, due to its annual average wave energy estimated at 40 kW/m. There are other factors which classify Portugal as one of the most favourable countries for the installation of wave energy conversion systems. Weather conditions, the existence of network connection points along the coast, the deeper waters near the coast, a tradition in the marine industry with good infrastructures and being located near the potential local power plant farms, with two official pilot zones for wave energy testing (Figure 1.10) [22], [31] are some of factors which have attracted several developers to the Portuguese Atlantic Coast.

The Aguçadora wave farm, located in the North of Portugal (composed of a Pelamis device) was

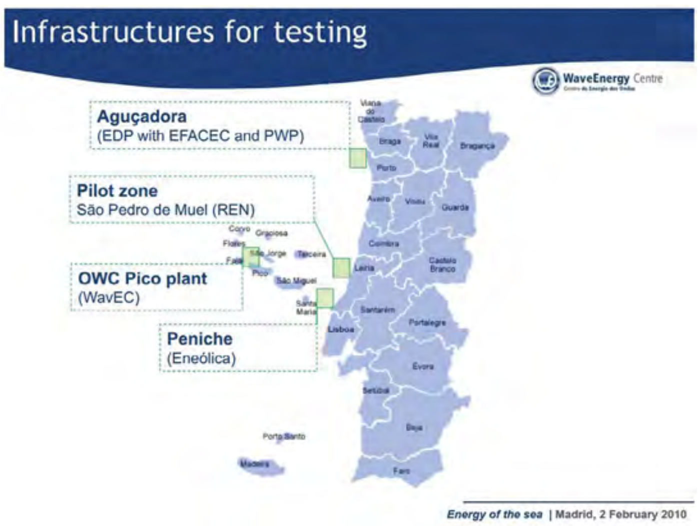


Figure 1.10 – Portugal's pilot zones created for wave energy testing in 2008 [22], [31].

Figure 1.11 - AWS MK I ready for departure at the Leixões harbor, Portugal, and future AWS MK II [33].

the first commercial wave farm in the world, with an installed capacity of about 2.3 MW [31],[32].

Another wave technology that was also tested in 2004 in Portugal is the 2 MW AWS MK I test platform, also in Aguçadoura. The primary extraction mechanism was tested together with the linear generator capability. AWS, Arquimedes Wave Swing, is a point absorber, harnessing the power of the wave due to the motion of a floating vertical cylinder and continues to be developed. A new AWS MK II is to be tested in Scotland [33] (Figure 1.11).

The Pelamis project[32] reached the most advanced status in wave energy development, through several upscales and test tanks. It is the world's first operational wave farm, with 3 Pelamis devices, each with 750 kW and installed offshore in Northern Portugal in 2009. Each device is made up of 4 cylindrical segments, with an overall length of 150 m and a diameter of 3 meters, with hydraulic

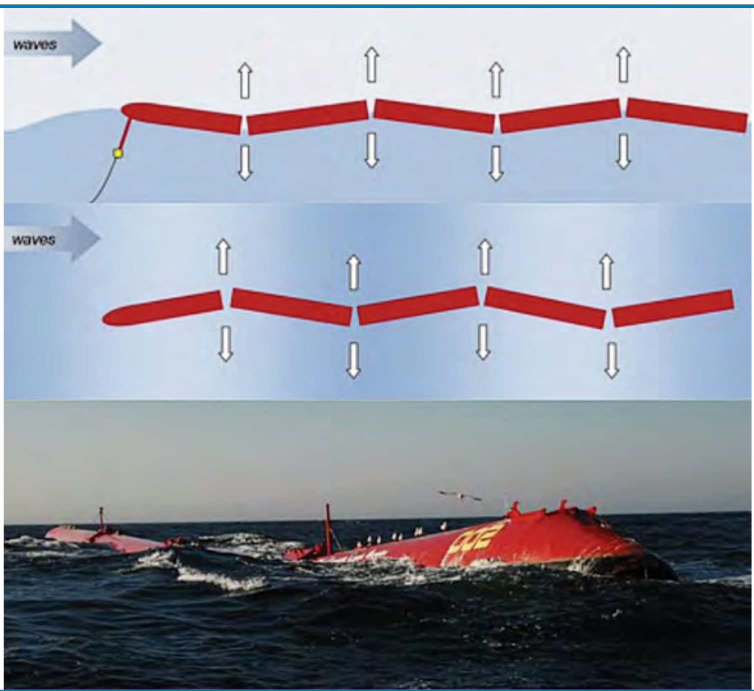


Figure 1.12 – Pelamis device [32].

Power Take Off (PTO) mechanisms, installed at the interconnections. Several technical problems related to these joints forced the wave farm to stop operational tests and the complete device is currently in the harbour for inspection and repairs. Presently, a Pelamis II device type is being developed, and will be installed in Scotland [32].

Figure 1.12 shows the Pelamis device in operation, the interconnections and the operation methods.

Also, in Peniche, Portugal, in 2012, a new device was installed for wave energy conversion, the WaveRoller property of AW-Energy (3 Units of 100kW each)[34]. The WaveRoller device is a plate anchored to the bottom of the sea.

The back and forward movement of surge moves the plate. A hydraulic piston pump collects the kinetic energy transferred to this plate (Figure 1.13).

The Oyster, Figure 1.14, shares the concept of a wing moving within the water column, but makes use of the full depth and was designed for near shore installation, according to the manufacturer, Aquamarine Power. A prototype with a wing area of 180 m2 and 350kW of expected capacity is presently installed in Scotland, whilst an Oyster 2 is being developed [35].

The Wave Dragon overtopping device elevates ocean waves to a tank above sea level where water is let out through a number of turbines and in this way transformed into elec-tricity, i.e. a three-step energy conversion [36].

Real sea tests at a scale of 1:4.5 have been performed in Denmark for more than 4 months. The

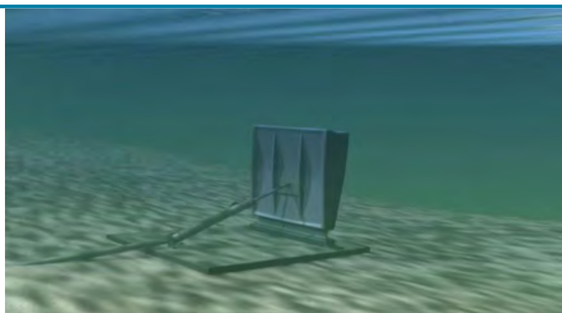


Figure 1.13 – Waveroller installed in Portugal [34].

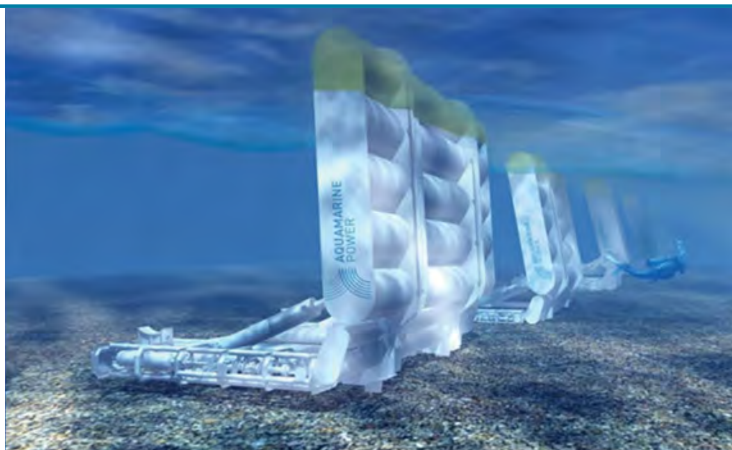


Figure 1.14 – Oyster wave farm [35].

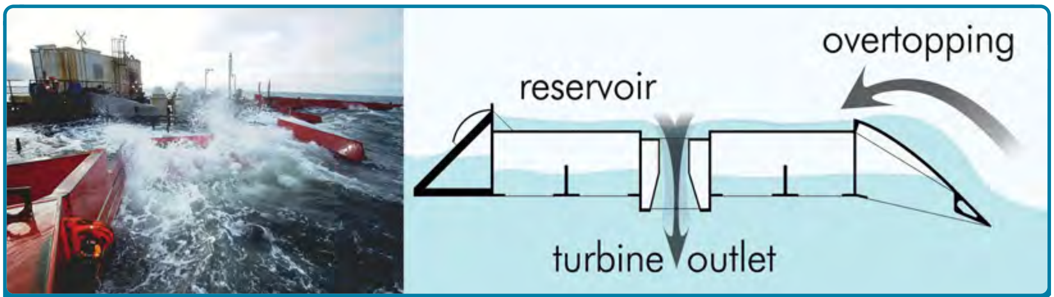


Figure 1.15 – Wave Dragon prototype in sea operation [36].

arms of an operating unit form a 300 meter open area which collects the water to the basin, with the turbines located more than 150 meters away, Figure 1.15. Several wave dragons can be combined to operate as a wave farm.

The FO3 is a device which gathers under a floating platform a set of point absorbers of smaller dimensions (Figure 1.16). The project is based at the Oil & Gas technology standard platform knowledge and uses more advanced materials and the point absorber technology to maximize the strength of the platform. The 1:3 test platform survived considerable storm conditions in Norway in early 2005 [37].

The Oceanlinx is an Australian born technology which is a floating application of the oscillating water column principle, OWC [38]. The wave motion is concentrated in a chamber connected to a Denniss-Auld turbine through which air is vented, with alternated flow directions due to the oscillation of the water column. The turbine is specially designed to maximize power take off and to guarantee the unique direction of rotation, despite of the alternated airflow. Successful 500kW prototype was tested in 2007, but in May 2010, a MK3 prototype at Port Kembla's was destroyed after breaking free from its moorings (see Figure 1.17).

The Wavebob is a point absorber technology which takes advantage of the heave motion to harness energy [39]. Next tests are scheduled for Portugal, under a FP7 financing program, and with a rated capacity of over 1MW test units. Figure 1.18 shows the main structural components with an impressive floater tank.

Figure 1.16 – FO3 project, wave tank tests [37].

Figure 1.17 – Oceanlinx schema and 2007 disaster [38].

Unlike the wind energy, where three bladed horizontal axis turbines are dominant, no distinctive technology is dominant up to now and further developments and investments are necessary to achieve one or more mature proven technological solutions. At the moment, no technology has achieved a commercial stage.

Many different technologies are available and being tested, depending on the type of movement (rotational and translational), on the methods of extraction of energy (hydraulic, mechanical, pneumatic and electric), on the location (on the coast, near the coast and away from the coast) and position (on land, floating and submerged).

Comparing onshore wind energy, offshore wind energy and wave energy, it can be seen (Figure 1.19) that these technologies are at different maturity stages and not in the same state of development in all countries. Portugal is amongst one of the first countries to contribute to wind energy (onshore) development and is leading in the development and is leading the development of wave energy [24].

Figure 1.20 presents different types of technologies installed worldwide for ocean tests.

Figure 1.22 presents a global view of the main wave energy conversion technologies presently being tested and developed around the world [31] – [38].

Figure 1.18 – The Wavebob ongoing ocean tests and harbor operations [39].

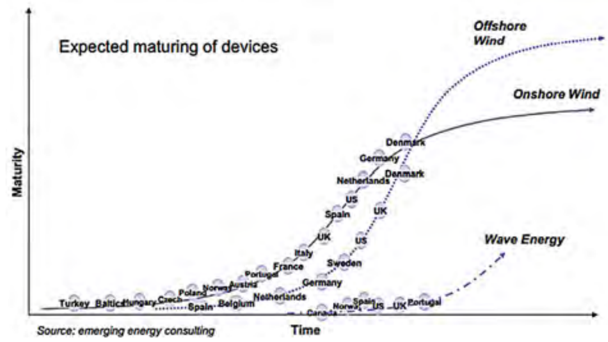


Figure 1.19 – Maturity stage of different offshore and onshore energy technologies in different countries [24].

Figure 1.20 – Main technologies already tested at sea conditions worldwide [5], [32]– [39].

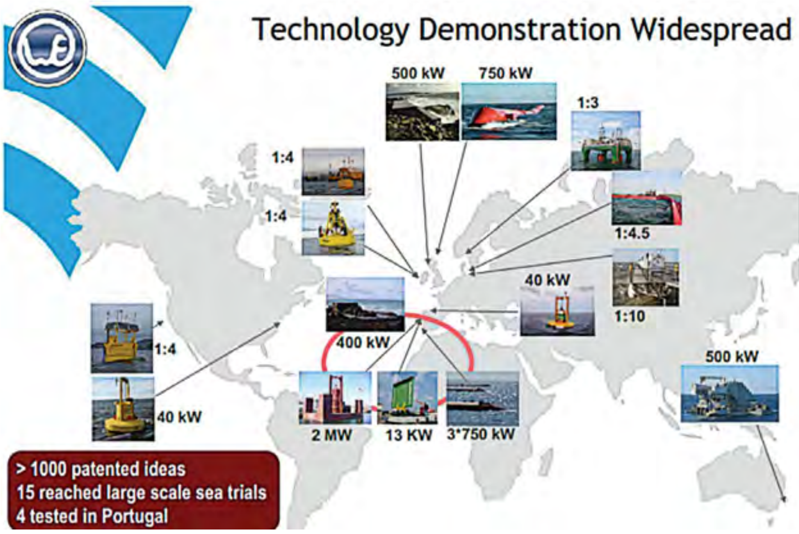


Figure 1.21 – Wave energy developments around the world [23].

1.1.3. TIDAL ENERGY

Tidal dynamics can be used to produce tidal energy in 2 different manners. The first is to use local tidal currents. The second is to use the rise and fall of the sea level.

The kinetic energy present in tidal currents, which designates the horizontal movement of water existing in the oceans, rivers, bays and ports under the influence of tide, wind and density differences, can be transformed into electrical energy. The technical solutions similar to those used in wind turbine, using horizontal or vertical axis turbines located at the surface, submerged or fixed to the seafloor.

This type of energy, when compared with wind energy, has a greater amount of energy due to the density of the water [40]. The technical tidal stream energy in Europe is estimated at about 36TWh/y, 20-30% of known global resource [41].

The commercial exploitation of tidal marine current energy needs to solve difficult problems [42] related to installation, survivability and maintenance of the systems. Although a the large amount of prototypes developed (Figure 1.22), only a few achieved a full commercial successful operation and there is still a need for further technological developments.

Tidal energy results from the rotation of the earth within the gravitational fields of the moon and the sun. The potential energy obtained by the difference in tide height, can be converted in energy through floating or fixed devices in estuaries or oceans. The production of electricity is obtained by exploring the differences between the water level upstream and downstream of the dam, causing a flow of water by opening its floodgates, forced by gravity to actuate the turbine [42], [43]. Figure 1.23 shows a worldwide view of tidal energy potential.

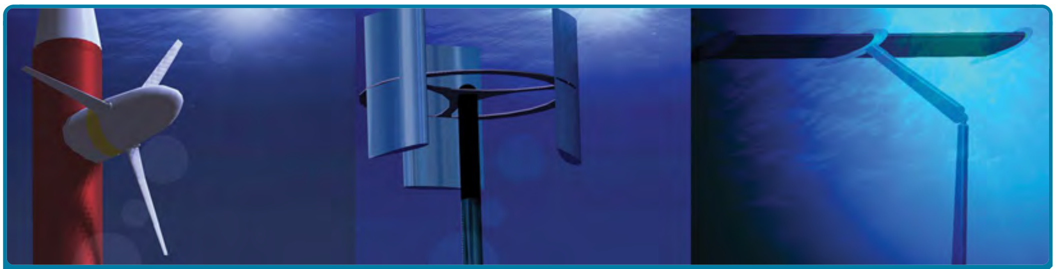


Figure 1.22 – Tidal marine current energy converters [40].

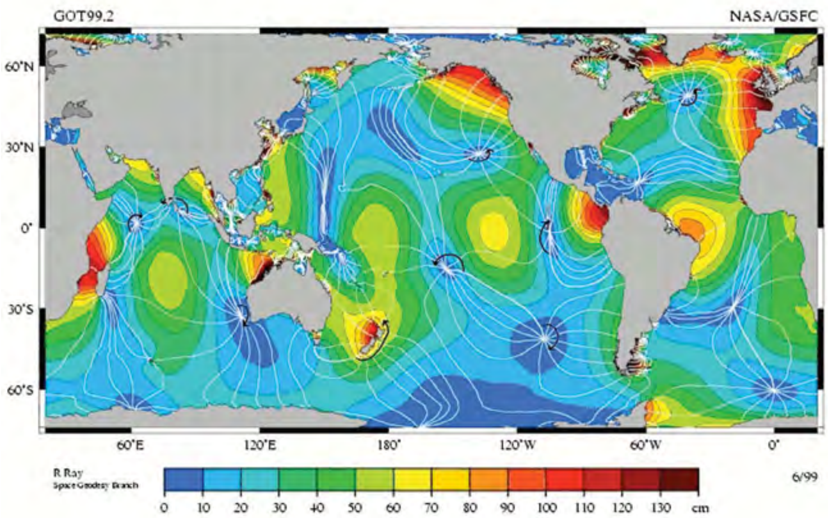


Figure 1.23 – World map with tidal energy gradients [43].

The first way to harness tidal power is to make its containment. In 1966, the construction of the dam of La Rance in France finished. This was the first dam of its kind and it is currently the second largest in production capacity (240 MW) [44].

In 2011, South Korea built a dam to contain more tidal power (254 MW), the Sihwa Lake Tidal Power Station [45].

In 2004, the tidal turbine from Hammerfest Strom HS300 was installed in Kvalsund, Norway, and was the first to be successfully connected to the grid. With a production capacity of 300 kW, it operated for 4 years. Its development allowed the same company later to create the model of 1 MW, the HS1000, which is currently being tested at EMEC (Figure 1.24) in Orkney [46], [47].

The MCT SeaGen, with a capacity to produce 1 MW, was the first system of harnessing energy from tidal stream developed on a commercial scale [48]. SeaGen was connected to the grid in July 2008 in Strangford Lough, in Northern Ireland. This was the result of a previous successful project (developed in 2003), the Seaflow 300 kW [49].

Figure 1.24 – Photo of OTEO project team in EMEC, Orkney, 2013.

Both SeaGen and HS1000 are horizontal axis turbines. In 2001 Kobald Turbine started production in the Strait of Messina on the Sicilian coast, a model of vertical-axis turbine of 30 kW [50].

Other new and promising developments are being carried like Pulse Tidal devices with oscillating hydrofoils (Humber River, UK, 2009) [51], or The OpenHydro, a turbine in a duct which has been tested in the EMEC's facilities [52]. The developments of this model continued in Nova Scotia, Canada. More recently, OpenHydro in partnership with Electricité de France began testing a new turbine with 2 MW in Paimpol - Brehat.

One of the most innovative concepts for harnessing energy from tidal currents is the Archimedes screw (Figure 1.25), developed by Flumill [53]. EMEC has already tested this concept and there are plans for developing a network connected to the Rystraumen facility near Tromsøn in Norway [47].

Another innovative concept is the Parrot Tide (Figure 1.26), from Minesto [54]. In 2012, a 1:10 scale prototype scale was installed in Stragford Lough, in Northern Ireland. The installation of this full-scale equipment could produce between 120 kW and 850 kW, depending on the speed of water flow.

Figure 1.25 – Archimedes screw, developed by Flumill [53].

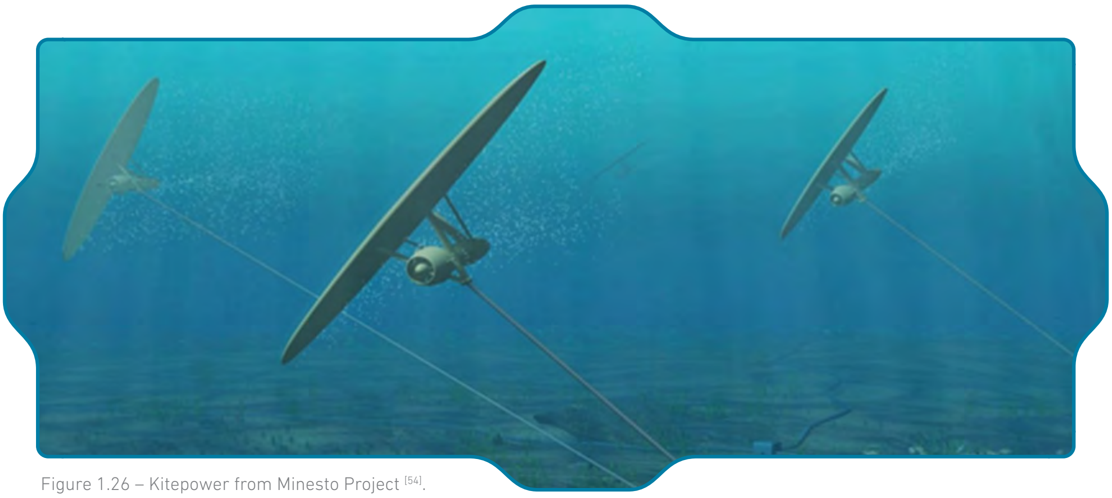


Figure 1.26 – Kitepower from Minesto Project [54].

1.1.4. THERMAL GRADIENT ENERGY

Thermal energy due to the temperature gradient between the sea surface and deepwater can be harnessed using different Ocean Thermal Energy Conversion (OTEC) processes. Ocean Thermal Energy Conversion (OTEC) can be used to generate electricity, desalinate sea water, support deep-water aquaculture, as well as aid the growth of fruit and vegetables and mineral extraction [55]. Due to the cost of installation, this technology is still at an early stage of development.

The first reference to the use of energy from ocean thermal gradient to produce electricity is the work of Jules Verne's "20.000 Leagues Under the Sea" in 1970 [56].

In 1881, the first proposal for OTEC system came from the French physicist Jacques Arsene d'Arsonval. His concept was based on the Rankine thermodynamic cycle.

In 1930, Georges Claude (d'Arsonval's student) built the first OTEC system in Matanzas, Cuba. However, this system used water from the ocean surface as the working fluid in its proposed cycle - the Claude cycle. The center was operated for several weeks until it was destroyed by a storm but with a production below the desired power (22 kW [57]) due to a poor choice of location. An interesting feature of the proposed Claude system is its ability to produce desalinated water [56].

The energy crisis in 1973 triggered an increasing interest in developing this technology. In 1979 the concept proposed by D'Arsonval was demonstrated in Hawaii, the "Mini-OTEC" project. The power unit had a gross output of 50 kW, 18 kW of nominal power, and was mounted on a floating platform. The period of operation was a few months, just to test the concept[56].

The first installation of the closed-cycle OTEC onshore, producing power for the grid, was developed by a consortium of Japanese companies in the Republic of Nauru during the 70s. This unit became operational in 1981 and had a gross output of 120 kW (30 kW of nominal power). The period of operation was also a few months [56].

In 1981, the Russian engineer Alexander Kalina first used a mixture of ammonia and water to produce electricity in an OTEC system. In 1994, Saga University designed and built a core of 4.5 kW to test the Uehara cycle, proposed by Uehara Haruo [57].

Between 1993 and 1998, in Hawaii, an OTEC closed cycle unit was installed, with a gross output of 255 kW. This facility was constructed to enable the production of desalinated water (0.4 liters/s of maximum production) and was the first installation with a hybrid cycle [56].

In March 2013, Saga University in partnership with various Japanese industries finished installing the only OTEC unit currently operating in the world. This device is located in Okinawa and has a production capacity of 50 kW for demonstrative purposes [58].

The temperature difference between the warm surface water and the cold deep water can reach more than 24ºC (Figure 1.27), which can produce a significant amount of power. It is estimated that the available resource is about 1013 Watts.

For countries which have a great dependence on imported fuel, and especially tropical countries, Thermal Gradient Energy has a promising future [5].

Figure 1.29 shows the schematic principle of an OTEC floating power plant.

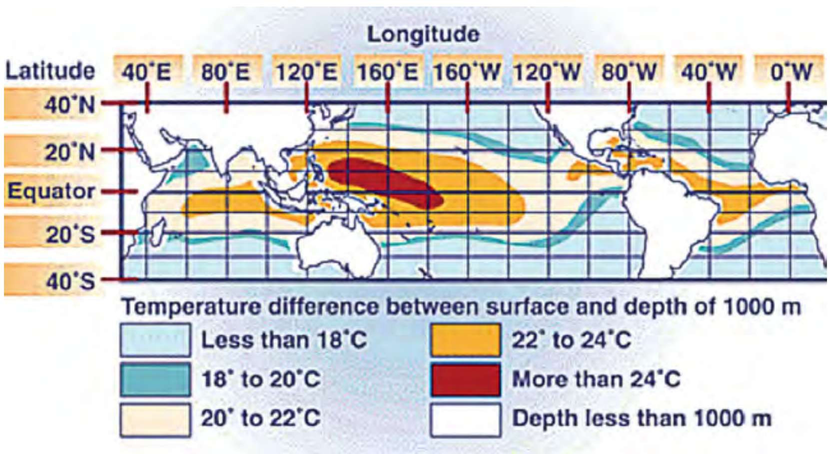


Figure 1.27 – World Map with temperature difference between surface and depth of 1000 meters [55].

Figure 1.29 – 1 MW [62] (left) and 30 kW [63] (right) OTEC demonstration devices from Saga University, Japan.

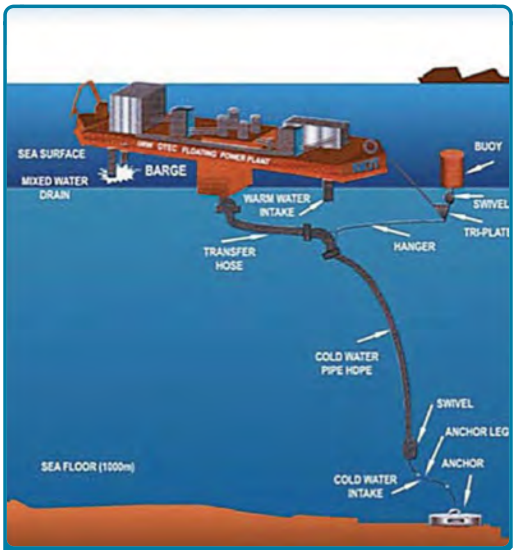


Figure 1.29 – Scheme of an offshore floating OTEC power plant [58].

1.1.5. SALINITY GRADIENT ENERGY

At the mouth of rivers where fresh water mixes with salt water, energy associated with the salinity gradient can be harnessed using a pressure-retarded reverse osmosis process and associated conversion technologies. The salt molecules move the fresh water through semi-permeable membranes, causing increased pressure in a tank of salt water and therefore the flow of salt water. The flow of salt water is used to drive a turbine which produces electric power [59].

From the flow of fresh water rivers into the ocean, it is estimated that in Europe, the potential osmotic energy is around 200 TWh/y [41].

Salinity gradient power tends to be a large attractive power resource, which is almost unexplored. Figure 1.30 shows an experimental research for osmotic salinity gradient energy conversion in Norway [59].

The first reference to the production of energy from the mixing of seawater with fresh water dates back to 1954, in a Nature article published by Pattle. The article published by Pattle had no immediate impact in the development of this technology. In 1973, the oil crisis truely aroused interest in power generation by pressure-retarded osmosis. However, it was not until the Kyoto meeting in 1997, that studies started in this area, especially after the sudden increase in oil prices in 2008 [60].

In 1974 Norman presented the first diagram for an osmotic power converter [60].

Figure 1.30 – Experimental research for osmotic salinity gradient energy conversion in Norway [59].

Loeb et al. published the first experimental results of pressure-retarded osmosis in 1976 and experimentally validated the concept [60].

In November 2009, over 30 years after the first experience with pressure-retarded osmosis, Statkraft opened the first prototype installation in Tofte, Norway, using the osmotic principle. This unit has a capacity of 10 kW. The company's plans are to build a plant of 25 MW in 2015 [61].

The process of reverse electro dialysis has been under investigation since 1978, by the Southern Research Institute in the United States. However, only in 1999 Wetsus and the University of Wageningen further investigated the concept in the Netherlands. In 2006 he created the REDstack, a spin-off company to commercialize Wetsus systems reverse electro dialysis. The first power plant of this technology was built in 2009, in Harlingen.

In South Korea, the Hongik University is developing a project funded by the government focusing on the development of key components of salinity gradient systems [61].

1.1.6. FUTURE PERSPECTIVES

In the future, special offshore energy harbours will have to be idealized in order to meet the great demands of this promising future market. Figure 1.31 shows a futuristic offshore energy harbour conceived at INEGI [1].

Other renewable ocean resource novel concepts are also being developed for energy uses other than electricity generation, such as, water desalination, oxygen production for aquaculture, and hydrogen production by electrolysis. The ocean

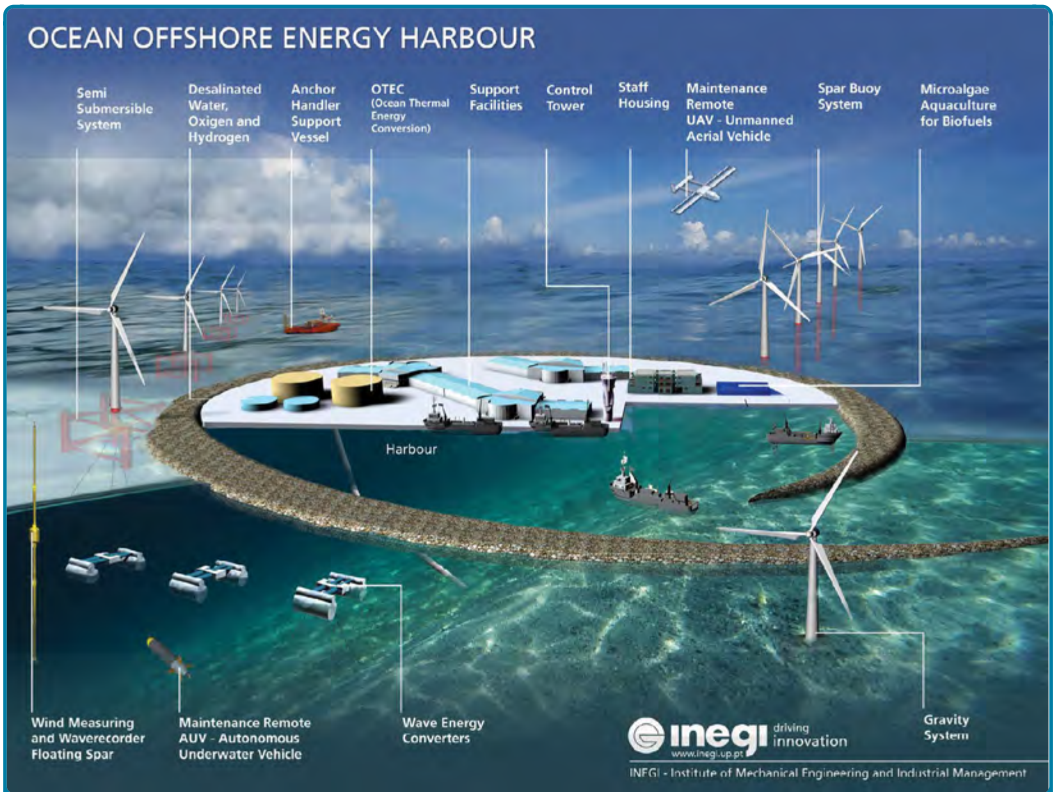


Figure 1.31 – Visionary concept of an offshore energy harbor. © INEGI [1]

renewable energy sector will gain significant attention throughout the world in the future.

Europe has the challenge of being the leader in developing technologies for Marine Energy production.

Portugal can play an important role in this challenge, in developing new technologies and testing these solutions on its coast. This country has a land extension of 92 212 km^2 and 15,3 Million citizens (10,5 million residents and 4,8 million emigrants).

Portugal has the 3rd largest Exclusive Economic Zone (EEZ) of the EU and the 10th largest EEZ in the world, with a total of 1,727,408 km^2:

- Continent = 327,667 km^2
- Azores Islands = 953,633 km^2
- Madeira Islands = 446,108 km^2

Portugal signed the 1982 United Nations Convention on the Law of the Sea on the day it was opened for signature and ratified it on 14th October 1997. The Convention came into force for Portugal on 3rd December of the same year, 30 days after its deposit with the Secretary-General of the United Nations. Portugal submitted to the Commission on the Limits of the Continental Shelf, in May 2009, the extension of the outer limits of its continental shelf, beyond 200 nautical miles [62].

After the approval of this resolution, to extend its jurisdiction over an additional 2.15 million square kilometers of the neighbouring continental shelf, Portugal will have an ocean continental shelf with a total of more than 3,877,408 km^2, which represents 40 times its continental land area and will be the 10th largestin the world and the 3rd in Europe (Figure 1.32 and Figure 1.33).

Offshore Energy is unlimited, it will never become a limiting factor, and there is enough space and energy over the seas of Europe to meet Europe's global electricity demand in the future [1].

This book presents an overview of offshore energy and the state of the art of the technologies for its implementation. Selective conversion technologies and demonstration projects worldwide are presented as well as new concepts to be developed to assure the success of these new technologies.

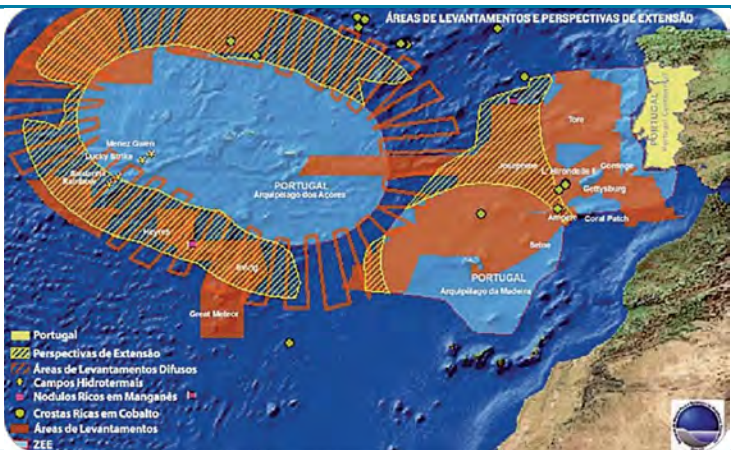


Figure 1.32 – Portuguese submission to the Commission on the Limits of the Continental Shelf, United Nation, in May 2009 [62].

Figure 1.33 – Portuguese limits of the Continental Shelf [63].

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OFFSHORE RENEWABLE ENERGY

2

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She has been active in R&D in ocean energy for twenty years, initially involved in the wave energy group of the Department of Mechanical Engineering at Instituto Superior Técnico and since 2004 integrated the newly formed WavEC non-profit association. At WavEC she has been responsible in these later years for several consultancy services for international clients.

She has been since 2002, Secretary of the Executive Committee of the Implementing Agreement on Ocean Energy Systems of the International Energy Agency. She is further a member of the executive committee of the International Conference on Ocean Energy (ICOE).

2.1. RESOURCES

OffshoreRenewable Energy is an umbrella term which refers to any ocean energy resource as well as offshore wind and marine biomass.

There are several marine sources from which energy could be extracted:

- The most familiar ocean energy resource is ocean waves caused by the wind as it blows across the surface of the ocean.

- But the oldest form of energy used by humans is tidal energy. This resource is associated with a periodic rise and fall of the tide, due to the gravitational attraction of the moon and the sun.

- The rise and fall of tide is accompanied by horizontal movement of the water called tidal current (or tidal stream). Kinetic energy can be harnessed, usually in coastal regions and particularly where there is a constraining topography, such as straits between islands.

- In addition to tidal currents, there are also oceanic currents which are not related to the tidal movement: these include the permanent currents in the general circulatory system of the oceans as well as temporary currents arising from meteorological conditions.

- The sun's heat warms the surface water thus creating a temperature gradient, or thermal energy which can be harnessed through a process called ocean thermal energy conversion (OTEC) which uses the difference in temperature between the warm surface of the ocean and the cold ocean deep water.

- The mixing of freshwater with the salty ocean, at river months, releases large amounts of energy. Osmotic power or salinity gradient power is the energy available from the difference in the salt concentration between sea water and river water.

- High-temperature water from hydrothermal vents on the deep ocean floor is also a source of energy known as submarine geothermal energy.

The IEA Ocean Energy Systems (OES) considers as ocean energy resources all ways to harness energy from the ocean, in which seawater forms the motive power, through its physical and chemical properties. However, in the ocean, other renewable energy resources can be harnessed, such as the winds above the water surface, known as 'Offshore wind' and by harvesting sea water plant biomass, Marine Algae Biomass (to be distinguished into Microalgae and Seaweed).

Globally the potential ocean energy resource is substantial, though it varies with location and some coastlines are more suited than others. As it can be seen in the maps below (Figure 2.1), wave energy is principally distributed in the temperate zone of the globe, in particular between latitudes of 40° - 60°, while ocean thermal energy is principally distributed in tropical and subtropical waters (0° – 35°). Other ocean energy resources, such as tidal energy, currents and osmotic power, are globally spread and very site specific.

The IPCC report refers to a global theoretical potential for ocean energy technologies of 7400 EJ/year and states that "the theoretical potential for ocean energy easily exceeds to present human energy requirements"[2].The theoretical energy resource is an important indicator of the potential market for a specific source of renewable energy. However,the resource that can be exploited is significantly reduced considering existing technology options, external constraints (grid accessibility, competing uses, maritime protected areas, shipping lines, etc.) and economic considerations. On a national level, efforts to estimate accurate technical potentials for ocean energy have been done in recent years, but still only relatively few assessment exists.

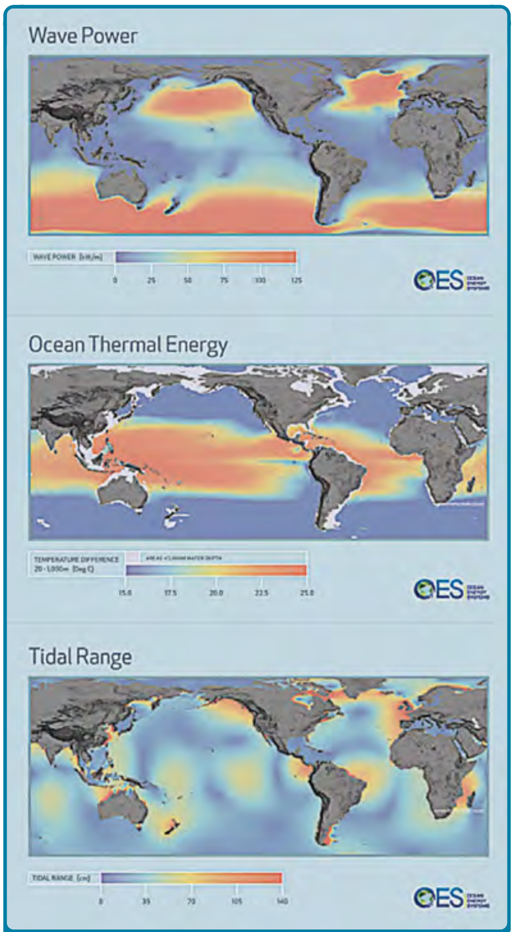

Figure 2.1 - Global distribution of wave power, ocean thermal energy and tidal range [1].

Offshore wind resource has gained rapid popularity in the recent past mainly due to the fact that the maritime resource is larger than onshore, more consistent and less turbulent. The IPCC report refers to several estimates for the worldwide technical potential of offshore wind energy resource, much depending of the assumptions taken: Lu et al. (2009) estimates 540 EJ/year (150,000 TWh/year) at water depths less than 200 m and at distances less than 92.6 km from the shore, of which 150 EJ/year (42,000 TWh/year) is available at depths of less than 20 m, being remarked however, that this study does not consider many development constraints or exclusion zones.

2.2. OPPORTUNITIES & CHALLENGE'S

The world energy consumption has been steadily increasing, in particular in the industrialized societies and much of this energy is coming from non-renewable unsustainable resources. Concerns over the future access to fossil fuels and greenhouse gas emissions have focused research efforts on finding alternative sources of energy. The ocean offers a vast renewable energy source for countries around the world which have a suitable coastline available. The call for reducing carbon emission has been intensified since the Kyoto protocol in 1997, and EU has adopted ambitious targets for energy from renewable sources. Consequently, some countries have adopted renewable energy commitments in particular from wave, tidal and offshore wind resources.

The discussion of the opportunities and challenges rely on the status of technology. Tidal barrages have reached a mature phase and therefore they are not covered in this section, being the focus of this book, technology innovation. Emerging offshore renewable energies have been continuously progressing towards commercialization, over the last decade but still they are at a much earlier stage of development compared to the other RE and the prospects of large scale commercial developments are still some years away. Currently, a relatively large variety of prototypes are being tested at sea.

Speaking in very broad terms it can be said that Offshore Renewable Energies, as a new industry, have the potential to create jobs and business opportunities. There is a significant opportunity for the countries to develop the workforce capable of supporting the technological developments. This includes manufacturing and providing operations and maintenance services over the life time of project deployments.

Looking at the wind industry, one of the fastest growing industries in Europe, the economic benefits from this sector for Spain, Denmark and Germany are well known. These three countries account for more than 90 percent of the EU's wind-sector employees.

A recent report by RenewableUK and Energy & Utility Skills looked into employment in the UK from the wind, wave and tidal energy sectors. The report "Working for a Green Britain & Northern Ireland 2013-23"[3] reports that the wind, wave and tidal energy sector directly employs in UK 18,465 people full time and when including indirect jobs (companies which supply goods and services to the sector) over 34,000 people are employed. The study shows that the offshore wind sector had the biggest growth between 2010 and 2013, with the number of direct jobs doubling from 3,151 to 6,830. A further two important findings in this report are highlighted: SMEs are experiencing growth, so this business is not only for big companies; and this new sector is characterized by a highly skilled workforce, related with the current development stage of the industry and therefore this represents an opportunity to create pools of qualified and available people. Looking towards the future, the report predicts that in the UK more than 70,000 jobs could be created over the next decade, nearly half of which would be in offshore wind.

The Sustainable Energy Authority of Ireland and Invest Northern Ireland commissioned a study to explore the potential economic opportunity from the industry and supply chain which could accompany the wave and tidal technologies' developments in Ireland [4]. According to the study there is evidence that by 2030 a fully developed ocean energy sector in Ireland could produce a total Net Present Value of around €9 billion and many thousands of jobs for the Irish economy. However this would require an appropriate level of investment in the sector. Both studies are just examples showing the contribution that Offshore Renewable Energies can make for national economies as an important source of employment.

Offshore Renewable Energy is becoming a field of great interest, not only because of offering a sustainable electricity generation but also because of the emergence of a new industry sector. However, this new industry faces a number of significant barriers in order to grow.

The main technical challenges are related with the insufficient experience and demonstration. There is a lack of information regarding performance, lifetime, operation and maintenance of offshore renewable energies in the sea environment. As long as there is insufficient experience, expensive offshore technologies have to be employed to survive in the marine environment.

A key milestone will be the installation and operation of the first array projects, which will help to clarify operational performance and costs. It is essential to understand the importance of different parameters on the overall performance, as the main driver for the development of the ocean energy arrays will be the cost of energy. This concern is the main focus of the European Commission FP7 Energy project for the "Optimal Design Tools for Ocean Arrays" (DTOcean) which was launched on 28 October 2013 with an overall value of over €6 million. This project is conducted by a consortium featuring 18 partners from 11 countries -utilities, project developers, supply chain companies and research teams - which will work together over the next 3 years aiming to accelerate the industrial development of ocean energy by providing shared-access design tools for the first and subsequent generations of wave and tidal energy converter arrays. A whole-system software design tools will be developed to enable the design, development and installation of arrays, which requires significant effort in a number of key areas: array layout, electrical system architecture, moorings & foundations, installation & logistics and control. One of the main objectives of the project is to provide the wave and tidal energy sector, with well validated guidelines for accelerating decisions by means of reducing risks and uncertainties.

In addition to the technical challenges, a major concern for project developers are barriers which are not directly related to the technology. Large-scale implementation will face a considerable number of obstacles. The term "non-technical" barrier is very often used in the context of the difficulties for the market penetration of renewable energy technologies in general. Within the EU funded project "Wave Energy Planning and

Marketing" (WAVEPLAM)[5] concluded in 2011, an attempt to identify and classify the most serious non-technical barriers for which solutions are still pending has been done with the aim of creating conditions to speed up introduction of wave energy onto the European renewable energy market. In the report "Non-technological Barriers to Wave Energy Implementation", six categories of non-technical barriers have been identified: financial incentives, regulatory issues, infrastructure and logistics, conflicts of use, environmental issues and public perception.

The most obvious barrier is cost. The current costs of offshore renewable energy technologies are considerably higher than conventional and other renewable energy generation. The key challenge common to all emerging offshore renewable energy technologies is directly related with the need to reduce the cost of energy. The article "Cost Reduction Pathways for Wave Energy"[6], highlights the need for strong RD&D programs to ensure technology innovation and lists several technological areas which could contribute to cost reduction, amongst them, the development of operation and maintenance strategies with lower costs, use of alternate materials and improved reliability. Research into lowering costs and improving performance of specific components in existing marine energy devices as well as next generation concepts, has been done by Carbon Trust in the UK working directly with industry leaders and technology innovators. The Marine Energy Accelerator program funded by DECC, which ran from 2007 to 2010 was a £3.5 million programme to understand and accelerate the cost reduction of energy extracted from wave and tidal stream resources and has shown that "significant cost of energy reductions can be achieved, ultimately making wave and tidal stream technologies competitive with other renewables. Cost of energy will fall as a result of experience and scale as installed capacity increases and also from technology innovation". The report also points out that a "continued focus on targeted innovation is required to bring costs down sufficiently, within a stable support environment". The result is a clearly defined pathway to achieve the cost of energy reduction needed to make these technologies competitive with other Renewable Energy technologies.

During the development of the wave energy project, WestWave (a 5 MW pre-commercial project planned in Ireland), ESB, Ireland's largest electricity utility, has established readiness, cost and performance criteria to guide suppliers of ocean energy technology towards viable, early project investment propositions [7]. Within this project, ESB concluded that while there are areas of significant cost and performance risk in the medium term, technical fundamentals indicate that ocean energy has the potential to meet the cost trajectory of other forms of renewable energy.

The topic costs reductions have been addressed by the Energy Technology Perspectives (ETP 2012), which is the International Energy Agency's main publication on energy technology. In this publication detailed scenarios and strategies until 2050 are presented aiming at demonstrating how technologies can in general make a decisive difference in limiting climate change and enhancing energy security. ETP 2012 highlights the dramatic cost reductions which are possible for renewables and give, as an example, the system costs for solar PV which have fallen by 75% in only three years in some countries [8].

Cost considerations are the most pressing concern for offshore renewable energies, which means that effective policies, legislation and implementation strategies are required. Without government support the market alone is not able to promote the introduction of new renewable energy technologies. The policy framework needs to be attractive for investors and the policy underpinning the targets must be transparent. In general, there are some generic obstacles related with the lack of transposing policy targets into concrete measures on an administrational level to speed up processes (in particular the so-called "one-stop-shop" approach). The difficulty and time framework required to obtain the necessary approvals for deployment and operation of offshore renewable energy projects is presently perceived as being the major threat to efficient implementation. In many cases the difficulties are mainly created by unfamiliarity with new technologies and their environmental effects in the sea.

The development of sea testing facilities for different stages of the development process is seen as a valuable measure at a governmental level. In addition, to direct support a funding scheme, such as feed-in tariffs, providing such infrastructure encourages ocean energy development by enabling practical experience of installation, operation, maintenance and decommissioning activities for full-scale prototypes and farms, as well as on services and streamlining procedures. Several initiatives of this type have been planned and conducted over the last years, around the world, following the successful expertise gathered in the European Marine Energy Centre (EMEC) in Scotland, since 2003. It has been pointed out, by relevant stakeholders, the need to progress from the demonstration level to commercial scale initiatives and the importance that these testing infrastructures can play in the actual stage of development: "Several ocean energy facilities in the open sea that have proliferated over the last years, mainly in European countries, are seen as the incubators for the development of prototypes, in which many problems will be faced and overcome (such as permitting, grid access, environmental monitoring, marine operations), thus catalyzing the growing industry of ocean energy"[9].

Port facilities will be required to support offshore renewable energy installations through the manufacture, construction and O&M stages of development. The experience with the use of port facilities so far has been very unique and not representative of the future requirements. Some countries have already identified the likely requirements for port infrastructure, aiming to accelerate their necessary effort to maximize the industrial and deployment benefits from the development of this new sector. In particular the Irish study "Review of Engineering and Specialist Support Requirements for the Ocean Energy Sector"[10] is a good example of exploring the engineering, infrastructure and logistics associated with the deployment of 250MW wave and tidal projects. Further, advances in vessel technology and cost-effective solutions to transport the components will be required and this particular issue discusses the offshore energy industry. The structure of the present electricity transmission network, unsuitable for large-scale, decentralized renewable energy generation, in particular in remote coastal zones, may be also an impediment. A recent study has been conducted in Ireland about the development direction of a potential offshore grid to guide future policy decisions regarding the long term offshore network's development [11]. In the context of large offshore wind farms, a inter-European subsea transmission grid network concept, has been widely discussed in the European Offshore Supergrid Project, proposed by Airtricity. However financial mechanisms for raising the capital to build this network are necessary.

As ocean energy technologies develop, synergies and opportunities with other engineering activities will need to be explored, such as engineering for oil or gas platforms, floating offshore wind, offshore aquaculture and others. Finding possible synergies can be a valuable contribution to accelerate the deployment of ocean energy. There is a growing interest in the synergetic use of ocean space. Multi-purpose floating platforms which could provide solutions for renewable energy production as well as for aquaculture and research and leisure purposes have been investigated. The Energy Island's concept has been addressed in particular by recent EU projects:

MARINA[12] and TROPOS[13] stipulate thatthere are also industry initiatives investigating joint floating offshore wind and wave platforms. In the ORECCA[14] project a preliminary assessment of the available sites for combined offshore wind and wave energy in Europe has been done.

Marine (or Maritime) Spatial Planning (MSP) may become a valuable process to explore and develop ocean-based renewable energy in the context of all ocean space and resource uses. Conflicts of use occur whenever there are traditional activities or existing designations of certain areas, making it difficult to introduce new players, even though this would not necessarily mean a conflict. Charles Ehler[15], a consultant to the Marine Spatial Planning Initiative of UNESCO's Intergovernmental Oceanographic Commission, in his very comprehensive explanation of Marine Spatial Planning, stated that while ocean energy has not been a principal driver of MSP so far, the situation is likely to change over the next two decades. Inclusion of offshore renewable energy requirements in MSP depends on the status of the industry in each country. MSP will have significant implications for the development of marine renewables, in general and for the ocean energy sector, in particular. On the other hand, policy developments are likely to influence the future development and functioning of MSP. These aspects are discussed by Anne Marie O'Hagan, a specialist in Marine Policy[16].

The major issue regarding environmental assessment of offshore renewable energy production is that, to date, there are still a large variety of devices and yet not much is known regarding potential environmental impacts. The high level of uncertainty regarding the potential effects of the technology on the marine environment is widely recognized. Several projects have been tested at sea but, on the one hand, possible environmental effects of these technologies have been dispersed amongst numerous developers and on the other hand different consenting regimes are in place in different countries which makes the Environmental Impact Assessment to be regarded as a non-technological barrier. This issue has been addressed on an international level, in these last 3 years, by the Implementing Agreement on Ocean Energy Systems[17]. The main findings of this research project, led by the USDepartment of Energy, was a publically-available, searchable online database called Tethys[18], containing environmental information relevant to the development and use of marine energy devices, which is seen as a first attempt to ensure that existing information and data about environmental monitoring are more widely accessible to those in the industry, governments and the public. On a European level there has been a further coordinated effort in the collection, analysis and discussion of the environmental data collected from the wave energy testing centers, with the SOWFIA[19] project. There is however a general opinion that it is still too early to assess whether impacts have been correctly identified and evaluated and whether proposed mitigation measures are effective[20].

Public awareness is one of the key factors which may interfere with implementation of offshore renewable energy projects across the world. It is a particularly sensitive matter and therefore substantial efforts have to be put into inspiring public confidence. This involves, in particular, promoting openness and direct contact with coastal communities and in a broader context, make the ocean known to the public as a huge, important and reliable source of energy.

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STATE-OF-THE-ART RENEWABLE ENERGY TECHNOLOGIES

3

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3.1. OFFSHORE WIND ENERGY

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3.1.1. INTRODUCTION

The present chapter covers issues specific to offshore wind. Space is here insufficient to go thoroughly through all the stages of the offshore's wind energy value chain but it is hoped, nonetheless, that the reader is provided with the most relevant information of the sector, current stage and expected future developments.

Offshore wind has, in the most recent years, gained a huge visibility within the context of renewable energy targets in Europe. Wind resource is quite interesting and the construction, particularly in the northern Sea seems more and more feasible.

However, both capital and operation expenditures are significantly higher than in offshore as are the risks and dimension of the projects. The cost of any deviations to the foreseen exploration of an offshore wind farm can result in an utter disaster.

Fortunately, and thanks to the commitment of several EU countries and to the fact that it used a stabilized technology, onshore wind, as a starting point for technology development, offshore wind has made a significant leap in the last few years making its own path. There is, nonetheless, much development to be done and offshore wind is very likely to diverge further from onshore wind.

3.1.2. THE OFFSHORE WIND RESOURCE

Offshore wind is driven by other facts than the one usually predominant in onshore, topography. But the absence of topography does not result in necessarily simpler models when characterizing offshore atmospheric flow.

For example, in onshore wind when the surface's roughness length (a parameter used to describe the roughness of the surface of the ground) is low the variation of wind speed in height, shear, is also low. Generically and neglecting issues as thermally derived phenomena, as the roughness increases, shear will also increase.

In offshore wind, the surface's roughness length is dependent on the sea state, namely wave height and frequency, which in its hand is also a influenced by wind conditions – many times, the ones quite apart from the area under appreciation. This relation can be quite complex as the sea surface is not characterized by constant elements such as trees, hills and buildings, as tends to be the case onshore.

Near coastal areas, where onshore effects may still be felt, complexity further arises as models can work fine for certain wind conditions and not for others leading to a potential ensemble of models to adequately characterize offshore wind.

Stable flow conditions are usually observed in offshore away from the shore. As the potentially low roughness length results in low turbulence intensity, the air streams will be slow to mix. It is not, for this reason, surprising to find within a project area, quite different flow in height. In rare situations wind speed may even reduce with height.

Another issue with significant influence in offshore wind is having a variable hub height, considering it in its classical definition of distance between the surface and the wind turbine's rotor, due to the tidal level with its consequences in terms of intraday seasonality on the variation in mean winds across the turbine rotor itself.

Finally, thermal phenomena also have a role to play in offshore, particularly costal. In fact, and, if compared to the land, the sea temperature is more constant. During daytime, as land heats up, the warmer air rises and is replaced by cooler air from over the sea creating an onshore wind.

3.1.3. OFFSHORE WIND MEASUREMENTS

Given the dimensions of offshore wind turbines – typically much larger than the onshore ones – it is important to characterize wind at very high heights to fully characterize wind conditions in all of the rotor's swept area. Measurements are, however, very expensive not only due to the experimental apparatus itself but also due to the cost of constructing the support structure for the meteorological mast and respective maintenance and operation. Such masts (Figure 3.1) may cost some EUR 1-5m, depending on site location and specification, which is perhaps 100 times that required for equivalent onshore work. Offshore monitoring towers are un-guyed and therefore need to be wider, which can mean measurements are more susceptible to wind flow effects from the tower. Anemometry equipment is otherwise standard. Alternatively, Lidar measurements are becoming more and more referred to as alternatives, installed in fixed platforms or buoys (Figure 3.2). Such technology is nonetheless quite sensitive and does not necessarily imply a reduction in costs.

Figure 3.1 – The 120 m height meteorological mast at Middelgrund Wind Farm [1].

If high quality wind measurements are not available from the site or nearby, there are other sources of information which can be utilised to determine the approximate long-term wind regime at the wind farm location. There are offshore databases for wind data, including meteorological buoys, light vessels and observation platforms. Additionally, mesoscale modelling (based

Figure 3.2 – The FLIDARTM prototype being tested 15 km off the Belgian coast [2].

on global reanalysis datasets) and earth-observation data play a role in preliminary analysis and analysis of spatial variability. Although not suitable for a robust financing report, they are producing increasingly accurate regional maps such as that for the North Sea (Figure 3.3).

The energy yield estimate step is similar to the one performed as in onshore predictions, aiming to generate a wind resource map based on local measurements. Given the absence of topography offshore and the similarity of conditions, namely wave length and frequency, all over the project area, measurements from a mast can be considered representative of a much larger area than would be possible onshore. However, for large offshore sites wake losses are likely to be higher than for many onshore wind farms. The wake losses are increased due to the size of the project and also due to lower ambient turbulence levels - the wind offshore is much smoother. There is therefore less mixing of the air behind the turbine, which results in a slower re-energising of the slow moving air and the wake lasts longer. Wake modelling is, thus, a challenge in offshore.

3.1.4. THE OFFSHORE WIND TECHNOLOGY

The idea of a wind driven rotor is ancient and, for energy yield purposes, the three bladed wind turbine model has paved its way as the dominant concept of the technology in the last 30 years. It has been this way onshore and, more recently, offshore. Despite some difference towards the onshore wind turbines, the offshore wind turbines technology remain practically unchanged and major difference concern on the wind turbine's support platform, accesses and grid connection. Given the scope of the present assignment, focus is made in the first subject and on the associated logistics.

Offshore substructures

The offshore manufacturing industry was originally developed by the oil and gas industry to supply a limited quantity of bespoke structures. As offshore wind turbine technology has its origin in the onshore wind turbine technology, the respective substructure is very much based on the oil and gas industry.

Today, there is no standard offshore substructuredesign and at depths of over 25m the foundation costs start to increase dramatically. Most offshore structures developed to date use 2–5 MW

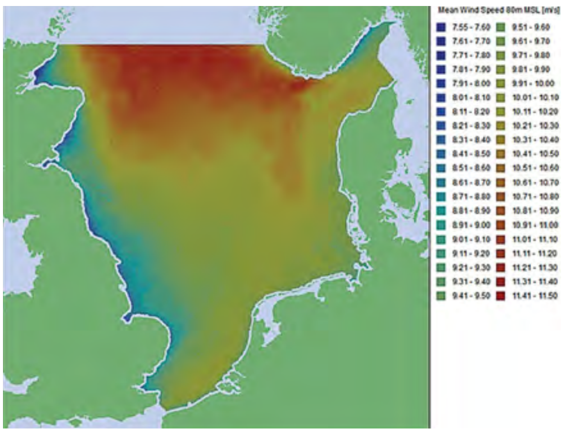

Figure 3.3 – North Sea Wind Map [3].

turbinesin water depths of up to 20m and most of those to be developed in the near future will do the same.

These will be largely based on monopile technology and gravity-based structures as described in Figure 3.4.a. However, as turbine size increases and the industry migrates into deeper waters, additional sub-structure designs will be required. Different concepts will compete, such as fixed structures with three or four legs (tripods/quadropods), spar buoys or semi-submersible, as shown in Figure 3.4.b. Such technologies are suitable for water depths of up to 50-60m, depending on the project economics and site conditions and would be therefore well adapted to countries with medium depth waters.

Wind turbine and substructure installation, O&M

There is a clear challenge in both deployment of wind turbines and respective substructures offshore as well in their maintenance particularly in what concerns the access to a technology often isolated due to severe weather conditions. In fact, whereas onshore only in very particular cases (severe snowing, roads fallout, etc.) access to project areas / wind farms is denied and, even in such cases, for relatively short-periods. When in offshore such incapacity to reach wind turbines may take much longer with severe consequences on the availability of wind turbines.

The current market for offshore wind turbine installation makes use of a number of different vessels for different projects, and also draws on some vessels from the oil and gas sector and civil marine sector. Compared to existing offshore sectors (oil and gas, marine installation), the installation processes for the offshore wind industry are extremely demanding, due to a higher number of operation days, and repetitive installation processes.

It is, thus, highlighted here that a major technological evolution in vessels designed for offshore wind purposes is one of the most significant vectors in which investment is required stressing, however, that a potential additional barrier to offshore wind is having sufficient offshore personnel trained to operate such vessels at the required security level.

It is also noted that offshore required a supply chain upstream and, particularly, the level of services provided by harbours for offshore operators is, without any doubt, crucial for the success of this industry.

3.1.5. THE OFFSHORE WIND ECONOMICS

Installation, operations and maintenance

The supply chain and port infrastructure requirements are similar for all types of offshore wind

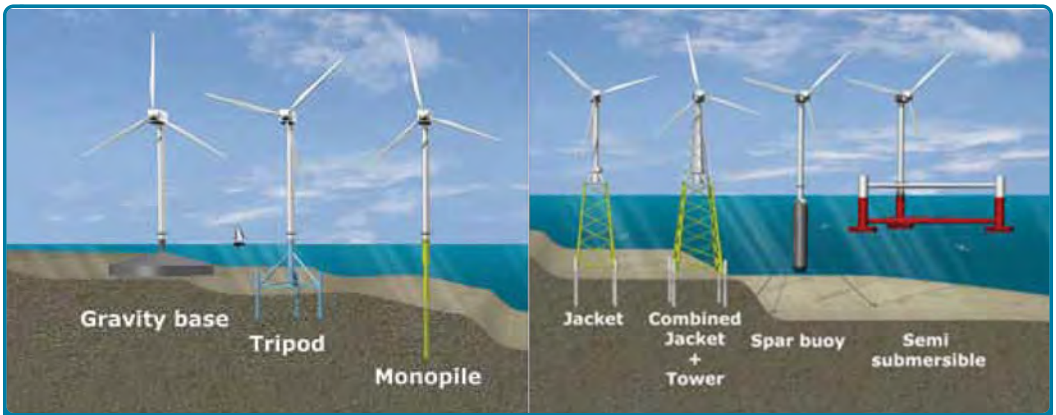

Figure 3.4 – Offshore wind substructures [4].

substructures. In common with fixed-bottom foundations, building a strong supply chain remains a priority for deep offshore deployment. Ports must allow for increased throughput and provide enough space to accommodate installation and component storage.

Infrastructure for the serial production of floating offshore components needs to be built, as is the case for fixed-bottom foundations.

Supply chain and port infrastructure requirements for floating turbines may be similar to those of bottom fixed offshore wind but the economics of deep offshore projects are different in terms of installation and operations and maintenance (O&M) costs. Offshore wind is a capital intensive technology, and installation costs are an important cost. But that is not the case for most of the deep offshore designs, which can be assembled onshore then towed out to sea. This reduces the need to use vessels, cutting overall installation costs.

It also reduces installation lead times as the deep offshore designs are less dependent on weather and sea conditions. The industry is, however, trying to minimise installation costs and must continue to develop self-installing and port assembled systems.

Handling and installing mooring lines and anchors may be the main installation challenge. Attention needs to be paid to what equipment is used. The moorings and anchors must be designed to ensure the concept's stability throughout its lifetime. Hooking up mooring lines to the floating platform is one of the most difficult phases of the installation process. Significant experience is being transferred from the oil and gas sector to reduce design and installation risks to the mooring systems of floating structures.

For O&M and logistics, the deep offshore turbine's motion remains the main challenge, although the inspection of the mooring lines and anchor system could also involve much effort and cost. However, most deep offshore wind designs could be assembled onshore and transferred to the site. In the case of a failure the whole structure could be transported for repair to an onshore location by tug boats. This would avoid using expensive vessels such as jack-up barges.

Some deep offshore wind designs also include a large platform where machinery as well as crew can remain available for O&M on site.

Assessing the costs of the deep offshore designs

Offshore wind is still in its infancy and therefore has high costs. Reduction is, thus, one of the main challenges for the industry and much work is being done to address it.

Large scale development of the technology, along with the support of a secure and stable regulatory framework, will help reduce costs. However, innovation must also be geared towards reducing turbine, foundation and other component costs. It is therefore essential to ensure sufficient public R&D financing to enable the offshore vision to become a reality.

The production and installation of substructures represents up to 20% of the capital expenditure (CAPEX)of offshore wind farms. Offshore wind costs can, therefore, be considerably reduced if substructure costs are reduced. This can be achieved through demonstrating new designs with low installation and production costs.

Along with the focus on reliable and cost effective solutions for bottom-fixed substructures for the near term market in deeper waters, cost effective floating substructures must be developed to secure a larger scale offshore wind market.

Floating offshore substructure costs mainly consist of the platform and the anchoring system. These costs are similar to those for fixed-bottom solutions installed in deep waters.

The major difference between the two solutions is in the design and installation costs where floating offshore designs are expected to be cheaper. Overall, floating offshore designs are also expected to produce more energy, as they can accommodate bigger turbines which lower the final cost per MWh.

The offshore industry is gradually leaving shallow waters behind. Deep offshore designs, although in their infancy, are not only innovative but competitive at a water depth above 50m. It is feasible to develop them and the offshore wind industry must continue investing in R&D to optimise the exploitation of this widely available marine resource at an affordable cost of energy.

3.1.6. ENVIRONMENTAL ISSUES

Offshore wind energy is a renewable technology capable of supplying significant amounts of energy in a sustainable way. According to EWEA estimates, between 20 GW and 40 GW of offshore wind energy capacity will be operating in the EU by 2020.

The total offshore installed capacity in Europe at the end of 2014 was almost 6.6 GW, distributed in the coastal waters of Denmark, Germany, The Netherlands, Sweden and the UK, estimated to represent about 0.7 % of the total European electricity demand [5]. But with the increase in generating capacity, evolution on the technology and the overcoming of the grid limitations, offshore wind could meet more than 4 per cent of EU electricity consumption. Concerning exclusively this point of view, offshore wind is as interesting as any other renewable source of energy due to the reduction of greenhouse gas emissions.

There is, however, some impact from an ecological point of view which cannot be neglected. Offshore developments include platforms, turbines, cables, substations, grids, interconnection and shipping, dredging and associated construction activity. The operation and maintenance activities include the transport of employees by ship and helicopter and occasional hardware retrofits.

Offshore wind farms usually have more and bigger turbines than onshore developments. However, visual impact is lower due to the greater distance from the coastline. Nevertheless, the coastal landscape is often unique and provides some of the most valued landscapes, thus special attention could be required.

Offshore wind farms are located far away from human populations, which are thus not affected by the noise generated by the turbines. However, marine animals could be affected by the underwater noise generated during the construction and operation of wind turbines. Any effects of the noise will depend on the sensitivity of the species present and their ability to adjust to it. Construction and decommissioning noise comes from machines and vessels, pile-driving, explosions and installation of wind turbines. In the operation phase, the sound generated in the gearbox and the generator is transmitted by the tower wall, resulting in sound propagation underwater.

Measurements of the noise emitted into the air from wind turbines and transformers have shown a small contribution to the underwater noise level. But although the sound level is moderate, it is permanent (until decommissioning), thus more research about its influence on marine animals behaviour is needed.

The influence of offshore wind farms on birds can be summarised as follows: collision risk, perceived as the one with most direct effect on bird populations, short-term habitat loss during construction phase, long-term habitat loss due to disturbance from wind turbines installed and from ship traffic during maintenance, barriers to movement in migration routes and disconnection of ecological units. Information about bird mortality at offshore wind farms is, however, very scarce and this happens for two reasons: the difficulty of detecting collisions and the difficulty in recovering dead birds at sea. Further investigations on this topic are, thus, needed to obtain reliable knowledge.

3.1.7. CONCLUSIONS

Offshore wind energy is today a reality and will become a key player in the electricity generation mix in Europe. The technology faces, still many challenges from which the lowering of costs, the adaptation of substructures to different scenarios, the logistics concerning deployment and O&M are highlighted.

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3.2. WAVE ENERGY

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ABSTRACT

Sea wave energy is being increasingly regarded in many countries as a major and promising resource. The paper deals with the development of wave energy utilization since the 1970s. Several topics are addressed: the characterization of the wave energy resource; theoretical background, with special relevance to hydrodynamics of wave energy absorption and control; how a large range of devices kept are being proposed and studied and how such devices can be organized into classes; the conception, design, model-testing, construction and deployment into real sea of prototypes; and the development of specific equipment (air and water turbines, high-pressure hydraulics, linear electrical generators) and mooring systems.

Keywords: Wave energy; Wave power; Renewable energy; Equipment; Power take-off; Review

3.2.1. INTRODUCTION

The energy from ocean waves is the most conspicuous form of ocean energy, possibly because of the, often spectacular, wave destructive effects. The waves are produced by wind action and are therefore an indirect form of solar energy.

The possibility of converting wave energy into usable energy has inspired numerous inventors: more than one thousand patents had been registered by 1980 [1] and the number has increased markedly since then. The earliest such patent was filed in France in 1799 by a father and a son named Girard [2].

Several reviews on wave energy conversion have been published in book form, as conference and journal papers and as reports. One should mention first the pioneering book by McCormick [1] published in 1981, and also the books by Shaw [3], Charlier and Justus [4] (their long chapter on wave energy was probably completed by 1986), Ross [2] (written from a non-technical point of view by a freelance journalist), Brooke [5] and Cruz [6]. A report prepared in 1999 for the UK Department of Energy [7] and the final report (2003) [8] from the European Thematic Network on Wave Energy (a project sponsored by the European Commission) provide abundant information on the state-of-the-art at the time. Shorter reviews can be found in [9-13].

Yoshio Masuda (1925-2009) (Figure 3.5) may be regarded as the father of modern wave energy technology, with studies in Japan since the 1940s. He developed a navigation buoy powered by wave energy, equipped with an air turbine, which was in fact what was later named as a (floating) oscillating water column (OWC). These buoys were commercialized in Japan since 1965 (and later in USA) [14]. Later, in Japan, Masuda promoted the construction, in 1976, of a much larger device: a barge (80m×12m), named Kaimei, used as a floating testing platform housing several OWCs equipped with different types of air turbines [15]. Probably because this was done at an early stage when the theoretical knowledge of wave energy absorption was in its infancy, the power output levels achieved in the Kaimei testing program were not a great success.

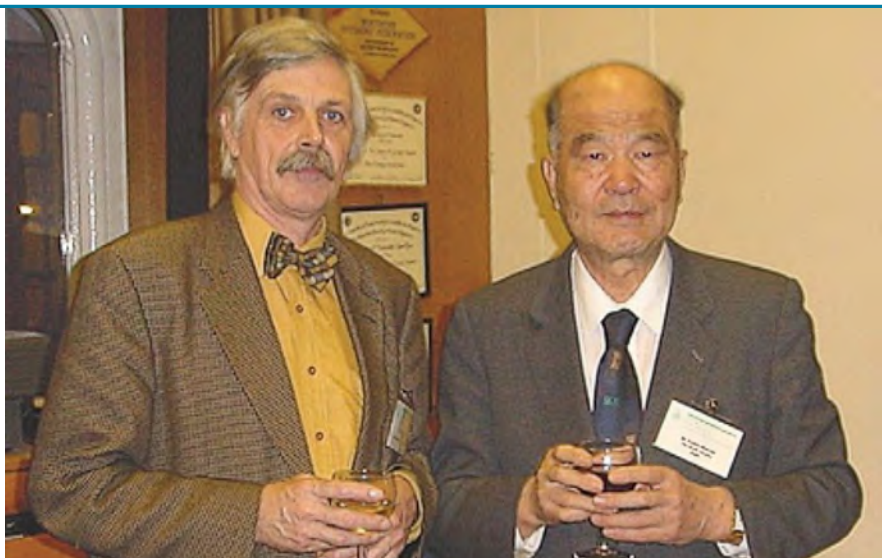

Figure 3.5 – Commander Yoshio Masuda (right) with Dr. A. W. Lewis, in 2001 (courtesy of A. W. Lewis, University College Cork).

The oil crisis of 1973 induced a major change in the renewable energies scenario and raised the interest in large-scale energy production from the waves. A paper published in 1974 in the prestigious journal Nature by Stephen Salter [16], of the University of Edinburgh, became a landmark and brought wave energy to the attention of the international scientific community. The British Government started in 1975 an important research and development program in wave energy [17], followed shortly afterwards by the Norwegian Government. The first conferences devoted to wave energy took place in England (Canterbury, 1976, and Heathrow, 1978). This was followed in 1979 by two more genuinely international conferences: Power from Sea Waves (Edinburgh, June) and the First Symposium on Wave Energy Utilization (Gothenburg, October-November). The Second International Symposium on Wave Energy Utilization (Trondheim, Norway, 1982) coincided with a marked decline in Government funding of the British wave energy program.

In Norway the activity went on to the construction, in 1985, of two full-sized (350 and 500 kW rated power) shoreline prototypes near Bergen. In the following years, until the early 1990s, the activity in Europe remained mainly at the academic level, the most visible achievement being a small (75 kW) OWC shoreline prototype deployed at the island of Islay, Scotland (commissioned in 1991) [18]. At about the same time, two OWC prototypes were constructed in Asia: a 60 kW converter integrated into a breakwater at the port of Sakata, Japan [19] and a bottom-standing 125 kW plant at Trivandrum, India [20].

The wave energy absorption is a hydrodynamic process of considerable theoretical difficulty, in which relatively complex diffraction and radiation wave phenomena take place. This explains why a large part of the work on wave energy published in the second half of the 1970s was on theoretical hydrodynamics, in which several distinguished applied mathematicians took leading roles.

An additional difficulty is related to the conception of the power take-off mechanism (PTO) (air turbine, power hydraulics, electrical generator or other) which should allow the production of usable energy. The problem here lies in the variability of the energy flux absorbed from the waves, in several time-scales: wave-to-wave (a few seconds), sea states (hours or days) and seasonable variations. Naturally, the survivability in extreme conditions is another major issue.

The situation in Europe was dramatically changed by the decision made in 1991 by the European Commission of including wave energy in their R&D program on renewable energies. The first projects started in 1992. Since then, about thirty projects on wave energy were funded by the European Commission involving a large number of teams active in Europe. A few of these projects took the form of coordination activities, the most recent one (2004-2007) being the Coordination Action in Ocean Energy, with forty partners. Also sponsored (and in some cases partly funded) by the European Commission were a series of European Wave Energy Conferences (the more recent ones including also Tidal Energy): Edinburgh, UK (1993), Lisbon, Portugal (1995), Patras, Greece (1998), Aalborg, Denmark (2000), Cork, Ireland (2003), Glasgow, UK (2005), Porto, Portugal (2007), Uppsala, Sweden (2009). Sessions on ocean energy (with a major or dominant contribution of papers on wave energy) are becoming increasingly frequent in annual conferences on ocean engineering (namely the OMAE and ISOPE conferences) and on energy (the case of the World Renewable Energy Congresses).

In 2001, the International Energy Agency established an Implementing Agreement on Ocean Energy Systems (IEA-OES, presently with 17 countries as contracting parties) whose mission is to facilitate and co-ordinate ocean energy research, development and demonstration through international co-operation and information exchange. The IEA-OES 2008 Annual Report [21] contains a survey of the ongoing activities in wave energy worldwide.

In the last few years, growing interest in wave energy is taking place in northern America (USA and Canada), involving the national and regional administrations, research institutions and companies, and giving rise to frequent meetings and conferences on ocean energy [22,23].

This paper is mainly concerned with technological aspects of wave energy conversion. Issues like policies, economics and environmental impacts are left aside or only mentioned occasionally.

3.2.2. THE WAVE ENERGY RESOURCE

The main disadvantage of wave power, as with the wind from which is originates, is its (largely random) variability in several time-scales: from wave to wave, with sea state, and from month to month (although patterns of seasonal variation can be recognized).

The assessment of the wave energy resource is a basic prerequisite for the strategic planning of its utilization and for the design of wave energy devices. The characterization of the wave climate had been done before for other purposes, namely navigation and harbour, coastal and offshore engineering (where wave energy is regarded as a nuisance), for which, however, the required information does not coincide with what is needed in wave energy utilization planning and design.

The studies aiming at the characterization of the wave energy resource, having in view its utilization, started naturally in those countries, where the wave energy technology was first developed. In Europe, this was notably the case of the United Kingdom [24,25]. When the European Commission decided, in 1991, to start a series of two-year (1992-93) Preliminary Actions in Wave Energy R&D, a project was included to review the background on wave theory required for the exploitation of the resource and to produce recommendations for its characterization [26]. The WERATLAS, a European Wave Energy Atlas, also funded by the European Commission, was the follow-up of those recommendations. It used high-quality results from numerical wind-wave modelling, validated by wave measurements where available and contains detailed wave-climate and wave-energy statistics at 85 points off the Atlantic and Mediterranean coasts of Europe [27]. The WERATLAS remains the basic tool for wave energy planning in Europe.

These data concern locations in the open sea, at distances from the coast of a few hundred km. As the waves propagate onto the shore, they are modified in a complex way by bottom effects (refraction, diffraction, bottom friction and wave breaking) and by sheltering due to the presence of land (namely headlands and islands). For these reasons, the wave energy resource characterization in shallower waters (say less than 50 m water depth) has been done only for specific sites where plants are planned to be deployed. An exception is the ONDATLAS, a detailed nearshore wave-energy atlas for Portugal whose 500-km-long western coast is relatively straight, the bottom profile exhibiting little change over long coastal stretches [28].

The wave energy level is usually expressed as power per unit length (along the wave crest or along the shoreline direction); typical values for "good" offshore locations (annual average) range between 20 and 70 kW/m and occur mostly in moderate to high latitudes. Seasonal variations are in general considerably larger in the northern than in the southern hemisphere [29], which makes the southern coasts of South America, Africa and Australia particularly attractive for wave energy exploitation.

Reviews on wave energy resource characterization can be found in [29,30].

3.2.3. HYDRODYNAMICS

Theoretical and numerical modelling

The study of the hydrodynamics of floating wave energy converters could benefit from previous studies on the, largely similar, dynamics of ships in wavy seas, which took place in the decades preceding the mid-1970s. The presence of a power take-off mechanism (PTO) and the requirement of maximizing the extracted energy introduced additional issues.

The first theoretical developments addressed the energy extraction from regular (sinusoidal) waves by a floating body oscillating in a single mode (one degree of freedom) with a linear PTO. An additional assumption of the theory was small amplitude waves and motions. This allowed the linearization of the governing equations and the use of the frequency-domain analysis. The hydrodynamic forces on the wetted surface of the body were decomposed into excitation forces (due to the incident waves), radiation forces (due to body motion) and hydrostatic forces (connected with the instantaneous position of the floating body with respect to the undisturbed free surface). Accordingly, (frequency dependent) hydrodynamic coefficients were defined, to be determined theoretically or computed with the aid of computer codes (usually based on the boundary element method). These were techniques already known through ship hydrodynamics.

This can be illustrated by the simple case of a floating body of mass m oscillating in heave (one degree of freedom). If the body position is defined by a vertical coordinate x (with $x = 0$ in calm water), the equation of motion is

$$(m + A)\ddot{x} = f_d - B\dot{x} - \rho g S x + f_{\mathrm{PTO}} \tag{1}$$

Here, $f_d(t)$ is (the vertical component of) the excitation force (acting on the assumedly fixed body; $f_d = 0$ in calm water), $f_{\mathrm{PTO}}(t)$ is the vertical force due to the PTO mechanism, $A(\mathrm{w})$ is the (hydrodynamic coefficient of) added mass (accounting for the inertia of the water surrounding the body), $B(\mathrm{w})$ is the radiation damping coefficient (accounting for the damping on the body due to energy transfer to waves radiated away), and S is the cross-sectional area of the body by the unperturbed free surface plane ($-\rho g S x$ is the hydrostatic restoring force). We assume the PTO force to consist of a linear damper (coefficient C) and a linear spring (stiffness K) and write $f_{\mathrm{PTO}} = -C\dot{x} - Kx$ Then the whole system becomes fully linear. In regular waves of amplitude A_w and frequency ω, we write $\{x, f_d\} = \mathrm{Re}\left(\{X, F_d\} e^{i\omega t}\right)$, where X and F_d are complex amplitudes and Re( ) means real part of. Then,

$$X = \frac{F_d}{-\omega^2 (m + A) + i\omega (B + C) + \rho g S + K} \tag{2}$$

from (1), we obtain

Since the system in linear, the excitation force is proportional to wave amplitude, i.e. $|F_d| = \Gamma A_w$, where $\Gamma(\omega)$ is a hydrodynamic coefficient of diffraction force.

The time-averaged absorbed power is $\overline{P} = \overline{f_d \dot{x}} = C\mathrm{w}^2 |X^2|$, which can be written as

$$\overline{P} = \frac{1}{8B}|F_d|^2 - \frac{B}{2}\left|U - \frac{F_d}{2B}\right|^2 \tag{3}$$

where $U = i\mathrm{w}X$ is the complex amplitude of the velocity $\dot{x}$.

For a given body and given incident regular wave, B and F_d are fixed. Then the absorbed power $\overline{P}$ depends on X, i.e. on the PTO damping and spring coefficients C and K. Equation (3) shows that its maximum value, equal to

$$\overline{P}_{\max} = \frac{1}{8B}|F_d|^2 \tag{4}$$

occurs for $U = F_d / 2B$, which, combined with (2), gives two optimal conditions involving real quantities

$$\omega = \left(\frac{\rho g S + K}{m + A(\omega)}\right)^{1/2} \tag{5}$$

$$C = B(\omega) \tag{6}$$

Equation (5) is a resonance condition: its right hand side is the frequency of free oscillations of an undamped mechanical oscillator of mass $m + A$ acted upon by a spring of stiffness $\rho g S + K$. Equation (6) shows that the optimal PTO damping should equal the radiation damping.

It is convenient to introduce the concept of capture (or absorption) width as $L = \overline{P}/E$, where E is the wave energy flux per unit crest length. It can be shown that

$$L_{max} = \frac{\overline{P}_{max}}{E} = \frac{\lambda}{2\pi} \qquad (7)$$

for a body with a vertical axis of symmetry (but otherwise arbitrary geometry) oscillating in heave, and $L_{max} = \lambda/\pi$ if the body oscillates in sway. Here λ is the wavelength. Equation (7) is an important theoretical result, obtained independently in 1975-76 by Budal and Falnes [31] Evans [32], Newman [33] and Mei [34], on the maximum power that can be absorbed from the waves, as is the well-known Betz limit for the power coefficient of wind turbines.

Illustrative performance curves for a floater oscillating in heave, whose submerged part is hemispherical, can be easily obtained from results for the hydrodynamic coefficients derived analytically by Hulme [35] for deep water. These are shown in a dimensionless representation in Figure 3.6, with the ratios $\overline{P}/\overline{P}_{max}$ and $|X|/A_w$ plotted versus dimensionless wave period $T^* = (g/a)^{1/2} T$ (a = sphere radius, $T = 2\pi/\omega$ = wave period) for several values of the dimensionless PTO damping coefficient $C^* = \rho a^{5/2} g^{1/2} C$. No spring is assumed to be present, i.e. $K = 0$. Optimal conditions (5,6) are to be met for maximum power absorption: the resonance condition (5) yields $T^* = 6.1$, whereas the damping condition (6) gives $C^* = 0.510$. With $g = 9.8\,\mathrm{m/s^2}$, we find the optimum radius $a = 0.262T^2$ (a in m, wave period T in s). Taking $T = 10$s as a typical value for the northern Atlantic, we obtain $a = 26.2$ m for the optimum radius of a hemispherical resonant buoy. The corresponding value for the oscillation amplitude is $|X|/A_w$ =0.909. The curves of Figure 3.6 show that an optimally damped buoy responds efficiently to a relatively narrow band of wave periods. Overdamping produces a less peaky response curve, which may be interesting since real waves comprehend a range of frequencies.

A radius value $a_{opt} = 26.2$m is too large to be practical and economical. Indeed, the early researchers in the mid-1970s realized that "small" buoys or "point absorbers" (say diameter up to 10-15m) would perform very poorly in the waves typical of the wide oceans. In section 3.2.4 we will mention control strategies which were devised to improve the performance of wave energy converters, especially point absorbers.

The results briefly mentioned above for single-mode oscillators were subsequently extended to oscillating-body converters with more than one degree of freedom and to multi-body converters. David V. Evans (in England), Johannes Falnes and Kjell Budal (1933-89) (in Norway), John Nicholas Newman, Chiang C. Mei (in USA) and others were pioneers who made fundamental contributions in the second half of the 1970s, which were subsequently reviewed by Evans [36] (see also [37]).

Although oscillating water columns (OWCs) were amongst the first wave energy converters to be developed and reach the full-sized prototype stage, their modelling was done a few years later [38-40], since it did not benefit from the existing ship-hydrodynamics theory to the same extent as oscillating body converters did.

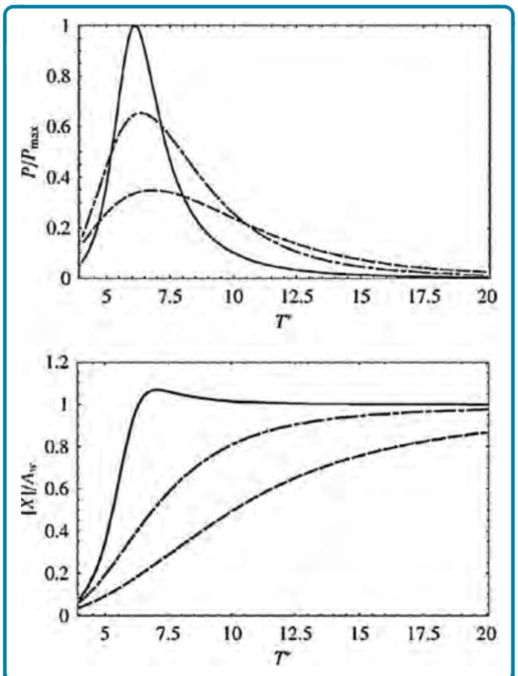

Figure 3.6 – Dimensionless performance curves versus wave period, of a heaving hemisphere with a simple linear-damping PTO. Solid lines: optimal damping C* = 0.510; chain lines: C* = 2; broken lines: C* = 5.

A linear PTO (in addition to regular waves) is a basic assumption in the frequency-domain analysis underlying the early results outlined above. Since, in practice, most converters are equipped with strongly nonlinear mechanisms, a time-domain theory had to be developed. This was done in 1980 for oscillating-body converters by Jefferys [41], closely following the theory, based on Fourier transform techniques, developed for ship hydrodynamics by Cummins [42]. In the case of the floater oscillating in heave considered above, the time-domain equation of motion can be written as

$$(m + A(\infty))\ddot{x}(t) + \rho g S\, x(t) + \int_{-\infty}^{t} L(t-\tau)\ddot{x}(\tau)\,d\tau = f_d(t) + f_{\mathrm{PTO}} \tag{8}$$

where

$$L(t) = \frac{2}{\pi}\int_0^\infty \frac{B(\omega)}{\omega}\sin\omega t\, d\omega$$

In Eq. (8), the radiation force is represented by the convolution integral, which shows the dependence on the past motion of the body.

The time-domain model produces time-series and is the appropriate tool for active-control studies of converters in irregular waves (see section 3.2.4). However it requires much more computing time as compared with the frequency-domain analysis. An alternative approach, that is computationally much less demanding (although limited to linear or nearly linear PTO), is the stochastic modelling which produces probability density distributions rather than time-series [43-44]. This was successfully used in optimisation procedures involving a very large number of simulations [45].

Large numbers of devices in arrays are required if wave energy is to provide a significant contribution to large electrical grids. The hydrodynamic interaction between devices was first studied theoretically for systems of oscillating bodies by Budal [46], Falnes and Budal [47], Evans [48], and later extended to systems of OWCs by Evans [39]. However, if the number of devices in the array is not small, the interactions become extremely complex and approximate methods have in practice to be devised, like the multiple-scattering method, the plane-wave method and the point-absorber approximation. This was dealt with in a European Commission project in the mid-1990s (see [49]).

The book by Falnes [50], himself one of the most distinguished pioneers in the theoretical hydrodynamics of wave energy absorption, is now the standard text book in these hydrodynamic studies.

Model testing

In the development and design of a wave energy converter, the energy absorption may be studied theoretically/numerically, or by testing a physical model in a wave basin or wave flume. The techniques to be applied are not very different from those in the hydrodynamics of ships in a wavy sea. Numerical modelling is to be applied in the first stages of the plant design. The main limitations lie in its being unable to account for losses in water due to real (viscous) fluid effects (large eddy turbulence) and not being capable to model accurately large amplitude water oscillations (nonlinear waves). Such effects are known to be important (they also occur in naval engineering and in off-shore structures, where more or less empirical corrections are currently applied). For these reasons, model tests (scales 1:80 to 1:10) are carried out in the wave basin when the final geometry of the plant is already well established.

Stephen Salter is widely regarded as the pioneer in model testing of wave energy converters. In 1974 he started the experimental development of the "duck" concept in a narrow wave flume at the University of Edinburgh. Salter's experimental facilities were greatly improved with the construction, in 1977, of the 10m×27.5m×1.2m "wide tank" equipped with 89 independently driven paddles, which made Edinburgh the leading centre for the experimental development in wave energy conversion (for detailed information, including early photographs, see [51]). Later, as the development of wave energy converter concepts progressed towards the prototype construction stage, the need of larger-scale testing required the use of very large laboratory facilities. This was the case, in Europe, of the large wave tanks in Trondheim (Norway), Wageningen (Netherlands) and Nantes (France).

3.2.4. CONTROL

The utilization of wave energy involves a chain of energy conversion processes, each of which is characterized by its efficiency as well as the constraints it introduces and has to be controlled. Particularly relevant is the hydrodynamic process of wave energy absorption, to which reference was made in the previous section.

The early theoretical studies on oscillating-body and OWC converters revealed that, if the device is to be an efficient absorber, its own frequency of oscillation should match the frequency of the incoming waves, i.e. it should operate at near-resonance conditions. The ignorance of this rule underlies many failures by inventors who regarded such systems as quasi-static (i.e. simply follow the wave surface motion) rather than dynamic. In practice, the frequency-matching meets with serious difficulties: (i) in most cases, except if the body (or the OWC) is quite large (this meaning possibly sizes substantially larger than ten metres, see section 3.2.3 above), its own frequency of oscillation is too high as compared with typical ocean-wave frequencies; (ii) real waves are not single-frequency.

As shown in section 3.2.3, for a single-mode oscillating body in regular waves, resonance (and maximum energy absorption) occurs when the body velocity is in phase with the excitation force (rather than with the total force on the wetted surface). Acting on the PTO to achieve such phase coincidence has been named phase-control. Several phase-control strategies have been proposed, including for devices in real irregular waves (for a review, see Falnes, [52]). We saw, in section 3.2.3 – Theoretical and numerical modelling, that the frequency of resonance ω of point absorbers (as given by Eq. (5) with $K = 0$, i.e. a PTO consisting of pure linear damping) is in general significantly higher than typical wave frequencies in the open ocean. Obviously, the solution ω of Eq. (5) can be lowered by allowing the spring stiffness K to take negative values. This is called reactive phase control. Figure 3.7 shows the modifications to Figure 3.6 if a spring of negative stiffness $K = -\rho g S/2$ (i.e. the spring force is half the hydrostatic restoring force and of opposite sign) is introduced into the PTO. Optimal performance, $\overline{P}/\overline{P}_{\max} = 1$, now occurs at a larger dimensionless period $T^* \cong 9.2$ (as compared with 6.1). Figure 3.7 (as compared with Figure 3.6) also shows the amplitude of body oscillations close to resonance to be substantially larger.

Apart from the impracticality of a negative mechanical spring in reactive phase control, this introduces another problem. Since the PTO force is no longer in phase with the body velocity, the energy flow direction is reversed during part of the wave cycle, with negative consequences if the reactive power peaks are not small and (friction) losses are significant in the two-way energy transfer process.

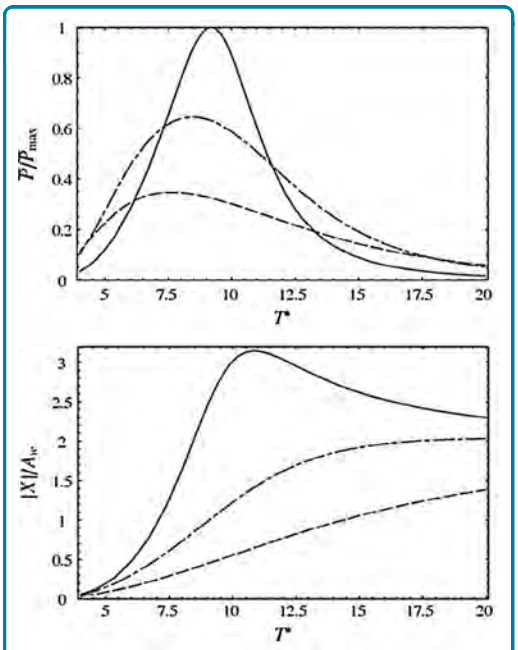

Figure 3.7 – Dimensionless performance curves versus wave period, of a heaving hemisphere with a reactive phase-controlled PTO consisting of a linear damper and a spring of negative stiffness K* = - ρgS/2. Solid lines: damping C* = 0.510; chain lines: C* = 2; broken lines: C* = 5.

An alternative control method which avoids the energy flow reversal was proposed by Budal and Falnes [47] (see also [53]) and consists of latching the device in a fixed position during certain intervals of the wave cycle so as to achieve approximate optimal phase control. Although latching should be regarded as suboptimal phase control as compared with optimal reactive phase control, it has been found that theoretically it may be almost as efficient [54] for a single-body converter. To optimally determine such latched time-intervals in real random waves turned out to be a complicated theoretical control problem, which, in addition to relatively heavy computing, requires the prediction of the incoming irregular waves some time into the future. Recently, an alternative to latching has been proposed and analysed, named unclutching, which also avoids the energy flow reversal [55]. It consists of switching on and off alternatively the wave energy converter's PTO. Apart from the pioneers Falnes and Budal, phase control (including latching) was the object of theoretical studies of other researchers, namely Naito and Nakamura [56], who established the relation between causality and optimum control of wave energy converters, Nancy Nichols and her co-workers [57,58], who applied the maximum principle of Pontryagin to numerically solve the problem, and Korde [59] who studied the phase control of converters with several degrees of freedom. Sub-optimal phase control in real random waves and its practical implementation in wave energy converters remains an open problem.

3.2.5. THE VARIOUS TECHNOLOGIES

Unlike large wind turbines, there is a wide variety of wave energy technologies, resulting from the different ways in which energy can be absorbed from the waves, and also depending on the water depth and on the location (shoreline, near-shore, offshore). Recent reviews identified about one hundred projects at various stages of development. The number does not seem to be decreasing: new concepts and technologies replace or outnumber those which are being abandoned.

Several methods have been proposed to classify wave energy systems, according to location, to the working principle and to size ("point absorbers" versus "large" absorbers). The classification in Figure 3.8 is based mostly on working principle. The examples shown are not intended to form an exhaustive list and were chosen among the projects which reached the prototype stage or at least were object of an extensive development effort.

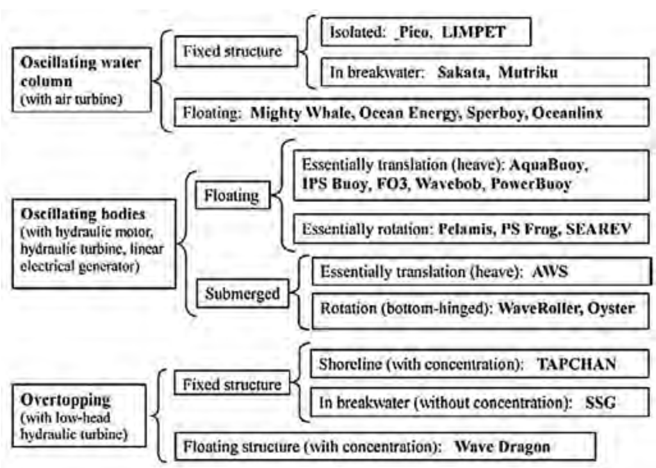

Figure 3.8 – The various wave energy technologies.

3.2.6. THE OSCILLATING WATER COLUMN (OWC)

Fixed-structure OWC

Based on various energy-extracting methods, a wide variety of systems have been proposed but only a few full-sized prototypes have been built and deployed in open coastal waters. Most of these are or were located on the shoreline or near shore and are sometimes named first generation devices. In general these devices stand on the sea bottom or are fixed to a rocky cliff. Shoreline devices have the advantage of easier installation and maintenance and do not require deep-water moorings and long underwater electrical cables. The less energetic wave climate at the shoreline can be partly compensated by natural wave energy concentration due to refraction and/or diffraction (if the device is suitably located for that purpose). The typical first generation device is the oscillating water column. Another example is the overtopping device Tapchan (Tapered Channel Wave Power Device), a prototype of which was built on the Norwegian coast in 1985 and operated for several years (see section 3.2.8).

The oscillating water column (OWC) device comprises of a partly submerged concrete or steel structure, open below the water surface, inside of which air is trapped above the water free surface (Figure 3.9). The oscillating motion of the internal free surface produced by the incident waves makes the air flow through a turbine which drives an electrical generator. The axial-flow Wells turbine, invented in the mid 1970s, has the advantage of not requiring rectifying valves. It has been used in most prototypes.

Full sized OWC prototypes were built in Norway (in Toftestallen, near Bergen, 1985, [60]), Japan (Sakata, 1990, [61]), India (Vizhinjam, near Trivandrum, Kerala state, 1990, [20]), Portugal (Pico, Azores, 1999, [62]), UK (the LIMPET plant in Islay island, Scotland, 2000, [63]). The largest of all, a nearshore bottom-standing plant (named OSPREY) was destroyed by the sea (in 1995) shortly after having been towed and sunk into place near the Scottish coast. In all these cases, the structure is fixed (bottom-standing or built on rocky sloping wall) and the main piece of equipment is the Wells air turbine driving an electrical generator. Except for the OSPREY, the structure was made of concrete. The cross-sectional area of these OWCs (at mid water-free-surface level) lies in the range 80-250m^2. Their installed power

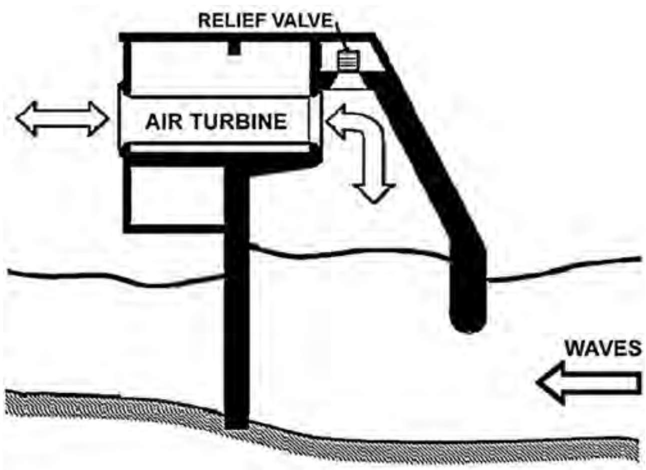

Figure 3.9 – Cross-sectional view of a bottom-standing OWC (Pico plant).

capacity is (or was) in the range 60-500 kW (2 MW for OSPREY). Smaller shoreline OWC prototypes (also equipped with Wells turbine) were built in Islay, UK (1991, [64]), and more recently in China.

It has been found theoretically [65] and experimentally since the early 1980s that the wave energy absorption process can be enhanced by extending the chamber structure by protruding (natural or man-made) walls in the direction of the waves, forming a harbour or a collector. This concept has been put into practice in most OWC prototypes. The Australian company Energetech developed a technology using a large parabolic-shaped collector (shaped like a Tapchan collector) for this purpose (a nearshore prototype was tested at Port Kembla, Australia, in 2005 [66]); the main novelty lies mostly in the large size of the converging wall compared with the dimensions of the OWC itself [67].

The design and construction of the structure (apart from the air turbine) are the most critical issues in OWC technology and the most influential on the economics of energy produced from the waves. In the present situation, the civil construction dominates the cost of the OWC plant. The integration of the plant structure into a breakwater has several advantages: the constructional costs are shared and the access for construction, operation and maintenance of the wave energy plant become much easier. This was done successfully for the first time in the harbour of Sakata, Japan, in 1990 [61], where one of the caissons making up the breakwater had a special shape to accommodate the OWC and the mechanical and electrical equipment. The option of the "breakwater OWC" was adopted in the 0.75 MW twin-chamber OWC plant planned to be installed in the head of a breakwater in the mouth of the Douro river (northern Portugal) [68] and in the recently constructed breakwater at the port of Mutriku, in northern Spain, with 16 chambers and 16 Wells turbines rated at 18.5kW each [69]. A different geometry for an OWC embedded into a breakwater was proposed by Boccotti [70], approaching a quasi-two-dimensional terminator configuration, with an OWC which is long in the wave crest direction but narrow (small aperture) in the fore-aft direction. The OWC cross-section is J-shaped, with its outer opening facing upwards. A field experiment was carried out off the eastern coast of the straits of Messina, in southern Italy [71].

Floating-structure OWC

As mentioned above in section 3.2.1, the first OWC converters deployed in the sea were floating devices developed in Japan in the 1960s and 1970s under the leadership of Yoshio Masuda: the wave-powered navigation buoys and the large Kaimei barge. Masuda realized that the wave-to-pneumatic energy conversion of Kaimei was quite unsatisfactory and conceived a different geometry for a floating OWC: the Backward Bent Duct Buoy (BBDB). In the BBDB, the OWC duct is bent backward from the incident wave direction (Figure 3.10) (which was found to be

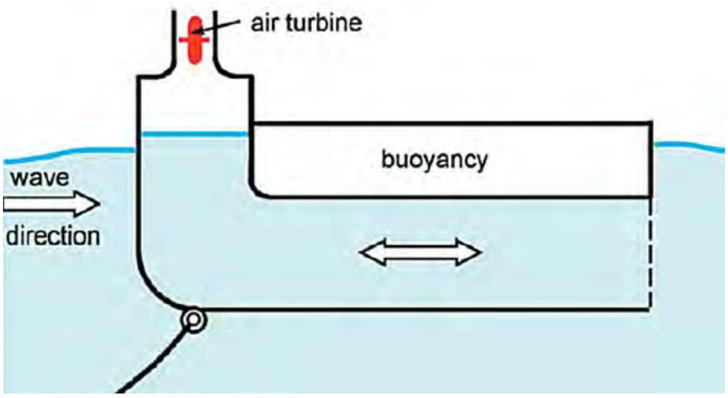

Figure 3.10 – Schematic representation of the Backward Bent Duct Buoy (BBDB).

advantageous in comparison with the frontward facing duct version) [72]. In this way, the length of the water column could be made sufficiently large for resonance to be achieved, while keeping the draught of the floating structure within acceptable limits. The BBDB converter was studied (including model testing) in several countries (Japan, China, Denmark, Korea, Ireland) and was used to power about one thousand navigation buoys in Japan and China [73,74]. In the last few years, efforts have been underway in Ireland to develop a large BBDB converter for deployment in the open ocean. A 1/4th-scale 12m-long model equipped with a horizontal-axis Wells turbine has been tested in the sheltered sea waters of Galway Bay (western Ireland) since the end of 2006 [75].

The Mighty Whale, another floating OWC converter, was developed by the Japan Marine Science and Technology Center. After theoretical investigations and wave tank testing, a full-sized prototype was designed and constructed. The device consists of a floating structure (length 50m, breadth 30m, draught 12m, displacement 4400t) which has three air chambers located at the front, side by side, and buoyancy tanks [76]. Each air chamber is connected to a Wells air turbine which drives an electric generator. The total rated power is 110 kW. The device was deployed near the mouth of Gokasho Bay, in Mie Prefecture, Japan, in 1998 and tested for several years.

The Spar Buoy is possibly the simplest concept for a floating OWC. It is an axisymmetric device (and so insensitive to wave direction) consisting basically of a (relatively long) submerged vertical tail tube open at both ends, fixed to a floater which moves essentially in heave. The length of the tube determines the resonance frequency of the inner water column. The air flow displaced by the motion of the OWC relative to the buoy drives an air turbine. Several types of wave-powered navigation buoys have been based on this concept, which has also been considered for larger scale energy production. The Sloped Buoy has some similarities with the Spar Buoy and consists of a buoy with three sloped immersed tail tubes such that the buoy-tube set is made to oscillate at an angle intermediate between the heave and surge directions.

A report prepared for the British Department of Trade and Industry (DTI) compared three types of floating OWCs for electricity generation in an Atlantic environment: BBDB, Sloped Buoy and Spar Buoy [77].

The floating OWC devices briefly described above are slack-moored to the sea bed and so are largely free to oscillate (which may enhance the wave energy absorption if the device is properly designed for that). The Orecon, under development in UK, is a floating OWC device which is tension moored to the sea bed. It is a multi-resonance converter with several vertical OWCs of different lengths, each chamber being connected to an air turbine[78].

“ 3.2.7. OSCILLATING BODY SYSTEMS

Offshore devices (sometimes classified as third generation devices) are basically oscillating bodies, either floating or (more rarely) fully submerged. They exploit the more powerful wave regimes available in deep water (typically more than 40m water depth). Offshore wave energy converters are in general more complex compared to the first generation systems. This, together with additional problems associated with mooring, access for maintenance and the need of long underwater electrical cables, has hindered their development, and only recently some systems have reached, or come close to, the full-scale demonstration stage.

Single-body heaving buoys

The simplest oscillating-body device is the heaving buoy reacting against a fixed frame of reference (the sea bottom or a bottom-fixed structure). In most cases, such systems are conceived as point absorbers (i.e. their horizontal dimensions are much smaller than the wavelength).

An early attempt was a device named G-1T, consisting of a wedge-shaped buoy of rectangular planform (1.8m×1.2m at water line level) whose vertical motion was guided by a steel structure fixed to a breakwater. The used PTO was an early example of the hydraulic ram in a circuit including a gas accumulator. The tests, performed in Tokyo Bay in 1980, are reported in [79].

Another early example was the Norwegian buoy, consisting of a spherical floater which could perform heaving oscillations relative to a strut connected to an anchor on the sea bed through a universal joint [80]. The buoy could be phase-controlled by latching and was equipped with an air turbine. A model (buoy diameter = 1 m), in which the air turbine was simulated by an orifice, was tested (including latching control) in the Trondheim Fjord in 1983 (Figure 3.11).

An alternative design is a buoy connected to a bottom-fixed structure by a cable which is kept tight by a spring or similar device. The relative motion between the wave-activated float on the sea surface and the seabed structure activates a PTO system. In the device that was tested in Denmark in the 1990s, the PTO (housed in a bottom-fixed structure) consisted of a piston pump supplying high-pressure water to a hydraulic turbine [81].

A version of the taut-moored buoy concept is being developed at Uppsala University, Sweden and uses a linear electrical generator (rather than a piston pump) placed on the ocean floor [82]. A line from the top of the generator is connected to a buoy located at the ocean surface, acting as power takeoff. Springs attached to the translator of the generator store energy during half a wave cycle and simultaneously act as a restoring force in the wave troughs (Figure 3.12). Sea tests off the western coast of Sweden of a 3 m diameter cylindrical buoy are reported in [82].

Another system with a heaving buoy driving a linear electrical generator was recently developed at Oregon State University, USA [83]. It consists of a deep-draught spar and an annular saucer-shaped buoy (Figure 3.13). The spar is taut-moored to the sea bed by a cable. The buoy is free to heave relative to the spar but is constrained in all other de-

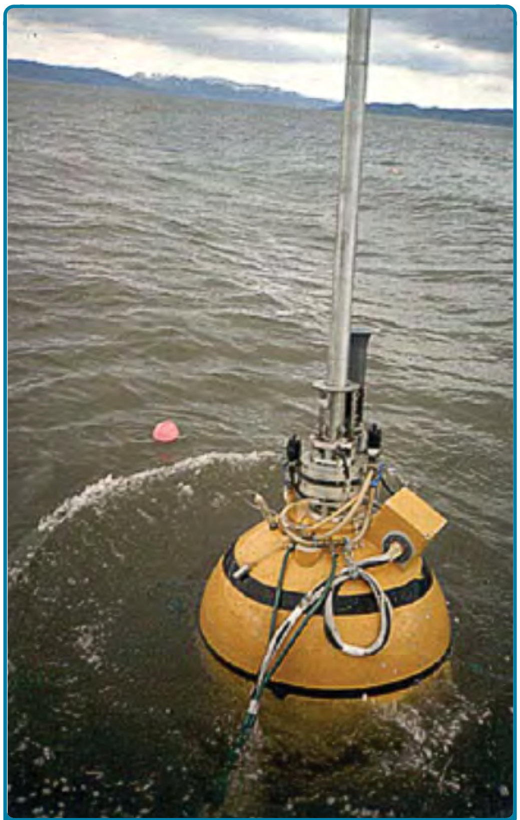

Figure 3.11 – Norwegian heaving buoy in Trondheim Fjord, 1983 (courtesy of J. Falnes).

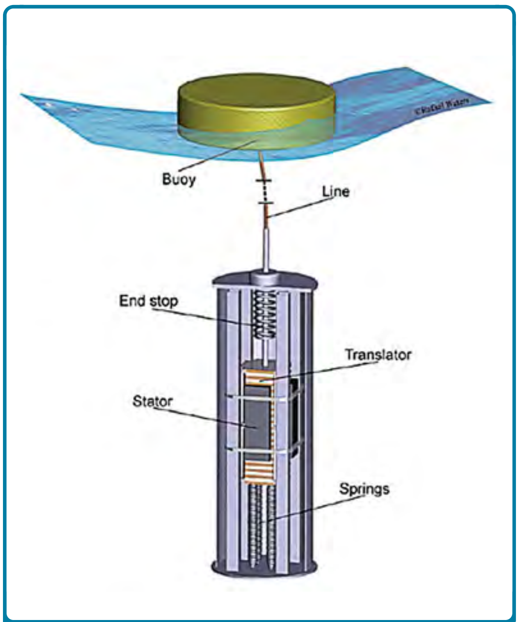

Figure 3.12 – Swedish heaving buoy with linear electrical generator (courtesy of Uppsala University).

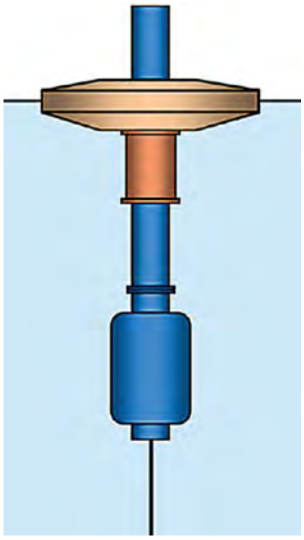

Figure 3.13 – L-10 wave energy converter with linear electrical generator, developed at Oregon State University.

grees of freedom by a linear bearing system. The forces imposed on the spar by the relative velocity of the two bodies are converted into electricity by a permanent magnet linear generator. The spar is designed to provide sufficient buoyancy to resist the generator force in the down direction. A 10kW prototype L-10 (buoy outer radius 3,5m, spar length 6.7m) was deployed off Newport, Oregon, in September 2008, and tested [82].

Two-body heaving systems

The concept of a single floating body reacting against the sea floor may raise difficulties due to the distance between the free surface and the bottom and/or to tidal oscillations at sea level. Multi-body systems may be used instead, in which the energy is converted from the relative motion between two bodies oscillating differently. The hydrodynamics of two-body systems were theoretically analysed in detail by Falnes [84]. Multi-body wave energy converters raise special control problems [59,85-86].

The Bipartite Point Absorber concept [87] is an early example of a two-point heaving system. It consists of two floaters, the outer one (with very low resonance frequency) being a structure which acts as the reference and the inner one acting as the resonating absorber. This device incorporates a concept which was later to be adopted in the Wavebob (see below): the mass of the inner body is increased (without significantly affecting the diffraction and radiation damping forces) by rigidly connecting it to a fully submerged body located sufficiently far underneath.

One of the most interesting two-body point absorbers for wave energy conversion is the IPS buoy, invented by Sven A. Noren [88] and initially developed in Sweden by the company Interproject Service (IPS). This consists of a buoy rigidly connected to a fully submerged vertical tube (the so-called acceleration tube) open at both ends (Figure 3.14). The tube contains a piston whose motion relative to the floater-tube system (motion originated by wave action on the floater and by the inertia of the water enclosed in the tube) drives a power take-off (PTO) mechanism. The same inventor later introduced an improvement which significantly contributes to solve the problem of the end-stops: the central part of the tube, along which the piston slides, bells out at either end to limit the stroke of the piston [89]. A half-scale prototype of the IPS buoy was tested in sea trials in Sweden, in the early 1980s [90]. The AquaBuOY is a wave energy converter, developed in the 2000s, which combines the IPS buoy concept with a pair of hose pumps to produce a flow of water at high pressure that drives a Pelton

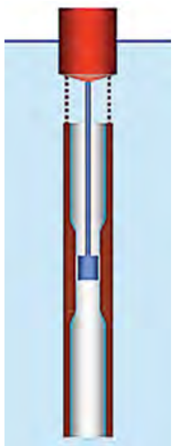

Figure 3.14 – Schematic representation of the IPS buoy.

turbine [91]. A prototype of the AquaBuOY was deployed and tested in 2007 in the Pacific Ocean off the coast of Oregon. A variant of the initial IPS buoy concept, due to Stephen Salter, is the sloped IPS buoy: the natural frequency of the converter may be reduced and in this way the capture width enlarged, if the buoy-tube set is made to oscillate at an angle intermediate between the heave and the surge directions. The sloped IPS buoy has been studied since the mid-1990s at the University of Edinburgh, by model testing and numerical modelling [92-94].

The Wavebob, under development in Ireland, is another two-body heaving device [95]. It consists of two co-axial axisymmetric buoys, whose relative axial motions are converted into electric energy through a high-pressure-oil system (Figure 3.15). The inner buoy (body 2 in Figure 3.11) is rigidly connected to coaxial submerged body located underneath, whose function is to increase the inertia (without reduction in the excitation and radiation hydrodynamic forces) and allow the tuning to the average wave frequency. A large (1/4th scale) model has been tested in the sheltered waters of Galway Bay (Ireland).

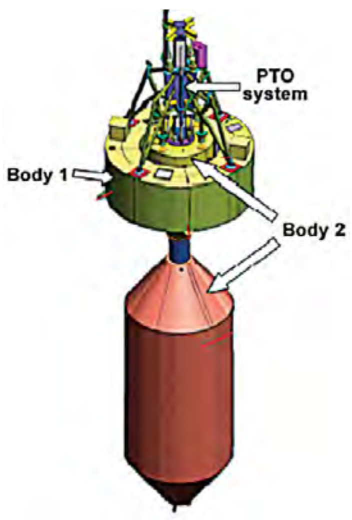

Figure 3.15 – Wavebob (courtesy of Wavebob Ltd).

The American company Ocean Power Technologies developed another axisymmetric two-body heaving WEC named PowerBuoy. A disc-shaped floater reacts against a submerged cylindrical body, terminated at its bottom end by a large horizontal damper plate whose function is to increase the inertia through the added mass of the surrounding water. The relative heaving motion between the two bodies is converted into electrical energy by means of a hydraulic PTO. A 40kW prototype without grid connection was deployed off the coast of Santoña, in northern Spain, in September 2008 (Figure 3.16). This was planned to be followed by a farm of 9 buoys rated at 150kW each, the first version of which would be deployed in Scotland in 2009.

Fully submerged heaving systems

The Archimedes Wave Swing (AWS), a fully submerged heaving device, was basically developed in Holland and consists of an oscillating upper part (the floater) and a bottom-fixed lower part (the basement) (Figure 3.17) [96]. The floater is pushed down under a wave crest and moves up under a wave trough. This motion is resisted by a linear electrical generator, with the interior air pressure acting as a spring. The AWS device went for several years through a programme of theoretical and physical modelling. A prototype was built, rated 2 MW (maximum instantaneous power). After unsuccessful trials in 2001 and 2002 to sink it into position off the northern coast of Portugal, it was finally deployed and tested in the second half of 2004 [97]. The AWS was the first converter using a linear electrical generator.

Pitching devices

The oscillating-body wave energy converters briefly described above are nominally heaving systems, i.e. the energy conversion is associated with a relative translational motion. (It should be noted that, in some of them the mooring system allows other oscillation modes, namely surge and pitch). There are other oscillating-body systems in which the energy conversion is based on relative rotation (mostly pitch) rather than translation. This is remarkably the case of the nodding Duck (created by Stephen Salter, from the University of Edinburgh) probably the best known offshore device among those which appeared in the

Figure 3.16 – The PowerBuoy prototype deployed off Santoño, Spain, in 2008 (courtesy of Ocean Power Technologies).

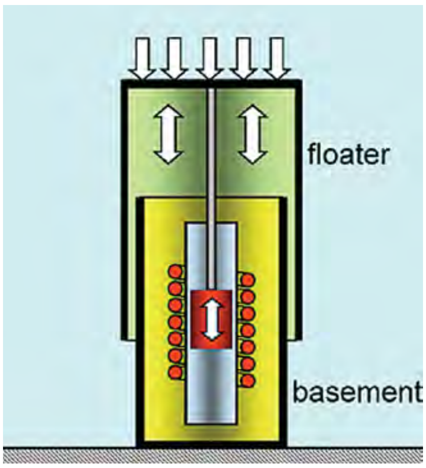

Figure 3.17 – Schematic representation of the Archimedes Wave Swing.

1970s and early 1980s [16] and of which several versions were developed in the following years [98]. Basically it is a cam-like floater oscillating in pitch. The first versions consisted of a string of Ducks mounted on a long spine aligned with the wave crest direction, with a hydraulic-electric PTO system. Salter later proposed the solo duck, in which the frame of reference against which the nodding duck reacts is provided by a gyroscope (Figure 3.18). Although the Duck concept was object to extensive R&D efforts for many years, including model testing at several scales [2], it never reached the stage of full-scale prototype in real seas.

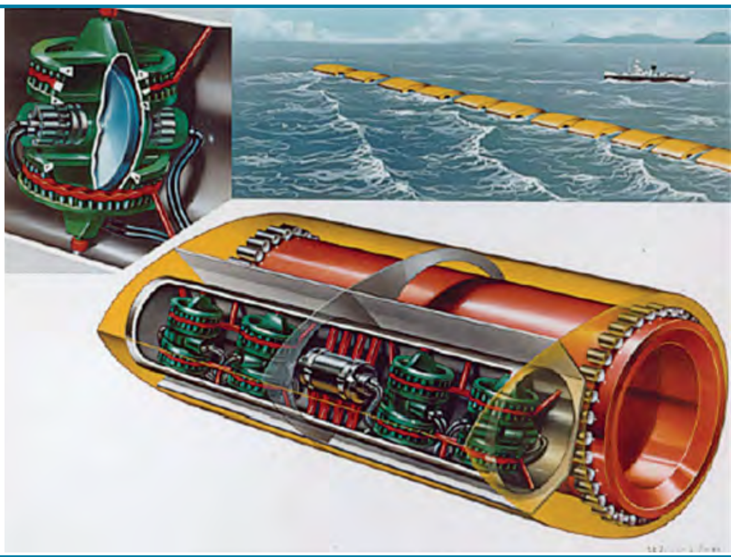

Figure 3.18 – The Duck version of 1979 equipped with gyroscopes (courtesy of University of Edinburgh).

Amongst the wide variety of devices proposed in the 1970s and 1980s which did not succeed in reaching a full-size testing stage (see [2]), reference should be made to the Raft invented by Sir Christopher Cockerell (who was also the inventor of the Hovercraft). This was actually a series of rafts or pontoons linked by hinges, which followed the wave contour, with a PTO system (possibly hydraulic) located at each hinge [2,17]. The Cockerell Raft may be regarded as the predecessor of a more successful device, the Pelamis, and also of the McCabe Wave Pump (see below).

The Pelamis, developed in UK, is a snake-like slack-moored articulated structure composed of four cylindrical sections linked by hinged joints, and aligned with the wave direction. The wave-induced motion of these joints is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors driving three electrical generators. Gas accumulators provide some energy storage. As other devices that reached full size, the Pelamis was the object of a detailed development program over several years, which included theoretical/numerical modelling and physical model testing at several scales [99,100]. Sea trials of a full-sized prototype (120m long, 3.5m diameter, 750 kW rated power) took place in 2004 in Scotland. A set of three Pelamis devices was deployed off the Portuguese northern coast in the second half of 2008 (Figure 3.19), making it the first grid-connected wave farm worldwide.

Figure 3.19 – The three-unit 3 x 750 kW Pelamis wave farm in calm sea off northern Portugal, in 2008 (courtesy of R. Barros).

The McCabe Wave Pump has conceptual similarities to the Cockerell Raft and the Pelamis: it consists of there rectangular steel pontoons hinged together, with the heaving motion of the central pontoon damped by a submerged horizontal plate [101] (Figure 3.20). Two sets of hydraulic rams and a hydraulic PTO convert the relative rotational motions of the pontoon into useful energy. A 40 m long prototype was deployed in 1996 off the coast of Kilbaha, County Clare, Ireland.

Two-body systems have been conceived in which only one body is in contact with the water: the other body is located above the water or is totally enclosed inside the wetted one (see [102] for an early example). The theoretical modelling and control of such devices (especially heaving ones and including also three-body systems) has been analysed by Korde [59,103].

A typical device based on the totally enclosed hull concept is the Frog, of which several offshore point-absorber versions have been developed at Lancaster University, UK. The PS Frog Mk 5 consists of a large buoyant paddle with an integral ballasted handle hanging below it [104,105] (Figure 3.21). The waves act on the blade of the paddle and the ballast beneath provides the necessary reaction. When the WEC is pitching, power is extracted by partially resisting the sliding of a power-take-off mass, which moves in guides above sea level.

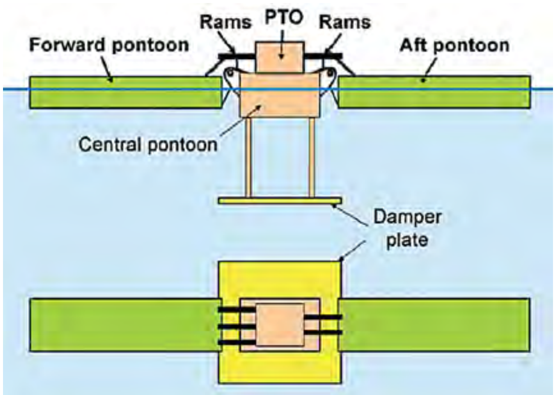

Figure 3.20 – Side and plan views of the McCabe Wave Pump.

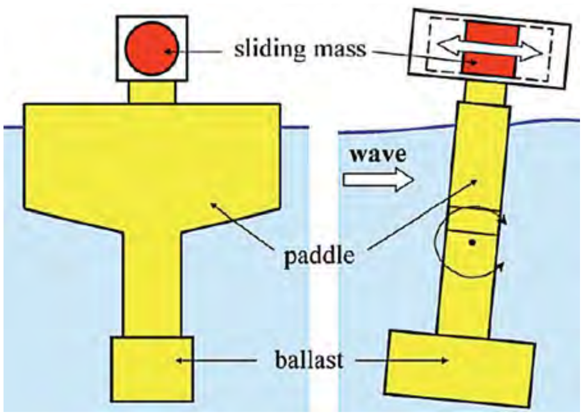

Figure 3.21 – Front and side views of the PS Frog Mk 5.

The Searev wave energy converter, developed at Ecole Centrale de Nantes, France [106], is a floating device enclosing a heavy horizontal-axis wheel serving as an internal gravity reference (Figure 3.22). The centre of gravity of the wheel being off-centred, this component behaves mechanically like a pendulum. The rotational motion of this pendular wheel relative to the hull activates a hydraulic PTO which, in turn, sets an electrical generator into motion. Major advantages of this arrangement are that (i) (like the Frog) all the moving parts (mechanic, hydraulic, electrical components) are sheltered from the action of the sea inside a closed hull, and (ii) the choice of a wheel working as a pendulum involve neither end-stops nor any security system limiting the stroke.

The Spanish company Oceantec is developing another offshore floating energy converter which extracts energy basically from the pitching motion. It has the shape of an elongated horizontal cylinder with ellipsoidal ends whose major axis is aligned with the incident wave direction [107]. The energy conversion process is based on the relative inertial motion that the waves cause in a gyroscopic system [108]. This motion is used to feed an electrical generator through a series of transformation stages. A 1/4th scale prototype (11.25 m long) was deployed off the coast of Guipúzcoa (northern Spain) in September 2008 and was tested for several months [107].

Bottom-hinged systems

Single oscillating-body devices operating in pitching mode have been proposed, based on the inverted pendulum hinged at the sea bed concept. The mace, invented by Stephen Salter [109], consists of a buoyant spar, with symmetry about the vertical axis that can swing about a universal joint at the sea bottom (Figure 3.23). The power take-off reaction to the sea bed is via a set of cables wound several times round a winch-drum leading both fore and aft in the prevailing wave direction. The wave-activated reciprocating rotation of the drum is converted into useful energy by means of a hydraulic system.

Two devices are presently under development that share the same basic concept: a buoyant flap hinged at the sea bed, whose pitching oscillations activate a set of double-acting hydraulic rams located on the sea bed that pump high pressure fluid to shore via a sub-sea pipeline. The fluid flow is converted into electric energy by a conventional hydraulic circuit. These devices are intended for deployment close to shore in relatively shallow water (10-15m). Apart from size (the Oyster is larger) and detailed design, there are some conceptual differences between them. The Oyster (under development in UK) has a surface piercing flap that spans the whole water depth and the fluid is sea water powering a Pelton turbine locat-

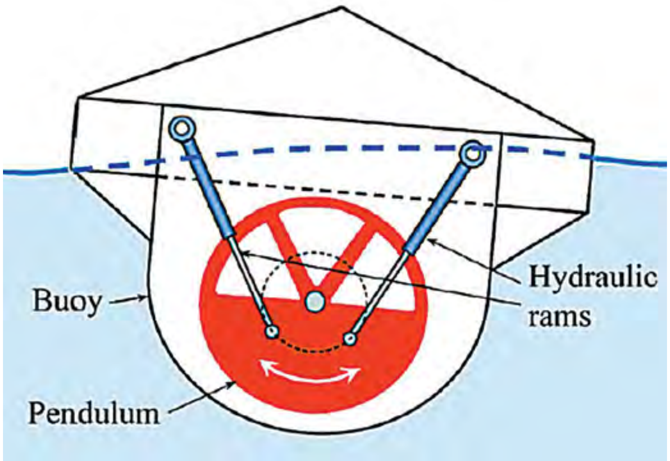

Figure 3.22 – Schematic representation of the Searev.

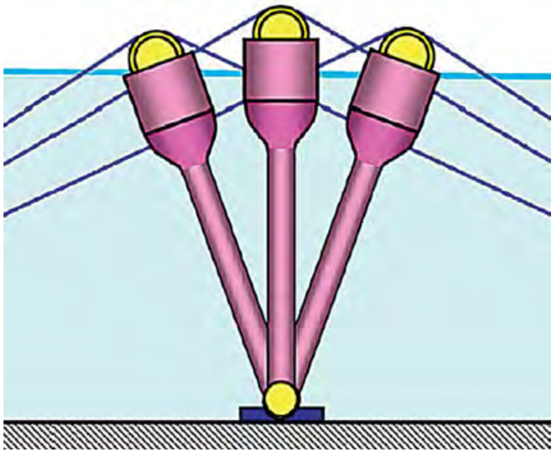

Figure 3.23 – The swinging mace in three angular positions.

ed onshore [110], whereas the WaveRoller (a Finish device) is totally submerged and uses oil as working fluid [111]. Several swinging flaps can feed a single onshore generator, attached to a single manifold pipeline. A 3.5m high, 4.5m wide prototype of the WaveRoller was deployed and tested in 2008 close to the Portuguese coast in Peniche. A large Oyster prototype was built in Scotland (Figure 3.24) and was planned to be tested in the sea in 2009. A comparison of designs for small seabed-mounted bottom-hinged wave energy converters can be found in [112].

Many-body systems

In some cases, the device consists of a large set of floating point absorbers reacting against a common frame and sharing a common PTO. This is the case of FO3 [113] (mostly a Norwegian project), a nearshore or offshore system consisting of an array of 21 axisymmetric buoys (or "eggs") oscillating in heave with respect to a large floating structure of square planform with very low resonance frequency and housing a hydraulic PTO. The Wave Star, developed in Denmark, consists of two rectilinear arrays of closely spaced floaters located on both sides of a long bottom-standing steel structure which is aligned with the dominant wave direction and houses a hydraulic PTO consisting of a high-pressure-oil hydraulic circuit equipped with hydraulic motors. The waves make the buoys swing about their common reference frame and pump oil into the hydraulic circuit. A 1/10-scale 24m long 5.5 kW model with 10 buoys on each side was deployed in 2006 in Nissum Bredning, Denmark and tested with a grid connection for a couple of years [114]. The Brazilian hyperbaric device is based on a similar concept, the main differences being that the reference frame about which the buoys are made to swing is a vertical breakwater and water is pumped to feed a Pelton turbine. A 1/10-scale model of the hyperbaric device was tested in a large wave tank [115].

3.2.8. OVERTOPPING CONVERTERS

A different way of converting wave energy is to capture the water that is close to the wave crest and introduce it, by over spilling, into a reservoir where it is stored at a level higher than the average free-surface level of the surrounding sea. The potential energy of the stored water is converted into useful energy through more or less conventional low-head hydraulic turbines. The hydrodynamics of overtopping devices is strongly non-linear and, unlike the cases of oscillating body and OWC wave energy converters, cannot be addressed by linear water wave theory.

Figure 3.24 – Oyster prototype (courtesy of Aquamarine Power).

The Tapchan (Tapered Channel Wave Power Device), a device developed in Norway in the 1980s, was based on this principle [116]. A prototype (rated power 350 kW) was built in 1985 in Toftestallen, Norway and operated for several years (for an aerial view see [117]). The Tapchan comprises of a collector, a converter, a water reservoir and a low-head water-turbine (Figure 3.25). The horn-shaped collector serves the purpose of concentrating the incoming waves before they enter the converter. In the prototype built in Norway, the collector was carved into a rocky cliff and was about 60-metre-wide at its entrance. The converter is a gradually narrowing channel with wall heights equal to the filling level of the reservoir (about 3 m in the Norwegian prototype). The waves enter the wide end of the channel and, as they propagate down the narrowing channel, the wave height is amplified until the wave crests spill over the walls and fill the water reservoir. As a result, the wave energy is gradually transformed into potential energy in the reservoir. The main function of the reservoir is to provide a stable water supply to the turbine. It must be large enough to smooth out the fluctuations in the flow of water overtopping from the converter (about 8500 m^2 surface area in the Norwegian prototype). A conventional low-head Kaplan-type axial flow turbine is fed in this way, its main specificity being the use of corrosion-resistant material.

In other overtopping converters, the incident waves overtop a sloping wall or ramp and fill a reservoir where water is stored at a level higher than the surrounding sea. This is the case of the Wave Dragon, an offshore converter developed in Denmark, whose slack-moored floating structure consists of two wave reflectors focusing on the incoming waves towards a doubly curved ramp, a reservoir and a set of low-head hydraulic turbines (Figure 3.26) [118]. A 57m-wide, 237 t (including ballast) prototype of the Wave Dragon (scale 1/4.5 of a North Sea production plant) was deployed in Nissum Bredning, Denmark, it was grid connected in May 2003 and was tested for several years. Another run-up device based on the slopping wall concept is the Seawave Slot-Cone Generator (SSG) developed (within the framework of a European project) for integration into a caisson breakwater [119,120]. The principle is based on the wave overtopping utilizing a total of three reservoirs placed on top of each other. The water enters the reservoirs through long horizontal openings on the breakwater sloping wall, at levels corresponding to the three reservoirs and is run through a multi-stage hydraulic turbine for electricity production.

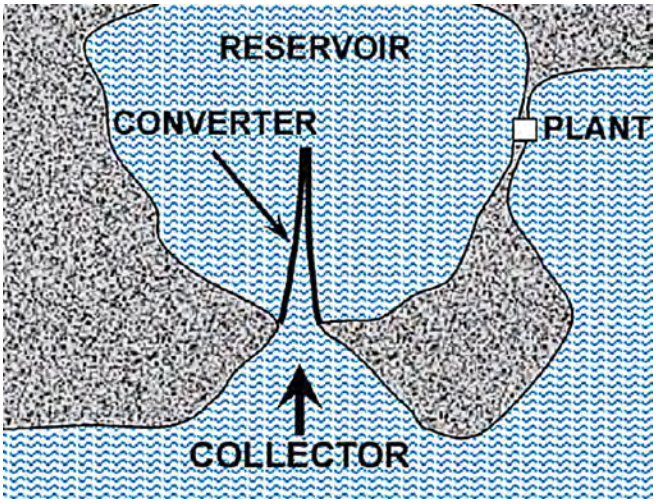

Figure 3.25 – Schematic plan view of the tapered channel wave power device (Tapchan).

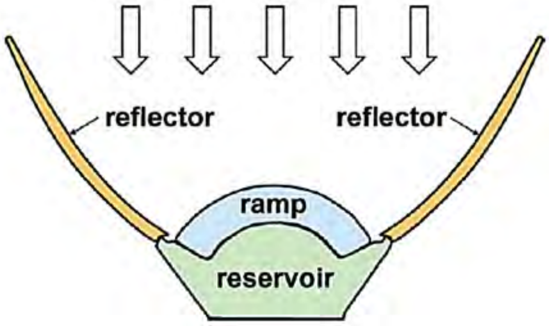

Figure 3.26 – Plan view of Wave Dragon.

3.2.9. POWER EQUIPMENT

In all cases considered here, the final product is electrical energy to be supplied to a grid. This energy has to be generated in some kind of electrical machine, either a more or less conventional rotating generator (as in small hydro and wind applications) or a direct-drive linear generator. In the former case, there has to be a mechanical interface which converts the alternative motion (of the oscillating body or body-pair or of the OWC) into a continuous one-directional motion. The most frequently used or proposed mechanical interfaces are air turbines, (low-and high-head) water turbines and (high-pressure oil driven) hydraulic motors. The power equipment is possibly the single most important element in wave energy technology and underlies many (possibly most) of the failures to date.

Air turbines equipped most of the early (small and large) wave energy converters and are still the favoured PTO for many development teams. Conventional turbines are not appropriate for reciprocating flows and so new types of turbines had to be devised and developed. Self-rectifying air turbines were probably the object of more published papers than any other piece of equipment for wave energy converters.

More or less conventional low-head hydraulic turbines are used in overtopping devices, whereas high-head (in general Pelton) turbines are an alternative to hydraulic motors in oscillating-body devices.

High-pressure-oil circuits, with rams, gas accumulators and hydraulic motors, have been used in several oscillating-body wave energy converter prototypes, including the Pelamis. This may be regarded as an unconventional use of conventional equipment.

Although linear electrical generators have been proposed since the late 1970s for wave energy devices with translational motion and have indeed equipped several devices tested in the sea (namely the AWS), they are still at the prototype development stage.

Energy storage capacity is a highly desirable feature in a wave energy converter and can be provided in a variety of manners, as is the case of the flywheel effect in air turbines, water reservoirs in run-up devices and gas accumulators in high-pressure hydraulic (water and oil) circuits. The use of large electrical capacitors in connection with linear-generator technology is being envisaged.

It is to be noted that, in his pioneering book on ocean wave energy conversion published in 1981 [1], McCormick dealt in considerable detail with air and water turbines and linear electrical generators but did not consider oil-hydraulics.

A review of mechanical power-take-off equipment for wave energy converters can be found in [121].

Self-rectifying air turbines

The air turbine of an OWC is subject to much more demanding conditions than the turbines in any other application, including wind turbines. Indeed the flow through the turbine is reciprocating (except if a rectifying system is provided, which so far has been found unpractical) and is random and highly variable over several time scales, ranging from a few seconds to seasonal variations. It is not surprising that the time-averaged efficiency of an air turbine in an OWC is substantially lower than that of a (water, steam, gas, wind) turbine working in nearly steady conditions. Several types of air turbines have been proposed and in some cases used, in wave energy conversion.

The Wells turbine was invented in the mid-1970s by Dr. Allan Wells (1924-2005) (at that time Professor at Queen's University of Belfast) [122,123]. It is an axial-flow turbine which is self-rectifying, i.e. its torque is not sensitive to the direction of the air flow. Several versions have been studied since then: a single rotor without (the initial version) or with guide vanes (used in Pico,Figure 3.27); twin rotors in series (bi-plane, used in Islay I); two counter-rotating rotors (used in OSPREY and in LIMPET-Islay II). All these versions have been object of considerable theoretical and/or experimental R&D, especially in Europe (UK, Portugal, Ireland, Japan, India and China). This gave rise to a substantial number of published papers.

The Wells turbine is clearly the most frequently proposed and/or used air turbine to equip OWC plants. Its favourable features are: (i) high blade to air-flow velocity ratio, which means that a relatively high rotational speed may be attained for a low velocity of air flowing through the turbine (this allows a cheaper generator to be used and also enhances the possibility of storing energy by flywheel effect); (ii) a fairly good peak efficiency (0.7-0.8 for a full-sized turbine); (iii) relatively cheap to construct. The weak points of the Wells turbine are: (i) low or even negative torque at (relatively) small flow rates; (ii) drop (possibly sharp drop) in power output due to aerodynamic losses at flow rates exceeding the stall-free critical value; (iii) aerodynamic noise; (iv) relatively large diameter for its power (2.3 m for the single-rotor 400 kW turbine of the Pico OWC plant, 2.6 m for the counter-rotating 500 kW turbine of the LIMPET Islay II plant, 3.5 m for the Osprey plant). For a review of the Wells turbine see [124]. An experimental investigation comparing the several versions of the Wells turbine is reported in [125].

Figure 3.28 represents (in dimensionless form, and from model testing results) the instanta-

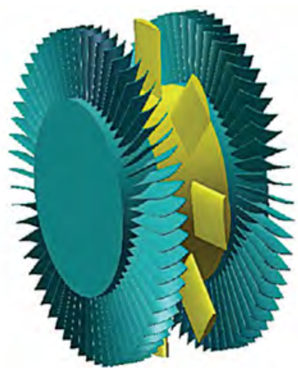

Figure 3.27 - Wells turbine, version with guide vanes.

neous efficiency η of a typical Wells turbine (single rotor and guide vanes) versus the available pressure head Ψ [43]

$$\Psi = \frac{\Delta p}{\rho_a N^2 D^2} \quad (8)$$

Here Δp is the pressure difference available to the turbine (coinciding approximately with the pressure difference between the plant's air chamber and the atmosphere), ρ_a the air density, N the rotational speed (radians per unit time) and D the turbine rotor outer diameter. Figure 3.28 shows that the efficiency remains at about 0.7 for instantaneous pressures within the range 0.05-0.11 but drops sharply on both sides of this interval. Of course, in reciprocating air-flow produced by real irregular waves, the pressure randomly oscillates, passing through zero from positive to negative values and vice-versa. In this case it is more useful to characterize the efficiency by its time-averaged value $\bar{\eta}$ and the pressure by its rms value (or variance) σ_Ψ [43]. This is shown by another line in Figure 3.28, which should be taken as representative of the turbine (average) performance in real random waves. We see that the average efficiency reaches a maximum of about 0.58 for $\sigma_\Psi \cong 0.05$. Obviously it would be desirable to keep σ_Ψ close to 0.05. We recall that Ψ

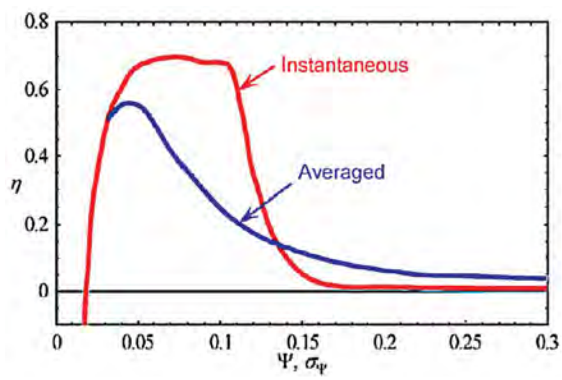

Figure 3.28 – Aerodynamic efficiency curves of a Wells turbine.

, and hence σ_Ψ , are dimensionless values ((Eq. (8)); it follows that in rougher seas (higher waves and larger amplitudes of pressure oscillation) the turbine should be controlled to rotate faster. An optimal control law is $L_e^\alpha = \text{constant} \times N$, where L_e is the instantaneous electromagnetic torque to be applied on the generator rotor and α is an exponent whose value is close to 3 and depends weakly on the OWC hydrodynamic coefficients [126] (this also applies to the impulse turbine, see below).

If the setting angle of the rotor blades of a Wells turbine can be controlled during normal operation, then the efficiency curve becomes substantially wider. This idea was put into practice a long time ago in the well-known Kaplan water-turbines and also aircraft and ship variable-pitch screw-propellers. The concept of the variable-pitch Wells turbine was proposed in the 1980s and was object of theoretical and experimental studies [127,128]. A full-sized 400 kW prototype was designed and constructed to be installed in the Azores OWC [129]. If the rotor blade pitch angle is adequately controlled, a substantial improvement in time-averaged turbine efficiency can be achieved. Of course, the negative side is a more complex and more expensive machine as compared to the mechanically simple and robust conventional Wells turbine.

The most popular alternative to the Wells turbine seems to be the self-rectifying impulse turbine, patented by I.A. Babinsten in 1975 [130]. Its rotor is basically identical to the rotor of a conventional single-stage steam turbine of axial-flow impulse type (the classical de Laval steam turbine patented in 1889). Since the turbine is required to be self-rectifying, instead of a single row of guide vanes (as in the conventional de Laval turbine) there are two rows, placed symmetrically on both sides of the rotor (Figure 3.29). These two rows of guide vanes are like the mirror image of each other with respect to a plane through the rotor disc. A severe limitation in the turbine efficiency results from aerodynamic stalling at the downstream row of guide vanes. Most of the R & D on this type of turbine has been done in Japan (and to a less extent in India, China, UK and Ireland) in the last twenty years or so (for a review, see [131]).

The advantages and disadvantages of the self-rectifying impulse turbine as compared to the Wells turbine are not clear and of course depend on which versions of each are being compared. It should be pointed out that the efficiency of the Wells turbine is quite sensitive to Reynolds number (more so than more conventional turbine types like the impulse turbine): tests done on small Wells turbine models should not be taken as representative of what can be achieved at full size. For this reason, comparisons between the Wells turbine and the impulse turbine, based on tests on small models, should be considered with some reservation. In general, one can say that the

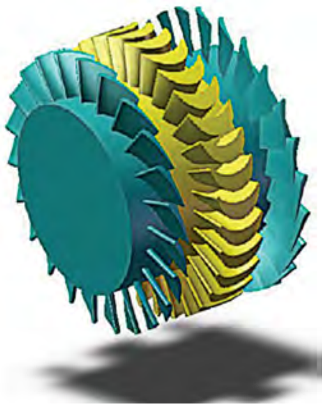

Figure 3.29 – Impulse turbine.

Wells turbine is characterized by a considerably higher rotational speed than the impulse turbine, which enhances the storage of energy by flywheel effect (with the resulting smoothing effect upon power delivered to the grid) and is expected to allow a cheaper electrical generator to be used (smaller number of poles). The impulse turbine, due to its smaller blade speed, is less constrained by Mach number effects and centrifugal stresses which may be an important advantage in very energetic wave climates [132].

The so-called Denniss-Auld turbine, developed in Australia to equip OWC plants [133], is also a self-rectifying turbine, which shares some characteristics with the variable-pitch Wells turbine, the main difference being that the angle of stagger ε ($\varepsilon=0$ means blade along a longitudinal plane, $\varepsilon=\pi/2$ on a cross-sectional plane) of the Denniss-Auld rotor blades may be controlled to vary within a range $-\alpha<\varepsilon<\alpha$ (where $\alpha\cong 55°$) (Figure 3.30), whereas in the variable-pitch Wells turbine it is $\pi/2-\beta<\varepsilon<\pi/2+\beta$ (with $\beta\cong 25°$). While in the Wells turbine the rotor blade rounded leading edge faces the incoming flow all the time, in the Denniss-Auld turbine both edges of a blade must be identical since each edge behaves alternately as a leading edge or as a trailing edge depending on the direction of the reciprocating flow through the turbine. It is to be noted that whenever the flow changes direction (exhaust to inlet or vice-versa) the blades of the Denniss-Auld turbine are required to pivot almost instantaneously between their extreme positions, whereas in the Wells turbine the blades are required to pivot smoothly within a relatively small angular range.

These self-rectifying air turbines, especially the fixed-geometry ones, are mechanically simple and reliable machines. Based on available information, their time-averaged efficiency is relatively modest (compared with more conventional turbines operating in near steady state conditions), hardly exceeding 0.5-0.6, even if their rotational speed is controlled to match the current sea state (especially the significant wave height).

Hydraulic turbines

As in conventional mini-hydroelectric low-head plants [134,135], axial-flow reaction turbines are used to convert the head (typically 3-4 m at full size) created between the reservoir of an overtopping device and the mean sea level. The flow may be controlled by adjustable inlet guide vanes. In some cases the blades of the runner can also be adjusted (Kaplan turbines) which greatly improves efficiency over a wide range of flows; however this can be costly and is not normally employed in the small turbines typical of wave energy applications.

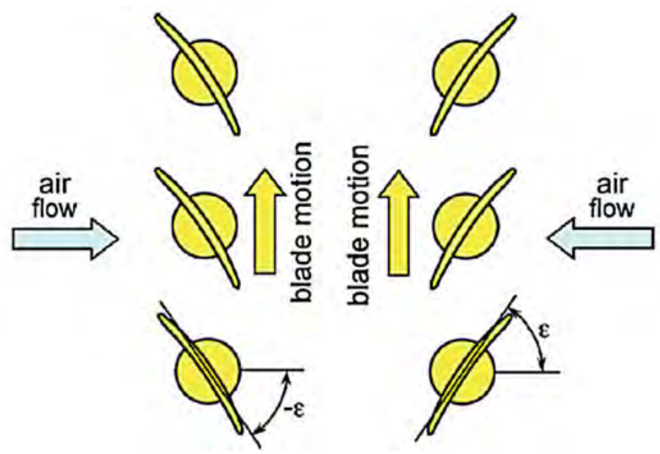

Figure 3.30 –Denniss-Auld air turbine. The rotor blades pivot rapidly between extreme positions when the air flow is reversed.

High-head (typically tens to hundreds of metres) impulse turbines (mostly of Pelton type) are adopted in some oscillating-body converters, as alternatives to hydraulic motors, with the advantage of using non-pollutant water (rather than oil) [91,110,115]. The flow may be controlled by a needle whose axial position within the nozzle is controlled by a servomechanism. The hydraulic circuit includes a ram (or set of rams) (a pair of hose pumps in Aquabuoy) and may include also a gas accumulator system.

These (low- and high-head) hydraulic turbines may reach peak efficiencies about 0.9. Their efficiency is in general quite sensitive to the head-to-rotational-speed ratio, which makes the use of variable-speed electrical generators highly advantageous, especially in the case of Pelton turbines equipping oscillating-body converters.

High-pressure oil-hydraulics

High-pressure oil systems are particularly suitable to convert energy from the very large forces or moments applied by the waves on slowly oscillating bodies (in translation or rotation) (Figure 3.31). The hydraulic circuit usually includes a gas accumulator system capable of storing energy over a few wave periods, which can smooth out the very irregular power absorbed from the waves. The body motion is converted into hydraulic energy by a hydraulic cylinder or ram (or a set of them). A fast hydraulic motor drives a conventional electrical generator.

The engineering problems raised in this kind of PTO for wave energy applications are analysed in [121,136].

The oil-hydraulic PTO was used to equip the heaving buoy tested in Tokyo Bay in 1980 (see section 3.2.7 – Single body heaving buoys) and, more recently, the Wavebob, PowerBuoy and Pelamis devices (section 3.2.7 – Two-body heaving systems) and the WaveRoller (section 3.2.7 – Bottom-hinged systems).

The most frequently used type of fast hydraulic motor in wave energy applications is the axial-piston bent-axis variable-displacement machine (Fig. 28), available from a few manufacturers in the rated power range between a few kW and about 1 MW, with operating oil-pressures of up to about 350 bar. Even large (one-MW) machines can drive an electrical generator at speeds exceeding 1500 rpm. The motor consists of a drive shaft with a flange, which is constrained to rotate together with a cylinder block inside in which there is a set (usually odd number) of cylinders arranged axially parallel to each other around the circumferential periphery of the block. The two axes of rotation make a non-zero angle β. The piston displacement depends on the angle β between the drive shaft axis and the cylinder block axis (Figure 3.32). The flow rate is proportional to $N\tan\beta$, where N is the rotational speed [137]. This allows the instantaneous flow rate to be controlled by changing the rotational speed N of the motor-generator set and/or by adjusting the setting-angle β.

Energy can be stored in and released from, a gas accumulator system, consisting of a high-pressure accumulator and a low-pressure reservoir (Figure 3.31). The gas, usually nitrogen, is separated from the oil by a bladder or by a free piston. In order to avoid cavitation in the circuit, the pressure in the reservoir is kept above a few bar. High-pressure gas accumulators are designed to withstand pressures of up to about 500-600 bar. The amount of energy stored per unit mass of gas is $\Delta E = c_v \Delta T$, where c_v is the specific heat at constant volume and T is absolute temperature. Over small time intervals (not exceeding, say, a few minutes) the compression/decompression process may be regarded as approximately isentropic. Assuming the gas to behave as a perfect gas, we may write

$$\Delta T = T\left\{\left(\frac{p+\Delta p}{p}\right)^{(\gamma-1)/\gamma} - 1\right\} \tag{9}$$

Here, p is pressure, Δp is increase in pressure and $\gamma = c_p/c_v$ is the specific pressure ratio. For nitrogen it is $\gamma \cong 1.4$ and $c_v \cong 0.74$ kJ/(kg K). Usually a set of high-pressure gas accumulators interconnected in parallel is required to provide a suitable smoothing effect to a full-sized wave energy converter and may represent a significant part of the PTO capital cost. Criteria for the specification/de-

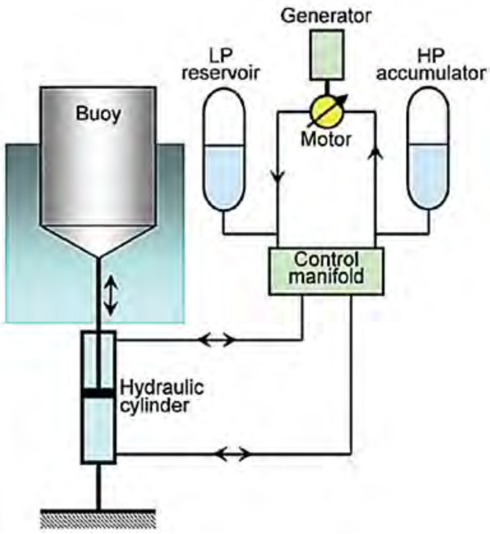

Figure 3.31 – Schematic representation of the hydraulic PTO of a heaving wave energy converter.

sign of gas accumulator systems for wave energy applications can be found in [138].

The damping provided by a hydraulic PTO is highly non-linear and (except if the reactive phase control is envisaged) it may be regarded as Coulomb damping: the piston in the hydraulic cylinder remains stationary for as long as the force applied on its shaft is less than $S(p_H - p_L)$, where S is piston area and $p_H - p_L$ is the pressure difference between the high-pressure and low-pressure accumulators. The oil flow rate admitted to the hydraulic motor should increase with the absorbed wave-power level. It may be shown that its instantaneous value should be controlled (by adjusting the rotational speed and/or the motor geometry) to remain proportional to the pressure difference $p_H - p_L$ [138]. This kind of PTO is highly suitable for phase control by latching: to do this, the control manifold in the hydraulic circuit remains locked for as long as the control algorithm specifies the piston to remain fixed. A simple latching control algorithm was proposed in [139].

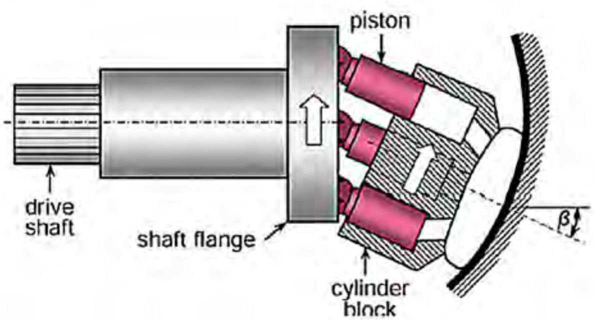

Figure 3.32 – Schematic representation of a variable-displacement hydraulic motor of axial-piston bent-axis type, showing the cylinder block with pistons and the drive shaft flange. The piston displacement can be varied by changing the setting angle β between the shaft axis and the cylinder block axis.

Although little has been disclosed on the performance of recent sea-tested prototypes equipped with hydraulic PTO, it appears that some concerns are related to lower-than-expected energy conversion efficiency and the limited estimated life-span of hydraulic ram seals. New designs of hydraulic equipment, specifically for wave energy applications, may be the way to proceed, as advocated by Stephen Salter and his co-workers [98,121].

Electrical equipment

In most wave energy converters, a rotating electrical generator is driven by a mechanical machine: air or hydraulic turbine, hydraulic motor. The electrical equipment, including variable rotational speed and power electronics, is mostly conventional and largely similar to wind energy conversion. If the driving machine is a variable displacement hydraulic motor, it is possible to keep the rotational speed fixed while controlling the flow rate and power by adjusting the motor geometry (see section 3.2.9 – High-pressure oil-hydraulics).

This is not the case of direct drive conversion, without mechanical interface, by a linear electrical generator, already considered in McCormick's book [1]. The first prototype equipped with a linear electrical generator (rated 2 MW) was the bottom-standing Archimedes Wave Swing (AWS) (Figure 3.17), tested in the sea in 2004 [97]. More recently, heaving buoys equipped with linear generators were sea-tested off Sweden (Figure 3.12) [82] and Oregon, USA (Figure 3.13) [83]. In these buoys, the force that drives the generator is provided by a taught mooring line.

Direct drive has the advantage of not requiring a mechanical interface and avoiding the non-negligible losses which take place in the mechanical machines (turbines and hydraulic motors) in the more conventional PTO systems. On the other hand, linear electrical generators for wave energy applications are subject to much more demanding conditions than high-speed rotary ones and are to a large extent still at the development stage in several countries: Holland [140], UK [141], Sweden [142], USA [143]. The generator consists of a stator and a translator (rather than a rotor). In wave energy applications, the generator reciprocating motion matches the motion of the actual device, at speeds two orders of magnitude lower than the velocities typical of high-speed rotary generators. At such low speeds, the forces are very large, which requires a physically large machine. For an overview of direct drive technology in wave energy converters, see [143,145]. The phase-control of a wave energy converter (like the AWS) equipped with a linear generator raises special problems [146].

3.2.10. MOORINGS

Free floating bodies, like oil and gas platforms, are subject to drift forces due to waves, currents and wind, and so they have to be kept on station by moorings [147]. This is also the case of a large class of floating wave-energy converters for deployment offshore, typically in water depths between 40 and 100m. (Early contributions to the mooring design of such wave energy converters can be found in [1,148]). Although similarities can be found between those applications, the mooring design requirements will have some important differences, one of them associated to the fact that, in the case of a wave energy converter, the mooring connections may significantly modify its energy absorption properties by interacting with its oscillations [149].

The mooring, especially the slack-mooring, of floating wave energy converters has been addressed in the last few years by several authors [149-154]. Due to the catenary effect, the inertia of the mooring lines and hydrodynamic drag forces, the three-dimensional dynamics of the mooring system and its interaction with the oscillating moored floater is non-linear and quite complex (there are several commercial codes available for mooring analysis). Fitzgerald and Bergdahl [152] studied in detail the effect of the mooring connections upon the performance of a wave energy converter, by linearizing the mooring forces about the static condition, which conveniently allows a frequency-domain analysis to be applied.

Little attention seems to have been devoted in the published literature to the mooring design of free-floating point absorbers in dense arrays. This may be explained by the present stage of development of the technology (focusing on single prototypes) and/or by the restricted availability of such information. In such cases, it may be more convenient that the array is spread-moored to the sea bottom by slack mooring lines through only some of its elements, located in the periphery, while the other array elements are prevented from drifting and colliding with each other by connections to adjacent elements. This has been analysed in [155], where the hydrodynamics of the mooring of an array of identical floating point absorbers located at the grid points of an equilateral triangular grid is considered.

3.2.11. CONCLUSION

Unlike in the case of wind energy, the present situation shows a wide variety of wave energy systems, at several stages of development, competing against each other, without it being clear which types will be the final winners.

In the last fifteen years or so, most of the R&D activity in wave energy has been taking place in Europe, largely due to the financial support and coordination provided by the European Commission and to the positive attitude adopted by some European national governments (especially in the last few years). However, in the last few years, interest in wave energy utilization has been growing rapidly also in other parts of the world.

In general, the development, from concept to commercial stage, has been found to be a difficult, slow and expensive process. Although substantial progress has been achieved in the theoretical and numerical modelling of wave energy converters and of their energy conversion chain, model testing in wave basin - a time-consuming and considerably expensive task - is still essential. The final stage is testing under real sea conditions. In almost every system, optimal wave energy absorption involves some kind of resonance, which implies that the geometry and size of the structure are linked to wavelength. For these reasons, if pilot plants are to be tested in the open ocean, they must be large structures. For the same reasons, it is difficult, in the wave energy technology, to follow what was done in the wind turbine industry (namely in Denmark): relatively small machines where developed first, and were subsequently scaled up to larger sizes and powers as the market developed. The high costs of constructing, deploying, maintaining and testing large prototypes under sometimes very harsh environmental conditions, has hindered the development of wave energy systems; in most cases such operations were possible only with substantial financial support from governments (or, in the European case, from the European Commission).

3.2.12. ACKNOWLEDGEMENT

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3.3. TIDAL ENERGY AND OCEAN CURRENT ENERGY

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Peter Scheijgrond is the owner of MET-support, a company that supports the realization of marine energy projects. He holds engineering degrees from the University of Glasgow, the Glasgow School of Art, Strathclyde University and the Hanzehogeschool Groningen, University of Applied Sciences. For over 15 years he has been actively involved in the marine energy sector as a technology developer and as a project consultant. At Ecofys, for over a period of 10 years he developed the Wave Rotor technology. As part of a spin-out company OceanMill, the Wave Rotor technology and all rights were sold to offshore contractor IHC in 2012 after which he started MET-support. He is a founding member of the Dutch Energy from Water Association (EWA) and an acting observer to the Implementing Agreement on Ocean Energy Systems of the International Energy Agency (IEA-OES). He currently chairs the IEC TC114 Dutch mirror committee for the development of standards of marine energy convertors.

3.3.1. INTRODUCTION

Over the years, numerous people have noticed the movement of ocean currents and speculated on their potential as a usable source of energy. As long as there seemed to be adequate reserves of fossil fuels to supply power plants, there was little reason to investigate the ocean currents as an alternative or even supplemental source of energy. The situation turned around when the world reached the point in time where it could see its supply of fossil fuels being depleted at a rapid pace. The consequent increase in the prices of those fuels following the 1970's fuel crisis and the subsequent concern for the environmental protection led energy planners, governments, utilities, scientists and engineers to seek out and develop those forms of energy which are renewable and are least polluting in their environmental impact on the world's ecology. Tidal and ocean currents started to receive serious consideration. In this chapter the technology status is described, focussing on technologies that have been demonstrated in open waters.

The Technologies

There are two fundamental concepts to harness tidal and ocean currents: those devices which rely mainly on drag forces and those which rely mainly on lift forces. Drag devices, such as the water wheel or Savonius, are usually large structures, which may be partially submerged or fully submerged. Drag devices have low rotor power coefficients (less than 0.2). Drag results from the relative velocity between the fluid and the device, so that the velocity of the device must always be less than the fluid velocity. This limits the power produced per unit of projected area. They are generally "high torque - low speed" devices.

Lift devices are said to be more efficient, because they use lifting surfaces which can operate at velocities well in excess of the fluid velocity. Three basic concepts can be distinguished (Figure 3.33): axial- flow rotors, cross-flow rotors (Figure 3.34) and (linear) translating devices.

The efficiency of all types of turbines is limited by Betz Limit of 59.3% when the rotor is place in a free unducted flow. Some technology look at a duct to create a venture effect, an accelerated flow through the turbine rotor. Locally this may increase the efficiency at the rotor beyond Betz' limit. However, Betz' limit still applies to the overall structure in the free stream, ie. at the entrance of the duct.

When tidal turbines are placed in a constricted duct and driven only by the pressure of a water column, created over a separation such as a dam, the situation would be best described as a tidal barrage.

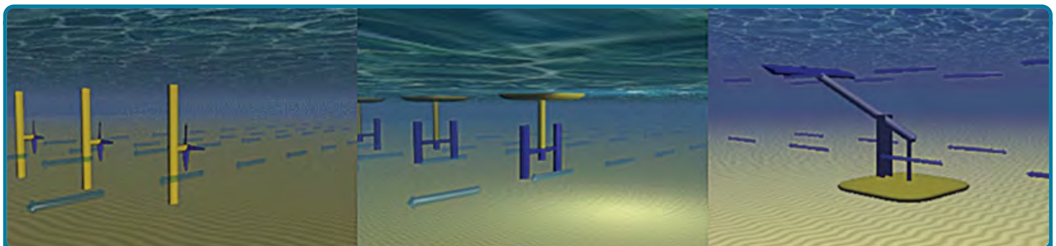


Figure 3.33 – Three principles of operation: horizontal axis turbines, cross-flow turbines and (linear) translating devices.

Cross-Flow Rotors	Axial-Flow Rotors
conveniente rectangular swept area	circular swept area
vertical shaft allows generator to be place above water level	right-angles transmission drive of submerged generator required
simplicity of blade design	asymetrically shaped blades
omni-directional, i.e. rotation in independent from flow direction	needs yawing system to point rotor in the direction of the flow
more construction materials needed for support arms	blades are radially attached to shaft, in line with tha radially transmitted forces
blade attachment to support arm is critical due to stress concentration	radial stress no problem
rapid decrease in performance when blades get growth of algae and barnacles	more "forgiving"
not an established and recognised technology	the technology is well proven and established in wind industry

Figure 3.34 – Comparison of cross-flow and axial-flow rotors on the basis of construction, architecture and technological status.

3.3.2. TIDAL BARRAGES

Tidal barrages are amongst the oldest methods of tidal power generation, with projects being developed as early as the 1960s, such as the experimental Kislaya Guba Tidal Power Station [1] in Kislaya Guba, near Murmansk, Russia (1968). The project was lead by the Gidroproekt Institute (chief design and construction engineer L. B. Bernshtein). After more than two decades of research, lead by Istorik, the plant was upgraded with a new type of turbine: an orthogonal turbine (Figure 3.35). The method of installation was also new: a steel caisson was constructed and towed to the site where it was ballasted and mounted. This new turbine showed good performance at low and varying heads (max 3.5m).

Other tidal power plants currently in operation include installations in La Rance in France completed in 1967 with a capacity of 240 MW [2], Annapolis in the United States [3], completed in 1986 with a capacity of 20 MW (Figure 3.36).

In China the Jiang Xia Tidal Power Plant was completed in 1980 with a capacity of 3.9 MW [4]. There are in total 6 bulb turbines of 3 types. In August 2012, Jiangxia Tidal Power Plant began the upgrading project. One of the six existing turbines will be replaced from 500kW to 700kW.

The latest and with 254 MW the largest of its kind, is the Lake Sihwa Tidal Plant in South Korea [5] (Figure 3.36 and Video 3.1). The Sihwa station features a dam that stores water at high tide and it generates power only from incoming tides, while outgoing tides flow without driving the turbines. As a body of water artificially isolated from the sea by a continuous sea wall, "Sihwa Lake" had suffered from poor water quality since 1994 but by opening the wall to allow water to enter and leave the "lake" has provided greater circulation.

In order to establish effective tidal power facilities, a significant tidal head is required as well as high capacity reservoirs. Sites with such characteristics are very geographic specific and thus limited. Most attractive options have either been realised or studied in detail. In 2001, the World Energy Council estimated the worldwide potential for new tidal barrage schemes at 150GW [7].

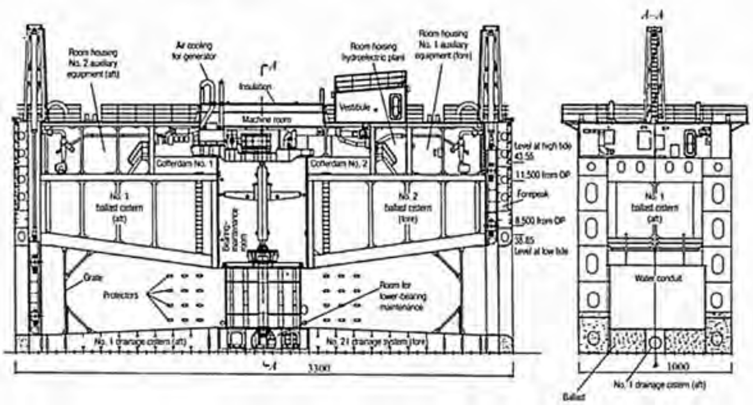


Figure 3.35 – Construction drawing of the upgraded Kislaya Guba Tidal Power Station with a 5m orthogonal (vertical axis) turbine.

Figure 3.36 – Tidal barrage plants in Annapolis – Canada (top left), Kislaya Guba – Russia (top right), La Rance – France (bottom left) and Sihwa Lake – South Korea (bottom right).

Video 3.1 – Sihwa Lake Tidal PowerPlant [6].

3.3.3. TIDAL AND OCEAN STREAM

The Early years (70s – 90s)

The first reported workshop dedicated to ocean currents was held in Miami in 1974: the MacArthur Workshop on feasibility of extracting usable energy from the Florida Current. Although ambitions designs were presented, there was little follow up on the recommendations. The oil prices stabilised again and interest slowly died out. This development is reflected in patent filing trends, which show a distinct decline in the number of filings from the early 1980s to 1990.

From the beginning of the 90s, climate change and concern for the environment led a number of groups to revive concepts of exploiting tidal and ocean currents. This trend was also noticeable in the increasing number of filed patent applications. From 1990 to 2000, some 30 projects considered this resource and build physical models and prototypes, albeit in small scale (kW size).

The most visionary project at the time was perhaps the 170m diameter, 83MW Coriolis One turbine proposed by Aerovironment (Figure 3.37). The US Naval Academy with its advanced test facilities took a recurring role in this project and many other US projects that followed.

Elsewhere, in Canada, in 1976 a proposal was submitted by Mr. Barry Davis (Nova Energy Ltd) to the Fundy Tidal Review Board, to investigate the feasibility of a floating vertical axis water turbine (Figure 3.38). The National Research Council of Canada became involved and awarded a number of contracts until 1986 to design turbine models for testing.

Since 1986 Nova Energy Ltd has sought to exploit the technology, dubbed the Davis Turbine, independently, later under the name Blue Energy. Despite ambitious plans for large scale deployment in the form of an integrated bridge in Philippines and China, little news about actual technological progress has been reported.

During the late 90s, Gorlov developed a vertical axis helical shaped turbine (Figure 3.39), reducing the torque ripple and thus vibrations and possibly fatigue. He started with tow tests in the Cape Cod Channel in 1997. After several small scale demo's a large 1 MW version was built in South Korea at Uldomok in 2009.

Perhaps most development efforts and experience can be attributed to Peter Fraenkel and the late Peter Garman, who together successfully

Figure 3.37 - The Coriolis One, proposal by Aerovironment for a 83 MW turbine in the Gulf Stream.

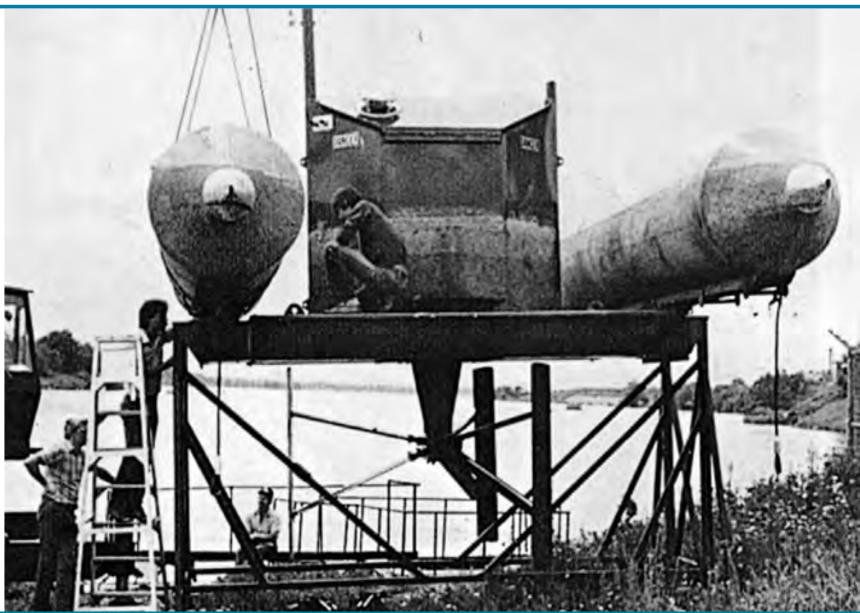


Figure 3.38 – Pontoon with 3-bladed Darrieus, designed by Nova Energy Ltd, tested by National Research Council of Canada St. Lawrence River in Cornwall in 1979.

Figure 3.39 - Twisted blades of the Gorlov turbine deployed in South Korea in 2009.

installed more than 30 Water Current Turbines (WCT) in Sudan, Egypt and Somalia for irrigation purposes. Their experience dates back to 1979 when the Intermediate Technology Development Group of Reading University developed a vertical axis cross flow turbine. In 1983 Peter Garman continued to develop his own design of a three bladed axial flow turbine. In 1987 the first of these turbines was installed in Sudan and in 1993 a licensing agreement was made with a local manufacturer in Sudan.

Meanwhile Peter Fraenkel from IT Power led a team in 1994 including Scottish Nuclear, National Engineering Laboratory and Evans Engineering, which demonstrated a tidal current turbine moored in Loch Linnhe [8]. The two-bladed axial flow turbine with a cast aluminium rotor of 3.5 m diameter was rated 15 kW in a 2.5 m/s current. The turbine was suspended 5m below the surface from a pontoon, which was anchored to the sea bed. The project provided valuable experience for what is now known as the Siemens MCT turbine.

From papers, patents and publications, the following observations can be made on the activities in the 90s:

- the earliest and most activities took place in the USA, followed by the UK, Canada, Australia, Japan and Russia;
- the longest running activity is by the Intermediate Technology Development Group (since 1976), later IT Power, resulting in the present day Marine Current Turbines (wholly owned by Siemens);
- From the 30 projects in the 90s, some 10 organizations are still involved in tidal stream development to date, carrying out research and development.

Into the new millennium (2000 – 2010)

From 2002 onwards, a number of policy studies and funding programs in the UK sparked off an unprecedented pace of development of technologies, several of which have resulted in today's state of play in the marine energy sector, such as Siemens (MCT), Alstom (TGL), DCNS (OpenHydro) and ScotRenewables (Figure 3.40).

The UK Department of Trade and Industry, the Crown Estate [9] and Carbon Trust [10] commissioned strategic studies into the resource potential of tidal stream and the impact on the UK economy. With industrial lobby and support via the BWEA (now RenewableUK [11]), the UK government and specifically the Scottish government, put in place a series of policy measure and incentives to support the marine energy industry. Notably in 2003 the European Marine Energy Centre on Orkney was created to attract and facility the industry, now hotspot to the highest density of marine energy devices anywhere in the world.

A few of the early developments, which received considerable attention and funding seemed to have disappeared from the scene, such as the StingRay by The Engineering Business (now IHC), SMD's TidEL and Rotech's Lunar projects (Figure 3.41). However, the know-how and experience was not lost, and key personnel are now involved in other related technology developments. Over time the UK has shown a high degree of resilience to failure, an important success factor in stimulating innovation.

Elsewhere in Europe, thanks to FP7 funding and EU structural funds, several projects were able to progress. In Italy the Ponte Di Archimede (PdA) company, in collaboration with Naples University developed the 100kWp Kobold turbine, a submerged vertical-axis turbine installed in the Strait of Messina, 150 metres off the coast of Ganzirri, since 2002 (Figure 3.42, left).

Although PdA have recently terminated their tidal activities, the technology (Figure 3.42, right) is being continued in China and Indonesia with UNIDO funding.

One of the scientists behind the Kobold turbine is professor Coiro from Naples University. Together

Figure 3.40 – SIEMENS (MCT), DCNS (OpenHydro) and Alstom (TGL) were all developed in the UK throughout the beginning of the millennium and are currently at the forefront of the industry.

Figure 3.41 – SMD's TiDEL, IHC's Stingray and Rotech's Lunar attracted considerable attention, but little progress has been reported over the last 5 years

with a group of companies from Venice he developed The Ocean's Kite (GEM) and deployed a 20kW prototype near Venice (Video 3.2). The concept consists of a submerged floating body linked to the seabed by means of a tether. This hull houses the electrical generators and auxiliary systems. Two turbines are installed outside the floating body and are exposed to the external currents.

In the Netherlands a vertical axis turbine (Figure 3.43) was developed by Ecofys (in fact by the author of this chapter) and thanks to the European Fund for Regional Development culminated in a grid-connected demonstration project in the province of Zeeland (see Video 3.3). The technology was picked up in 2012 by IHC-Merwede (Video 3.4), who bought the technology and rights to develop a 1.5 MW array project in the Oosterschelde storm surge barrier.

Similarly Tocardo [14] developed a direct drive twin bladed horizontal axis turbine (Figure 3.43 and Video 3.5). A consented pilot project is in preparation in the Oosterschelde storm surge barrier, next to IHC's project. The Tocardo turbine has

Figure 3.42 – Ponte Di Archimedes 100kW vertical axis turbine with passive pitch control in the strait of Messina (Italy) and the UNIDO funded 500kW twin VATT deployed in 2013 in the tidal channel between Gaoting on Daishan Island in Zhejiang province (China).

Video 3.2 – The Ocean Kite, Venice.

been demonstrated in the Afsluitdijk since 2008 and units have been sold to Nepal. Shareholders of Tocardo are oil & gas company Repsol and offshore construction company Huisman Equipment BV.

Other notable developments took place in Canada by Clean Current Turbines who tested a 65kW ducted turbine in 2006 at Race Rock [16](Figure 3.44). Clean Current was backed by Alstom Hydro for some time but withdrew from the development in 2012.

From 2010 onward

From 2012 onward, the marine industry witnessed a number of significant commercial developments. Siemens acquired Marine Current Turbines and Alstom purchased Tidal Generation Limited (TGL) from Rolls-Royce. While Andriz

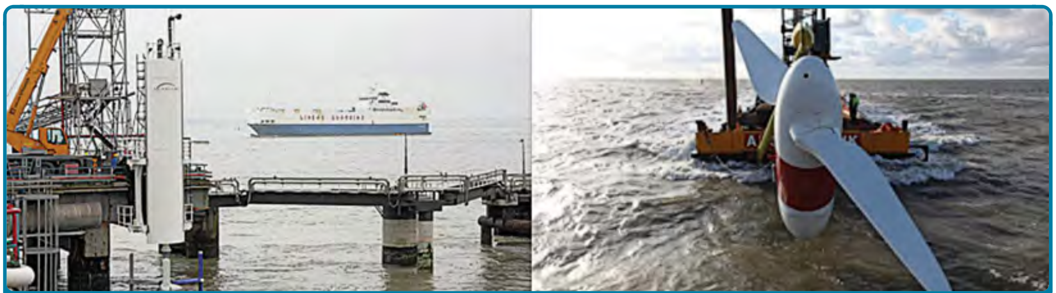


Figure 3.43 - C-Energy project (left) in the Westerschelde in 2009 developed by Ecofys, taken over by IHC Merwede and Tocardo's sea trials with the T100 tidal turbine (right) (2013).

Video 3.3 – C-Energy demonstration project, developed by Ecofys [12].

Video 3.4 – Oceanmill tidal turbine by IHC Tidal Energy [13].

Video 3.5 – Tocardo's twin bladed horizontal axis tidal turbine [15].

Hydro increased its 33% share in Hammerfest Strøm AS to a majority share in 2012. Early 2013 French shipbuilder DCNS bought a $176 million majority stake in Irish tidal developer Open Hydro.

At the same time as the strategic investors were moving in, some utilities seemed to be withdrawing or at least reviewing their options. After several years of support, E.ON recently announced that "delays in wave technology progress and a focus in E.ON on other more mature renewable technologies have been part of the decision to reduce the level of effort in the marine area". Also SSE announced it would review its marine energy portfolio amid rumours that the utility could be preparing to exit the sector. Responding to the speculation, SSE stated: "Although there is considerable marine energy technology development to be done over the next few years, SSE continues to believe that marine-based technologies (wave and tidal) have the potential to make an important contribution to the UK's renewable generation capacity in the next decade."

In the following sections a more detailed description is given for technologies that are still under development at the time of publishing and that have made significant progress in terms of real experience in open water. A few exceptions are made for companies that have terminated their activities but are relevant in the context of technology development.

This overview is by no means trying to be exhaustive or complete, knowing that there are some 100 developments worldwide still active to date.

Figure 3.44 – 65kW Clean Current demonstrator.

3.3.4. AXIAL FLOW TURBINES

Alstom

The TGL concept is an axial flow, three-bladed, pitch-controlled, upstream tidal turbine (Figure 3.45). The nacelle is attached to a separate foundation which is pinned to the seabed. A mechanical clamp facilitates yawing powered by a rear mounted thruster. TGL was formed in 2005 by a group of engineers from the Marine Current Turbines development team.

In 2009 TGL became a wholly owned subsidiary of Rolls-Royce. Their 500kWe demonstrator machine at EMEC has been generating power since September 2010. In March 2013, Alstom took over TGL from Rolls-Royce. Later that summer the next 18m, 1MW tidal turbine was successfully deployed at EMEC. In November 2013 it was announced that 100MWh had been produced.

The company was originally established in 1997 in Norway by the local utility company Hammerfest Energi, who built the 300kW turbine at Kvalsundet in Finnmark [18] (Figure 3.46 left), which made over 17000hrs of production between 2003 and 2009. After an initial 33% share, Andritz Hydro took a majority share in the company in 2012.

The technology has been selected by Scottish Power Renewables for use at their 10MW Islay site, together with Alstom [19].

Atlantis Resource Corporation

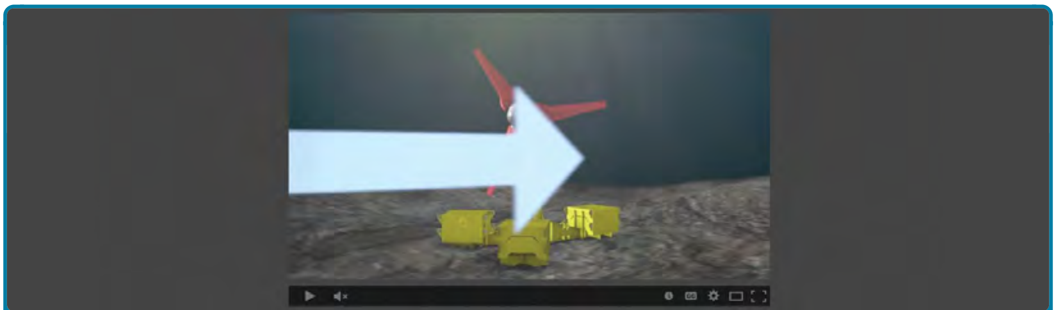
Originally a company from Australia, Atlantis followed an unusual technology development trajectory; each subsequent device looks very different from its previous. In 2002 they tested a translation rotor, comprising of a large number of

Figure 3.45 – TGL's 500kWp device and the 1MW device ready for deployment at EMEC.

ANDRITZ HYDRO Hammerfest (Video 3.6)

Video 3.6 – Andritz Hydro Hammerfest [17].

Figure 3.46 – Hammerfest HS300 turbine deployed in Norway (2003-2009) and the HS1000 ready for deployment at EMEC (2011).



Video 3.7 – Atlantis Resource Corporation tidal turbine [20].

hydrofoils stacked on a chain facing the direction of the flow (Figure 3.47). Later in 2008, Atlantis developed a ducted axial flow turbine, similar to that of Clean Current turbines. In 2011 a twin axial turbine was unveiled and installed at EMEC (Figure 3.47). The rotor blades had a fixed pitch. Shortly after commissioning the blades had to be replaced after all six had snapped (blade manufacturer Tempco was held responsible). The turbine was reinstalled with a single rotor. ARC is

Figure 3.47 - Atlantis' demonstration projects: 150kW 30 tonne Nereus deployed in San Remo (Victoria, Australia) in 2002 (top left), the AS140 ready for tow testing in Singapore (top right), the original AR1000 with twin rotors in 2010 (bottom left) and the pared-down, single-rotor configuration as deployed in 2011 at EMEC (bottom right).

Video 3.8 – AR1500 concept, from Atlantic Resources Corporation, with variable pitch blades [21].

ScotRenewables (Video 3.8)

Video 3.9 – ScotRenewables's SR250 testing in EMEC [22].

now developing a next generation turbine, the AR1500, with variable pitch blades (see Video 3.8). Meanwhile Atlantis has acquired an impressive portfolio of site development, notably 100% of the rights to develop up to 398MW in the Inner Sound of the Pentland Firth (MeyGen project).

The ScotRenewables tidal turbine (Figure 3.48) is a unique floating tidal technology designed to minimise installation and operational costs. The device hosts two turbines, which fold up while being towed. The counter-rotating rotors each have a diameter of 8m and each drive a separate gearbox and variable-speed electrical generator within the sub-surface nacelle.

ScotRenewables also developed an innovative single point catenary mooring system with a mooring turret system designed for rapid mechanical and electrical connection and disconnection. This mooring system allows the device to self-orientate in a tidal flow.

The system has been extensively trialled through scale model testing and a 250kW prototype, the SR250, successfully connected to the national grid at the Fall of Warness tidal test site at the end of March 2011. The device, measuring 33m long weighs 100 tonnes. ScotRenewables are in the process of developing the SR2000: a larger 2MW 'commercial scale' turbine more suited for tidal array deployment. This is due to be tested at EMEC prior to commercial deployment in the Lashy Sound between the islands of Eday and Sanday.

At the end of 2012, ABB announced an $8.12 million investment in ScotRenewables, alongside an additional $6.24 from Fred Olsen and Total S.A.

Figure 3.48 - Scotrenewables SR250 at EMEC, Scotland.

Siemens

The MCT technology is based on an axial flow rotor with variable pitch blades. The technology is the result of over 30 years of R&D, which started with Peter Franked at IT Power. MCT installed the 300kW Seaflow system near Lynmouth in Devon in 2003. In 2008, the installation and commissioning of the world's first commercial scale tidal turbine was completed, the 1.2 MW SeaGen [23] located in Strangford Narrows in Northern Ireland (Figure 3.49).

Royal Haskoning lead an extensive Environmental Monitoring Programme (EMP) which commenced in 2005, the main findings were:

1. No major impacts have been detected from any of the monitoring programmes;

2. There have been no changes in abundance of either seals or porpoises detected which can be attributed to SeaGen; seals and porpoises are continuing to swim past SeaGen, demonstrating a lack of any concern or hindrance.

In 2010 Siemens became a shareholder in MCT, providing a significant vote of confidence for the technology and the development work being carried out. Siemens made the decision in 2012 to acquire all of the shares of MCT with the intention of becoming the leading OEM in the emerging tidal energy market. MCT is currently focusing on the development of the first tidal array projects in the UK:

- 8MW Kyle Rhea project [24];

- 10MW Anglesey Skerries project [25];

The Voith tidal turbines feature a direct drive and fixed pitched blades. The turbines use a permanent magnet generator and to avoid sealing solutions, the flow of sea water is deliberately channelled through the turbine, where it serves as a lubricant for the bearings.

A first tidal turbine of this type with a capacity of 110 kW (Figure 3.50) was installed in 2011 near the South Korean island of Jindo in partnership with Sustainable Marine Technologies (SMT). The turbine had a rotor diameter of 5.3 m, and achieved a rated capacity of 110 kW at a current speed of 2.9 m/s.

Voith constructed the first full-scale 1MW prototype, dubbed HyTide (Figure 3.50), in Cherbourg during May-June 2013, before it will be installed at the EMEC testing site in Orkney. The rotor diameter is 13m and the nacelle weights 200 tonnes.

French energy company GDF Suez is currently developing tidal power projects at Raz Blanchard and has selected the HyTide turbine to equip all or part of the plant.

Figure 3.49 – Siemens 1.2MW MCT turbine at Strangford Narrows, producing over 5GWh per year.

Voith (Video 3.10)

Video 3.10 – Voith Hydro Tidal [26].

Minesto

Minesto develops the Deep Green solution, a ducted horizontal axis turbine, mounted below a rigid wing (kite) tethered and controlled via a seabed-based swivel anchor (Figure 3.51). The swivel and its control system guide the kite to move along a pre-destined trajectory. The wing accommodates systems for buoyancy, batteries and pressure sensors. The tether is mainly a force bearing element designed to take the high loads created by the wing but also accommodates power cables from the generator and signal cable to the control system.

The kite solution has the ability to produce electricity from low velocity tidal and ocean currents. A scaled Deep Green model underwent a test programme in Strangford Lough in 2011/2012. Minesto follows a development plan where the goal is to deploy a 3MW Deep Green array in 2015, increasing to a 10MW array in 2016.

Tidal Energy Ltd

Tidal Energy Ltd (TEL) is developing a three-bladed horizontal axis turbine known as DeltaStream (Figure 3.52). Three turbines are mounted on a delta shaped (triangular) frame, one on each corner, creating a modular and

Figure 3.50 – Voith 110kW turbine deployed in Korea in 2011. The 1MW HyTide turbine ready for deployment at EMEC.

Figure 3.51 – Minesto's Deep Green Kite solution tested in Strangford Lough, Northern Ireland in 2012.

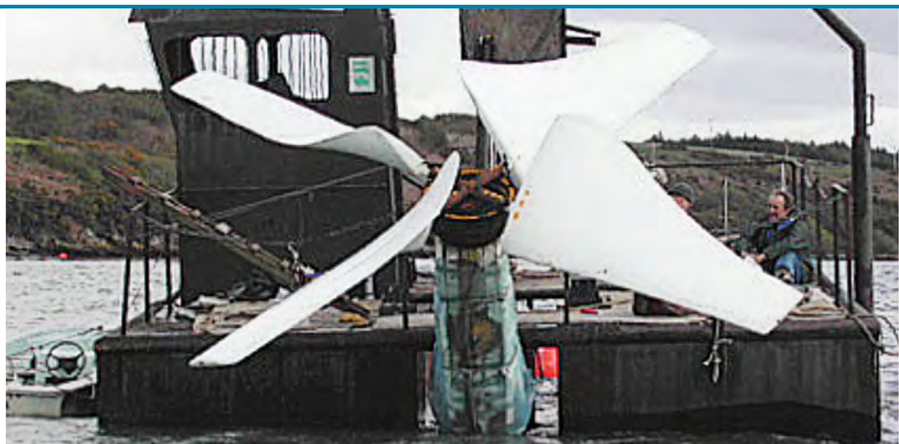


Figure 3.52 – Trials with the Deltastream turbine in Pembrokeshire.

robust seabed foundation with low centre of gravity for stability. The Delta Stream concept was conceived by Richard Ayre, a Marine Engineer from Pembrokeshire, Wales. In 2001 the first turbine was tested using an experimental rig in the Cleddau Estuary off Milford Haven, with the help of European Structural Funds. The main funder and driving force behind TEL is Eco2 Ltd [27], Wales' leading renewable energy company in Cardiff.

Tidal Energy Ltd is currently planning the deployment of a single 1.2MW Delta Stream unit off the coast of Pembrokeshire at Ramsey Sound for 12 months. The turbine has a diameter of 15 m.

An agreement for Lease has been established with The Crown Estate to develop a 10MW commercial array project at St Davids Head in Pembrokeshire, expected to be constructed in 2017. The project will comprise of up to 9 Deltastream units.

3.3.5. CROSS FLOW TURBINES

HydroQuest

Around 2004 a group of four laboratories in the Rhone-Alpes Region (France), led by LEGI, started investigating a new type of cross-flow turbine based around an invention by Achard and Maitre. The project was dubbed HARVEST (Hydrolienne à Axe de Rotation Vertical Stabilisé) and received funding from EDF. The novelty of this Darrieus type turbine focused on 'delta' shaped blades. Blades feature variable profiled cross-section area to reduce cyclic loading. Furthermore winglets at the tips of the blades serve to reduce tip losses. For a farm layout, a series of stacked tower were proposed and modelled. This work resulted in 9 patent filings.

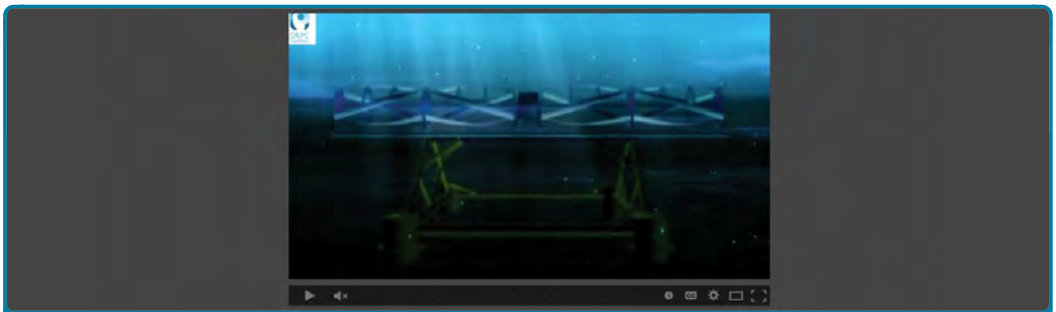
In 2010 the company HydroQuest was established to further develop and market the technology. In 2012 a first demonstration project was realized in open water (Figure 3.53). The features of the delta blades and winglet have been abandoned. Instead a conventional 3-bladed Darrieus turbine, with fixed pitch blades were mounted in pairs between a set of diffusers that guide the in-and outgoing flow. Currently HydroQuest is collaborating on the HydroFluv project with a view to install a large device in the Loire in Orleans in 2014.

Since 2004, ORPC has been commercially advancing the Gorlov turbine, renamed TidGen, RivGen and OCGen. Each ORPC turbine features 4 twisted blades and has an axis, which is horizontal to the flow (Figure 3.54). A structure comprising multiple turbines sits on the floor of a bay or deep river. The turbines drive a central permanent magnet generator.

In 2012, ORPC delivered the first power to the grid in the US from the Cobscook Bay Tidal Energy Project in Maine (Figure 3.54), under an 8-year Pilot Project License from FERC. According to ORPC, the Maine Tidal Energy Project has already brought more than $25 million into the state economy and has created or helped retain more than 100 jobs in 14 Maine counties.

Figure 3.53 – Installation of the first HydroQuest turbines starting end of 2012.

ORPC – Ocean Renewable Power Company (Video 3.11)



Video 3.11 – ORPC TidGen. More videos available in [28].

Figure 3.54 – ORPC's barge mounted turbine (left) and the 300kWp Cobscook Bay Tidal Energy Project in Maine, grid-connected since 2012 (right).

Through a partnership with the Village of Igiugig, Alaska, ORPC plans to demonstrate the river solution in Nikiski, Alaska, using ORPC's barge mounted solution and later the complete RivGen system in the Kvichak River in Igiugig.

ORPC has formed a partnership with Canadian independent power producer, Fundy Tidal Inc., to develop a tidal energy project in the Bay of Fundy off of southwestern Nova Scotia. The initial project will be installed in the tidal resource of Digby Gut at the entrance to the Annapolis Basin.

Natural Energy Corporation (Video 3.12)

NEC was founded in December 2003 and is based in Calgary, Alberta, Canada. The NEC team is developing the EnCurrent™ turbine (Figure 3.55), a conventional Darrieus type cross-flow turbine with a vertical axis mounted between the hulls of a floating catamaran.

In the fall of 2010, NEC and FTI conducted a test of the 5 kW EnCurrent™ PGS in Grand Passage tidal currents. NEC currently has 5, 10 and 25 kW models of the EnCurrent™ PGS commercially available and is working to scale up its core technology to provide 125 and 250 kW models. The 250 kW turbines will be approximately 7.62 m in diameter and about 7.6 m in height with four vertical hydrofoils mounted around a central rotor shaft. The initial deployment shall be floating and moored to the seafloor through the use of cables and anchors.

Video 3.12 – EnCurrent 25 kW Turbine Install and Test [29].

Figure 3.55 – The EnCurrent turbine mounted on a catamaran. The turbine can be rotated out of the water.

3.3.6. TRANSLATING DEVICES

Tidal Sails was a Norwegian company which developed an interesting translating system for tidal energy generation (Figure 3.56). Tidal Sails was established in 2004 based on an idea by Are Børgesen, a commercial airline pilot. In 2012, the company ceased its activities for unknown reasons. Pultrusion composite sail profiles pull two belt loops with the current at an angle, capturing energy and converting it into clean electricity. Linearly moving sails have the inherent advantages over rotating turbine solutions that each sail or blade can have an optimum angle towards the flow over the full length of the sail without any disturbance of the upstream or downstream flow.

Based in Sheffield, Pulse Hydro develops the system known as Pulse-Stream, a set of horizontal blades or hydrofoils that move up and down in a current to drive a generator (Figure 3.57). During operation, the system sits on the seabed and is fully submerged. For maintenance, the system can come to the surface without the need for cranes or vessels.

The rectangular swept area, and adjustable stroke length, makes the solution ideal for shallow water and inherently fish friendly.

In 2009, Pulse Tidal deployed the 100kW "Pulse-Stream 100" into the mouth of the River Humber in the UK. Pulse was awarded a 7m UKP EU FP7 grant towards a 20mUKP project to start building a 1,2MW machine in 2010 for deployment at Lynmouth in the South West Marine Energy Park in Devon, UK. The Crown Estate awarded Pulse an Agreement for Lease for the site. However, to date there has been little advancement of the project, apparently because the co-financing of the project has not been secured.

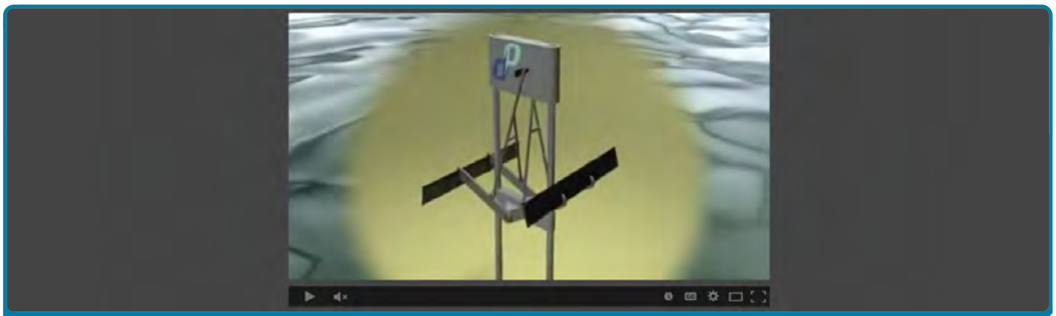
Tidal Sails (Video 3.13)

Video 3.13 – Introduction to Tidal Sails AS. More videos available in [30].

Figure 3.56 – Tidal Sails scale tests (left) and larger scale device (right).

Pulse Hydro (Video 3.14 and Video 3.15)

Video 3.14 – Pulse Tidal on BBC Look North [31].



Video 3.15 – Pulse Stream 100 – Pulse Tidal [32].

Figure 3.57 – 100kWp Pulse Tidal devices in the Humber in 2009.

3.3.7. LOOKING INTO THE FUTURE

Low head tidal barrage solutions

Recently, a number of feasibility projects have been initiated in the Netherlands looking at tidal energy generation in dams at very low heads (less than 3m), because the Netherlands have many such sites available. Notably, the Dutch Government is considering a 400mEUR operation to open up the Grevelingen Lake to the sea, normally cut off from the sea by the Brouwersdam. It is thought that this operation could be made economically more feasible if it would be combined with a public-private-partnership development of a tidal barrage plant. The cost of a 30-60MW tidal power plant in the Brouwersdam is estimated at 200mEUR. Government hopes that this cost can be borne by the private sector. (Relevant projects: Energising Delta's [33], Pro-Tide project[34], Brouwersdam Tidal Power Plant [35] market consultation).

Several low head turbines are under development, for example Nijhuis-Pentair pumps are developing a fish friendly bulb type turbine. University Lancaster is investigating the use of a siphonic hydro turbine, while VLH (Very Low Head Hydro) have developed a fan-like, slow rotating turbine for low head sites. In the US, Lucid Energy has developed a ducted cross-flow solution for integration in existing waterways (Figure 3.58).

It is expected that over the next 5 years more turbines will be developed and deployed for very low head sites, coinciding with the increased interest for such sites, not primarily for the energy generation but for the ecological need of a drive to make existing waterworks more energy balanced.

Floating Tidal and Ocean Currents systems

It is expected that over the next 5 years, several deployments of floating tidal solutions will be realised. Now that experience has been gained with the deployment and operation of several large tidal turbines, the industry has come to realise that the main cost reduction potential of a project is not in its turbine technology or power take-off, but in its installation, station keeping and cost of access for operation and maintenance. This realisation has sparked of a number of floating solutions in the sector (Figure 3.59). Most are integral solutions of a floating structure with a proprietary turbine (such as Tidalys, EvoPod, Magallanes, ScotRenewables), others only develop the floating structure and are turbine independent (Bluewater).

Early 2014 SIEMENS/MCT announced a joint development with Bluewater for the development of floating solutions for the Siemens SeaGEN turbine for projects at the Bay of Fundy[39].

Figure 3.58 – Lucid Energy (US) installing a low head cross-flow turbine in a ducted, which can be integrated in existing water channels.

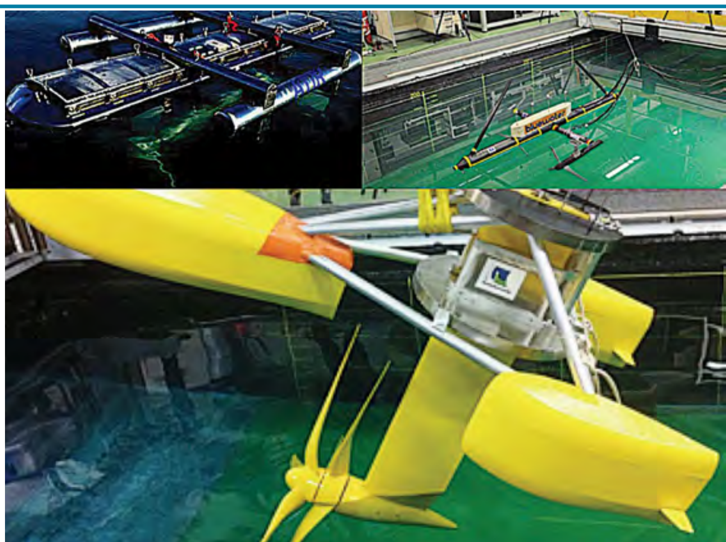


Figure 3.59– Magallanes, Bluewater's BlueTEC (Video 3.16 - Video 3.18) and Tidalys all proposing floating structures for future tidal farms, reducing installation and O&M cost.

Video 3.16 – Working with the tides for clean energy: Allar van Hoeken at TEDx Binnenhof [36].

Video 3.17 – BlueTEC in operation [37].

Video 3.18 – BlueTEC presentation [38].

3.3.8. REFERENCES

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3.4. OCEAN THERMAL ENERGY

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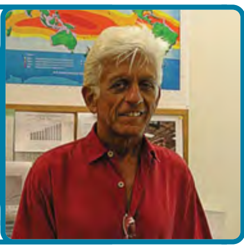

Luis Vega is currently the manager of the National Marine Renewable Energy Center at the University of Hawaii. He holds degrees in Applied Mathematics, Aerospace Engineering and Applied Ocean Sciences from the US Naval Academy, CALTECH and the University of California. His professional experience ranges from analytical studies to laboratory scale and model basin tests as well as at-sea tests of marine renewable energy equipment. He lead the team that designed and tested an Ocean Thermal Energy Conversion (OTEC) experimental plant demonstrating 24/7 production of electricity and desalinated-water and obtaining operational data required for estimating realistic costs of production. He has also worked in the electrification of remote villages in the South Pacific Island Nations utilizing solar and wind resources and establishing a Rural Energy Service Company in the nation of Fiji.

SUMMARY

This report summarizes the viability of utilizing ocean-thermal resources to produce baseload electricity and desalinated water. At the onset, it must be noted that although Portugal does not have the required ocean-thermal resources within their Exclusive Economic Zone (EEZ), its industrial sector could supply others the equipment required for ocean-thermal-energy-conversion (OTEC) plants.

To standardize the process used to estimate ocean energy resources, a set of three terms has been recommended[1] : theoretical resource, technical resource, and practical resource. As illustrated in Figure 3.60, the technical resource is the portion of the theoretical resource that can be captured using a specific technology. The parameter η refers to the conversion efficiency. The practical resource which is that portion of the technical resource that would be available after considering all other constraints, e.g. social, economic, regulatory and environmental.

1 U.S. Department of Energy

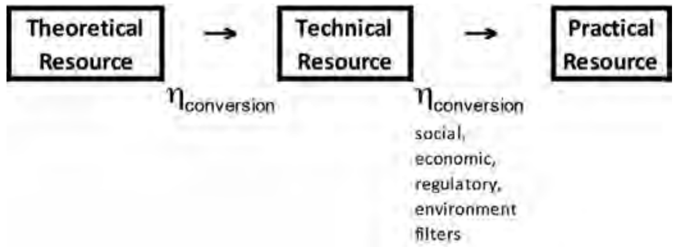

Figure 3.60 - Ocean Energy Resources Assessments.

OTEC technology has been validated with experimental plants such that for a given theoretical thermal resource, as represented by the temperature difference (ΔT) between surface waters (heat source) and water from 1000 m depth (heat sink), the technical resource can be estimated as the electrical energy (kWh) generated at the plant. Analyzing the practical resource is country and site specific. Cost estimates, however, indicate that under certain scenarios, cost effective baseload electricity can be produced. Table 3.1 provides a summary of the OTEC status.

For the purpose of identifying world-wide locations with an appropriate technical resource, the annual electricity production with a baseline 100 MW OTEC plant has been estimated at the University of Hawaii by Professor Gerard Nihous (Figure 3.61) and made available at http://hinmrec.hnei.hawaii.edu/. The annual generation is given in Gigawatt-hours/year (GWh)[1] .

1 GWh = 106 kWh

3.4.1. INTRODUCTION

There are two OTEC cycles, namely closed- and open-cycles, whose technology has been proven in the field and for which all required equipment is available [1]. The closed-cycle concept uses the relatively warm (24 °C to 30 °C) surface water of tropical oceans to vaporize a pressurized working fluid (e.g., anhydrous ammonia) through a heat exchanger (evaporator) and the resulting vapor drives a turbine-generator. The cold ocean water transported to the surface from 800 m to 1000 m depths, with temperatures ranging from 8 °C to 4 °C, condenses the vapor through another heat exchanger (condenser). Because the working fluid

Theoretical Resource Availability	Equipment Siting Requirements	Additional Resource Information Needed	Equipment to Convert Resource into Electricity	Cradle-to-Grave Environmental Impact	Development Incentives	Overall Assessment	Overall Recommendation
Yes, widely available.	- Water Depths >1000m - Baseline: 100 MW plant housed in moored ship-shaped vessel the size of a standard super tanker. Submarine power cable connected to land.	- Identify sites close to electricity distribution lines; - Identify any additional ocean temperature data available (vertical distribution to 1000m).	Available off- the-shelve but capital intensive system.	Not different from well established technologies and ocean installations with the exception of: seawater return to ocean below photic layer.	- Implement OTEC feed-in-tariff ; - Loan guarantees; Target Tariff: > 0.25 $/kWh (> 50 MW plant) 0.50 $/kWh (10 MW plant)	- Need to implement pilot plant to obtain operational record required to secure financing; - Commercial OTEC plants could be available in - 5 to 10 years.	Monitor progress of pilot (pre-commercial) projects; and, implementation of small plants (< 10 MW) in island nations.

Table 3.1 – Ocean Thermal Energy Conversion: World-Wide Status.

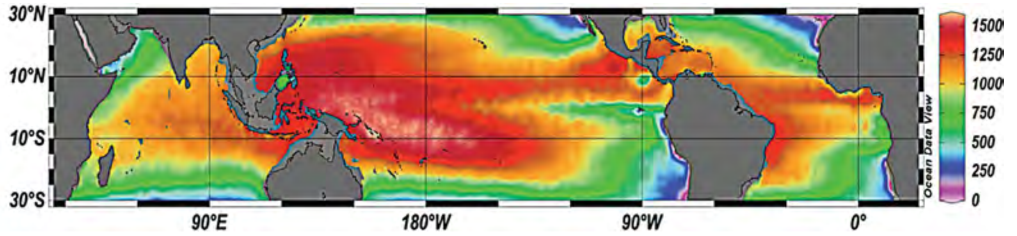

Figure 3.61 - 100 MW OTEC Plant Annual GWh output (1/4°x1/4° Lat/Long Cells). The reference electricity generation is 877 GWh/year @ ΔT = 20 °C (provided by G. C. Nihous using tools described in [4]).

circulates in a closed loop, this concept has been named closed-cycle OTEC (CC-OTEC).

The CC-OTEC concept was demonstrated in 1979, when the state of Hawaii and a consortium of U.S. companies produced more than 50 kW of gross power, with a net output of up to 18 kW, from a small plant mounted on a barge off Hawaii. Subsequently, a 100 kW gross power, land-based plant was operated in the island nation of Nauru by a consortium of Japanese companies. These plants were operated for a few months to demonstrate the concept. They were too small to be scaled to commercial size systems.

Alternatively, the open-cycle uses the ocean water as the working fluid. In this cycle the surface water is flash-evaporated in a vacuum chamber. The resulting low-pressure steam is used to drive a turbine-generator and the relatively colder deep seawater is used to condense the steam after it has passed through the turbine. Therefore, this cycle can be configured to produce desalinated water as well as electricity. This concept is referred to as open-cycle OTEC (OC-OTEC) because the working fluid flows once through the system.

The OC-OTEC cycle was first demonstrated in Cuba by its inventor G. Claude (1930) with a small land-based plant. The plant failed to achieve net power production because of a poor site selection (e.g., thermal resource) and a mismatch of the power and seawater systems. However, the plant did operate for several weeks. Claude, subsequently, designed a 2.2 MW floating plant for the production of up to 2000 tons of ice (this was prior to the wide availability of household refrigerators) for the city of Rio de Janeiro in Brazil. Claude housed his power plant on a ship (i.e., plantship), about 100 km offshore. Unfortunately, he failed in his numerous attempts to install the vertical long pipe required to transport the deep ocean water to the ship (the cold water pipe, CWP) and had to abandon his enterprise in 1935. His failure is attributed to the absence of the offshore industry and ocean engineering expertise presently available.

The next step towards answering questions related to operation of OC-OTEC plants was the installation of a small land-based experimental facility in Hawaii (Figure 3.62). The turbine-generator was designed for an output of 210 kW for 26 °C warm surface water and a deep water temperature 6 °C. A small fraction (10 percent) of the steam produced was diverted to a surface condenser for the production of desalinated water. The experimental plant was successfully operated for six years (1993-1998). The highest production rates achieved were 103 kW-net and 0.4 l/s of desalinated water. These are world records for OTEC [7].

A number of possible configurations for OTEC plants have been proposed. These range from floating plants to land-based plants, including shelf-mounted towers and other offshore structures. The primary candidate for commercial size plants appears to be the floating plant, positioned close to land, transmitting power to shore via a submarine power cable [6].

The use of the cold seawater as the chiller fluid in air conditioning (AC) systems has been implemented in several locations. These Seawater Air Conditioning (SWAC) systems provide significant energy conservation and have been installed independently of OTEC [1].

OTEC energy could also be transported via chemical, thermal and electrochemical carriers. The evaluation of non-electrical carriers led to considering hydrogen produced using electricity and desalinated water generated with OTEC technology. The product would be transported from the OTEC plantship located at distances of as much as 1,500 km (i.e., nominal distance from tropical oceans to major industrialized centers throughout the world) to the port facility in liquid form to be used as a transportation fuel. A 100 MW OTEC plantship can be configured to yield (by electrolysis) 1300 kg per hour of liquid hydrogen. Unfortunately, the production cost of liquid hydrogen delivered to the harbor would be equivalent to about $400 barrel-of-crude-oil (approximately four times present cost). The situation is similar for the other energy carriers considered (e.g., anhydrous ammonia). Presently, the only energy carrier that is cost-effective for OTEC energy is the submarine power cable.

This situation will be different in the forthcoming post fossil-fuels era. There are sufficient petroleum resources (≈ 1400 billion barrels) to meet current worldwide demand (> 30 billion barrels/year) for almost 50 years. Production, however, is peaking and humanity will face a steadily diminishing petroleum supply and higher demand due to emerging economies. Coal and natural gas resources could meet current worldwide demand for 100 to 120 years respectively.

The major analytical conclusion is that there is a sustainable ocean-thermal resource to supply OTEC plants with a cumulative power rating of at least 7 TW to as much as 14 TW[1] [5].

1 TW = 106 MW

3.4.2. OTEC MARKET

Numerous nations and territories with access to ocean-thermal resources within their 200 nautical mile EEZ have been identified [1]. There is also a market for nations like Portugal that could manufacture and supply the equipment required for OTEC plants, even if they do not have the required resource within their EEZ.The world wide sustainable ocean-thermal resource can supply at least 7 TW of OTEC installed capacity [equivalent to 70,000 one hundred megawatt (100 MW) plants.] Each

Figure 3.62 – The 210 kW OC-OTEC Experimental Apparatus [7].

100 MW plant would require a capital investment of about three quarters of a billion dollars such that the ultimate market, in a few decades, would be valued in trillions of dollars.

In discussing OTEC's market potential it is important to note that implementing a floating pilot plant would take about five years. No technical breakthroughs are required, but some components would require as long as three years to be delivered after the order is placed. In addition, one year would be required to mobilize and complete the deployment, with a second year set aside for commissioning. The floating pilot plant would be operational (i.e., supplying electricity to the distribution grid) within five years and would need to be operated for a couple years to gather technical as well as environmental impact information. Some of the valid questions regarding potential OTEC environmental impacts on the marine environment can only be answered by operating pilot plants which are large enough to represent the commercial-size plants of the future.

The design of the first commercial plant sized at 50 to 100 MW would be completed and optimized after the first year of operations with the pilot plant. This would be followed by installing several plants connected to shore via submarine power cables. The design of the grazing factory plantships that would produce the fuels of the future (e.g., hydrogen and ammonia could be initiated as early as 15 years after OTEC is commercialized.

3.4.3. OTEC SITE SELECTION

The OTEC concept utilizes the differences in temperature, ΔT, between the warm tropical surface waters (Tw), and the cold deep ocean waters (Tc) available at depths of about 1,000 m, as the source of the thermal energy required. Deep seawater flows from the Polar Regions. Therefore, Tc at a given depth, approximately below 500 m, does not vary much throughout all regions of interest for OTEC [5].

Ocean Thermal Resource: The ΔT gives a good indication of available OTEC resources across tropical oceans. For example, values less than 18°C may not be economically viable for OTEC power generation. The NOAA National Ocean Data Center's World Ocean Atlas (WOA) database (2005 version) has been used to construct a link[1] :

http://hinmrec.hnei.hawaii.edu/hinmrecftp/AnnualTempDiff.html which provides color coded annual and monthly ΔT averages across the world oceans on a quarter-degree horizontal grid. The user can choose any region of interest defined by specific latitude and longitude ranges to view the data. Further, clicking on any location gives a plot of monthly averages of the temperature difference there.

The historical (2005) annual averages of ΔT are given in Figure 3.63. Values are colour coded as indicated in the right side of the Figure.

OTEC Power: OTEC technology has been validated with experimental plants such that for a given thermal resource the electrical energy (kWh) which could be generated over a specified time can be quantified. That is, an estimate of OTEC electricity generation can be made with the temperature difference data available from the WOA database. The link: http://hinmrec.hnei.hawaii.edu/hinmrecftp/powermaps.html gives annual and monthly averages of the power that would be produced by a single generic OTEC plant rated at 100 MW in standard conditions (ΔT of 20°C). The display is limited to a latitude band between 30°S and 30°N. The link provides the user with a colour-coded distribution of OTEC power production from the generic 100 MW plant. The user can choose any region of interest between 30°S and 30°N to view detailed values of annual average power. Further, clicking on any location provides the user with a plot of the monthly averages of net power there, in GWh per month. The annual average (GWh/year) is also depicted in Figure 3.61.

1 Please use Google Chrome or Safari to view the links given below because Internet Explorer does not provide the display we intended.

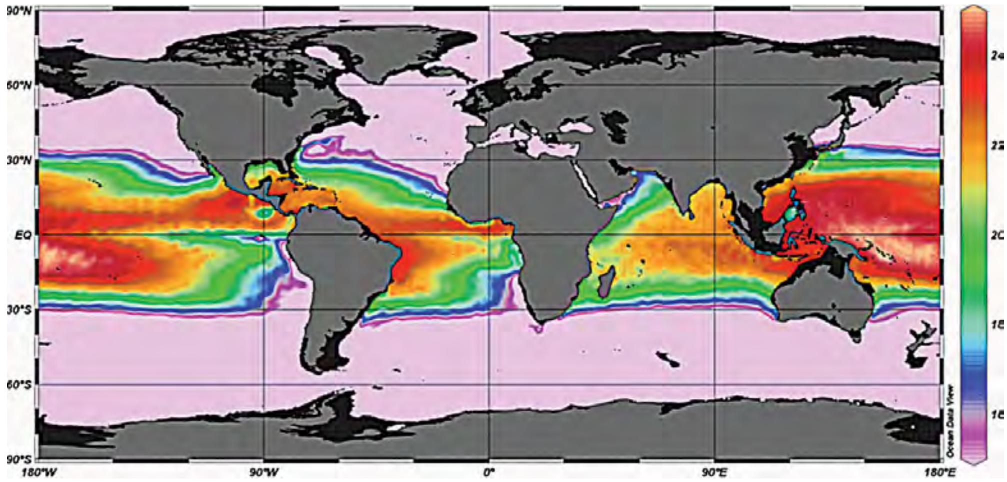

Figure 3.64 – Worldwide average ocean temperature differences (between 20 m and 1000 m water depths) from WOA 2005 (1/4°) data. The color palette is from 15°C to 25°C [4].

The following summarizes the availability of the OTEC thermal resource throughout the world:

- Equatorial waters, defined as lying between 10°N and 10°S are adequate except for the West Coasts of South America and Southern Africa.

- Tropical waters, defined as extending from the equatorial region boundary to, respectively, 20°N and 20°S, are adequate, except for the West Coasts of South America and of Southern Africa; moreover, seasonal upwelling phenomena would require significant temperature enhancement for the West Coast of Northern Africa, the Horn of Africa, and off the Arabian Peninsula.

This presents an interesting question about the size of the OTEC resource: Could a massive deployment of this technology affect ocean temperatures on which the process itself depends? In other words, could OTEC be self limiting?

Prof. Nihous at the University of Hawaii utilized a 3D oceanic general circulation model, to account for the complex interplay between planetary heat fluxes and potentially large OTEC intakes and discharges spread over more than 100 million square kilometers, to estimate a 30 TW[1] maximum for global OTEC power production [5]. As OTEC flow rates increase, the erosion of vertical seawater temperature gradients is much slower in 3D ocean models because any heat locally added to the system can be horizontally transported and re-distributed at a relatively fast rate. Another distinctive feature of the model results is the persistence of slightly cooler surface waters in the OTEC region. This is compensated, however, by a warming trend at higher latitudes. A boost of the planetary circulation responsible for the overall supply of deep cold seawater is also shown. A more modest OTEC scenario with, for example, a global potential of the order of 7 TW shows little impact. The baseline commercial size OTEC plant is sized at 100 MW such that 70,000 plants would correspond to 7 TW.

3.4.4. LIMITATIONS AND CHALLENGES OF OTEC

The performance of OTEC cycles is assessed with the same thermodynamics concepts used for conventional steam power plants. The major difference arises from the relatively large quantities of warm and cold seawater required for heat transfer processes, resulting in the consumption of a portion of

1 This amount is more than current worldwide energy consumption by all sectors.

the power generated by the turbine-generator in the operation of pumps. The power required to pump seawater is determined by accounting for the pipe-fluid frictional losses and in the case of the cold seawater for the density head, i.e., gravitational energy due to the differences in density between the heavier (colder) water inside the pipe and the surrounding water column. The seawater temperature rise, due to frictional losses, is negligible for practical designs.

The thermal performance of CC-OTEC and OC-OTEC is comparable. OTEC design parameters are, therefore, generalized as follows:

- In-house or parasitic electrical loads Ploss represent about 30% of Pgross , such that the exportable power (Pnet) is about 70% of Pgross;

- A cold water flow rate (Qcw) of 2.7 m3/s is required per MWnet;

- The optimal warm water flow rate (Qww) is about 1.9 x Qcw.

Pgross is proportional to the square of the temperature differential (ΔT) and the seawater flow rate, such that:

$$\underline{P_{net} = P_{gross} - P_{loss} = \beta Q_{cw}(\Delta T)^2 - P_{loss}}$$

where β and Ploss are system specific. Considering nominal values it can be shown that a 1 °C change in ΔT leads to a change of approximately 15% in Pnet. In summary, in the absence of seawater flow rate constraints, extractable power can be characterized by providing ΔT estimates [5].

For example, a 100 MW CC-OTEC plantship moored off Hawaii within 20 km of the shoreline under a baseline average ΔT of 20 °C would generate 877 GWh per annum (Figure 3.61). In the South China Sea the production would be 27% higher (1100 GWh). In the case off Fiji, production would be 53% higher (1320 GWh) and in the Philippines production would be 63% higher (1410 GWh).

The design and installation of a cost-effective pipe to transport relatively large quantities of cold water to the surface (i.e., cold water pipe, CWP) presented an engineering challenge of significant magnitude, complicated by a lack of evolutionary experience. This challenge was met in the U.S. with a programme relying on computer-aided analytical studies integrated with laboratory and at-sea tests. The greatest outcome achieved has been the design, fabrication, transportation, deployment and test at-sea of an instrumented 2.4 m diameter, 120 m long fiberglass reinforced plastic (FRP) sandwich construction pipe attached to a barge [1]. The data obtained was used to validate the design technology developed for pipes suspended from floating OTEC plants. This type of pipe is recommended for floating OTEC plants.

For land-based plants, there is a validated design for high-density polyethylene pipes of diameter less than about 2 m. In the case of larger diameter pipes offshore techniques used to deploy large segmented pipes made of steel, concrete or FRP are applicable.

Pressurized pipes made of reinforced elastomeric fabrics (e.g., soft pipes), with pumps located at the cold-water intake, seem to offer the most innovative alternative to conventional concepts. However, the operability of pumps in 800 m to 1000 m water depths over extended periods must be verified and the inspection, maintenance and repair (IM&R) constraints established before soft pipes can be used in practical designs.

Other components for OTEC floating plants which present engineering challenges are the position keeping system and the attachment of the submarine power cable to the floating plant. Deep ocean-mooring systems, designed for water depths of more than 1000 m, or dynamic positioning thrusters developed by the offshore industry can be used for position keeping. The warm water intake and the mixed return water also provide the momentum necessary to position the surface vessel [1]. The offshore industry also provides the engineering and technological backgrounds required to design and install the riser for the submarine power cable.

One argument in favor of OTEC lies in its renewable character: it may be seen as a means to provide remote and isolated communities with some degree of energy independence and to offer them a potential for safe economic development. Paradoxically, however, such operational advantages are often accompanied by serious logistical problems during the plant construction and installation phases: if an island is under development, it is likely to lack the infrastructure desirable for this type of project, including harbors, airports, good roads and communication systems. Moreover, the population base should be compatible with the OTEC plant size: adequate manpower must be supplied to operate the plant and the electricity and fresh water plant outputs should match local requirements.

3.4.5. ECONOMICS OF OTEC

The analytical model available to estimate the levelized cost of electricity (LCOE) production can be used to assess scenarios under which OTEC might be competitive with conventional technologies. First, the OTEC capital cost, expressed in $/kW-net, is estimated (Figure 3.64). Subsequently, the levelized cost of producing electricity ($/kWh) is determined as a function of the terms of the investment loan (Figure 3.65). In the case of OC-OTEC the cost is offset by the desalinated water production revenue to determine conventional scenarios (given by fossil fuel costs and cost of fresh water production) under which OTEC could be competitive [3].

In this fashion, two distinct markets were previously identified: (i) industrialized nations; and, (ii) small island developing states (SIDS) with modest needs for power and fresh water. OC-OTEC plants could be sized at 1MW to 10 MW, and 450 thousand to 9.2 million gallons of fresh water per day (1,700 to 35,000 m3/day) to meet the needs of developing communities with populations ranging from 4,500 to 100,000 residents. This range encompasses the majority of SIDS throughout the world and specifically the Pacific Island Nations.

Floating plants of at least 50 MW capacity would be required for larger nations [2]. These would be moored or dynamically positioned a few kilometers from land, transmitting the electricity to shore via submarine power cables. The moored vessel could also house an OC-OTEC plant and transport the desalinated water produced via flexible pipes. As stated above, the use of energy carriers (e.g.: Hydrogen, Ammonia) to transport OTEC energy generated in floating plants, drifting in tropical waters, was determined to be technically feasible but requiring increases in the cost of fossil fuels equivalent to $400/barrel to be cost competitive.

As indicated in Figure 3.64, the CC-OTEC capital cost estimates are a strong function of plant size.

These estimates are for first generation plants and include installation costs. One might speculate, based on the implementation of similar

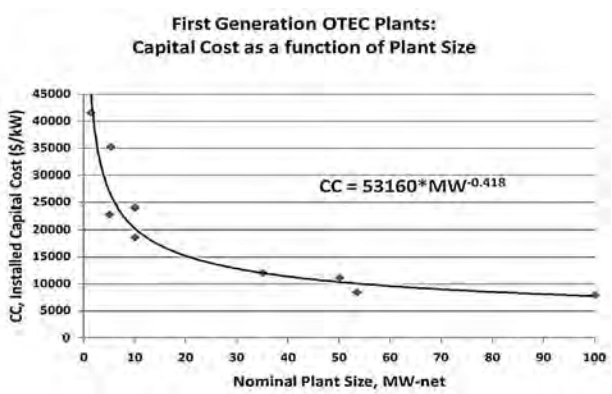

Figure 3.64 – Capital Cost Estimated for First Generation CC-OTEC Plants [3].

technologies, that later generation designs might reach cost reductions of as much as 30%. However, first generation plants can be cost effective under certain scenarios if the cost estimates presented herein are met. For convenience and future reference a least-squares curve fit is provided:

CC ($/kW) = 53,000 x MW-0.42

The LCOE is defined by adding the amortized annual capital-loan repayment divided by the annual production ($/kWh) to the annual levelized cost incurred due to operations, maintenance, repair and equipment replacement (OMR&R) divided by the annual electricity production ($/kWh). Figure 3.65 provides the LCOE in U.S. cents per kilowatt-hour (kWh) for first generation CC-OTEC plants. It must be emphasized that the LCOE given in Figure 3.65 is estimated under a baseline average ΔT of 20 °C.

As stated above, the baseline 100 MW OTEC plant housed in a floating platform stationed less than 10 km offshore would have the capability of delivering more than 877 GWh (million kWh) to the electrical grid every year under baseline conditions. Budgetary quotes from potential equipment suppliers indicate that the installed cost would be about $790 million using state-of-the-art components.

The annual costs for operations and maintenance, including repairs and equipment replacement (OMR&R), are estimated at $40 million, such that under realistic financing terms (15 year loan at 8% annual interest and 3% average annual inflation) electricity could be produced at a levelized cost of less than 0.17 $/kWh under the baseline thermal. It is interesting to note that if the plant could be funded via a concessionary loan with a rate of 2.5% over 20 years the LCOE would be 0.12 $/kWh (Figure 3.65). Furthermore, considering the site-specific electricity generation given in Figure 3.61, the LCOE would be lower at most sites. For example, in the South China Sea the production would be 27% higher (1100 GWh vs. 877 GWh) such that the LCOE would be 20% lower. In the case off Fiji, production would be 53% higher (1320 GWh) resulting in a LCOE reduction of 35%. In the Philippines, production would be 63% higher (1410 GWh) with LCOE 38% lower.

Therefore, as indicated in Table 3.1, a power-purchase-agreement for a 100 MW OTEC plant of about 0.25 $/kWh should provide ample return on investment.

In the case of the OC-OTEC plant, the combination of electricity rate ($/kWh) and desalinated water rate ($/m3) required to breakeven can be estimated. In the case of the baseline 50 MW OC-OTEC plant described in [2], there are two (of many) scenarios which illustrate the breakeven point:

(i) sell electricity for at least 0.15 $/kWh; and water for 0.8 $/m3 (3 $/kgallon)

(ii) sell electricity for at least 0.07 $/kWh; and water for 1.6 $/m3 (6 $/kgallon).

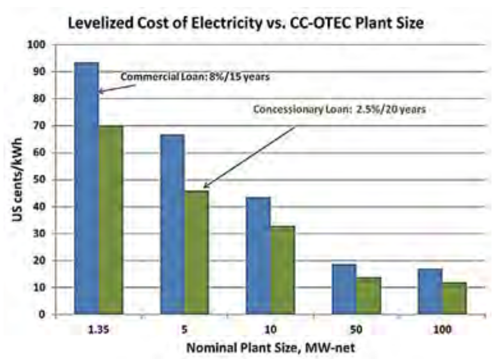

Figure 3.65 – Levelized Cost of Electricity (Capital Cost Amortization + OMR&R Levelized Cost) Production for First Generation CC-OTEC Plants as a function of Plant Size with Loan Terms (interest and term) as Parameter. Annual Inflation assumed constant at 3%.

3.4.6. ENVIRONMENTAL IMPACT OF OTEC

OTEC might offer a relatively benign power production technology, since the handling of hazardous substances is limited to the working fluid (e.g., ammonia for CC-OTEC), and no noxious by-products are generated. For example, the amount of CO2 released from electricity-producing plants (expressed in gr of CO2 per kWh) ranges from 1000, for coal fired plants, to 700, for fuel-oil plants, and 500 for natural gas plants, while for OC-OTEC plants it is at most ~ 1 % of the amount released by fuel-oil plants. The value is much lower than 1% in the case of a CC-OTEC plant [1, 8].

To have effective heat transfer, it is necessary to protect the heat exchangers from biofouling. It has been determined that, with proper design, biofouling only occurs in CC-OTEC heat exchangers exposed to surface seawater. Therefore, it is only necessary to protect the CC-OTEC evaporators by, for example, intermittent chlorination (50-100 parts per billion chlorine for 1 hr/day). This amount is well below what is allowed under current U.S. regulations. The use of biocides and ammonia are similar to other human activities. If occupational health and safety regulations like those in effect in the U.S. are followed, working fluid and biocide emissions from a plant should be too low to detect outside the plant sites. It must be emphasized that no chlorination is required in the OC-OTEC process.

A sustained flow of cold, nutrient-rich, bacteria-free deep ocean water could cause sea surface temperature anomalies and biostimulation if resident times, in the mixed layer and the euphotic zone respectively, are long enough. This describes the situation in naturally upwelling oceanic regions like off Peru where the vertical speed of upwelled water averages about 20 m per day.

The euphotic zone is the upper layer of the ocean in which there is sufficient light for photosynthesis. This has been taken to mean the 1 percent-light-penetration depth (e.g., 120 m in Hawaiian waters). This is unduly conservative, because most biological activity requires radiation levels of at least 10 percent of the sea surface value. Since light intensity decreases exponentially with depth, the critical 10 percent-light-penetration depth corresponds to 60 m in Hawaiian waters.

The analyses of specific OTEC designs off Hawaii, for example, indicate that mixed seawater returned at depths of 60 m results in a dilution coefficient of 4 (i.e., 1 part OTEC effluent is mixed with 3 parts of the ambient seawater) and equilibrium (neutral buoyancy) depths below the mixed layer and the euphotic zone throughout the year. This water return depth also provides the vertical separation, from the warm water intake at about 20 m, required to avoid reingestion into the plant. This value will vary as a function of ocean current conditions. It follows that the residence time of the OTEC effluent and the resulting plume equilibrium depth are such that marine food web should not be affected and that persistent sea surface temperature anomalies cannot be induced. These conclusions need to be confirmed with actual field measurements which could be performed with pilot plants.

A report describing the modeling work by Makai Ocean Engineering, Inc. to simulate the biochemical effects of the nutrient-enhanced seawater plumes which are discharged by one or several 100 MW OTEC plants is available at: http://www.osti.gov/scitech/servlets/purl/1055480

Other potentially significant concerns are related to the construction phase. These are similar to those associated with the construction of any power plant, shipbuilding and the construction of offshore platforms. OTEC operations might affect commercial and recreational fishing. Fish will be attracted to the plant, potentially increasing fishing in the area. However, the losses of inshore fish eggs and larvae, as well as juvenile fish, due to impingement and entrainment and to the discharge of biocides may reduce fish populations. The net effect of OTEC operation on aquatic life would depend on the balance achieved between these two effects.

In summary, potential environmental impacts must be evaluated and all licensing and permitting requirements must be fulfilled. However, it is of extreme importance to understand that the only process which differentiates OTEC from other well established human activities and industries is the use of ocean water drawn from ~1,000m depths and its return to the ocean below the photic zone. Given the intricate and dynamic nature of the ocean, it is nearly impossible to determine with a high degree of certainty what would be the effect of such process through basic research or the development of ecological theory. The only way to evaluate the OTEC environmental differentiator is to obtain field data with a pilot plant operating with flow rates corresponding to about a 5 MW plant. Such a plant must be operated and monitored through ongoing and adaptive experience for one to two continuous years.

3.4.7. OTEC: CONCLUSIONS AND RECOMMENDATIONS

In theory, ocean-thermal resources could be used to generate most of the energy required by humanity. Numerous nations and territories with access to the OTEC thermal resource within their 200 nautical mile EEZ have been identified. There is also a market for nations that could manufacture and supply the equipment required for OTEC plants. OTEC systems, however, are in the pre-commercial phase. Several experimental projects have already demonstrated that the baseload technology works 24/7. The next step requires the realistic determination of the costs and the potential global environmental impact of OTEC plants and this can only be accomplished by deploying and subsequently monitoring operations with pre-commercial plants.

Accounting for externalities in the conventional production and consumption of electricity and desalinated water might eventually help the development and expand the applicability of OTEC. Unfortunately, it is futile to use these arguments to convince the financial community to invest in plants without an appropriate operational record. The major challenge continues to be the requirement to finance relatively high capital investments which must be balanced by the expected but yet-to-be demonstrated low operational costs. Perhaps a lesson can be learnt from the eventually successful commercialization of wind energy, which occurred due to consistent government funding and support of pilot projects that led to an appropriate and realistic determination of technical requirements and operational costs in Germany, Denmark and Spain.

Recommendations for future work are given in Table 3.1.

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3.5. OFFSHORE ALGAE CULTIVATION FOR BIOFUELS

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After starting his career at IST Lisbon (Technical University) and WW–Consultores de Hidráulica e Obras Marítimas in Portugal (Hydraulics and Maritime Consultants - Pre-design and evaluation of advanced coastal structures and wave energy devices), he acquired operational experience at sea and hands-on planning and analytic skills with AWS II BV (Netherlands and Portugal), during the prototype tests in 2004.

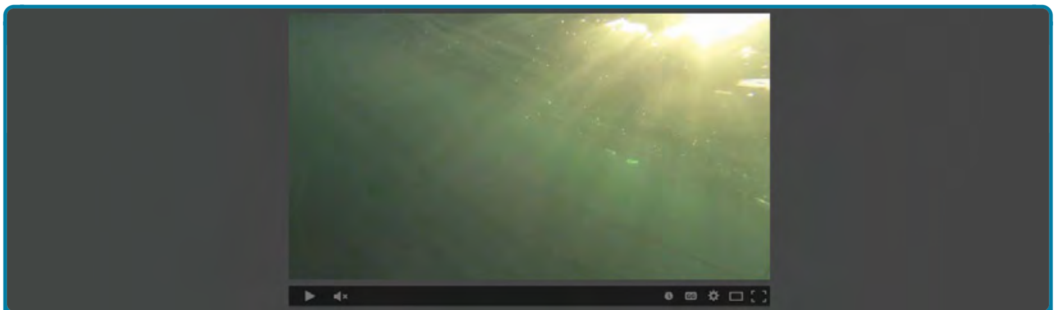
Between 2005 and 2011 he coordinated the rehabilitation and monitoring of the Pico OWC wave power plant on the Azores island (Portugal) and has lead various other wave energy projects, including two international training networks.

In 2008, Neumann was appointed Associate Director of the Wave Energy Centre (www.wavec.org), which he helped to create. In 2011 he was also one of the Directors of the European Ocean Energy Association EU-OEA. Neumann speaks German, Portuguese and English.

“3.5.1. OFFSHORE ALGAE CULTIVATION FOR BIOFUELS – A SIGNIFICANT PIECE IN THE PUZZLE

CONTEXT – THE SEAWEED-FOR-ENERGY CASE

The idea of cultivating seaweed for energy purpose goes back to the energy crisis in the seventies, when mainly in North America studies evaluated the viability of large seaweed farms for this purpose [1]. However few projects went beyond the conceptual phase. The large-scale cultivation of Marine Biomass for fuel has gained increasing attention in the recent past, as a potential contributor for a more sustainable energy mix. Seaweed has significant advantages as a large-scale source for biomass cultivation when compared to land-based crops. The cultivation methods for large seaweed farms for higher value products (see e.g. [2]) is typically to suspend vertically seeded ropes along horizontal long lines (see Video 3.19), and then harvest them in small boats manually. None of these existing cultivation techniques or approaches to natural harvest are applicable to the systems required for large-scale cultivation of seaweed for energy. Seaweed Energy Solutions AS (SES) pioneered the development of low cost seaweed



Video 3.19 - Underwater view of a 'classical' long line short after deployment of the seeded and incubated drop ropes near Frøya/Norway.

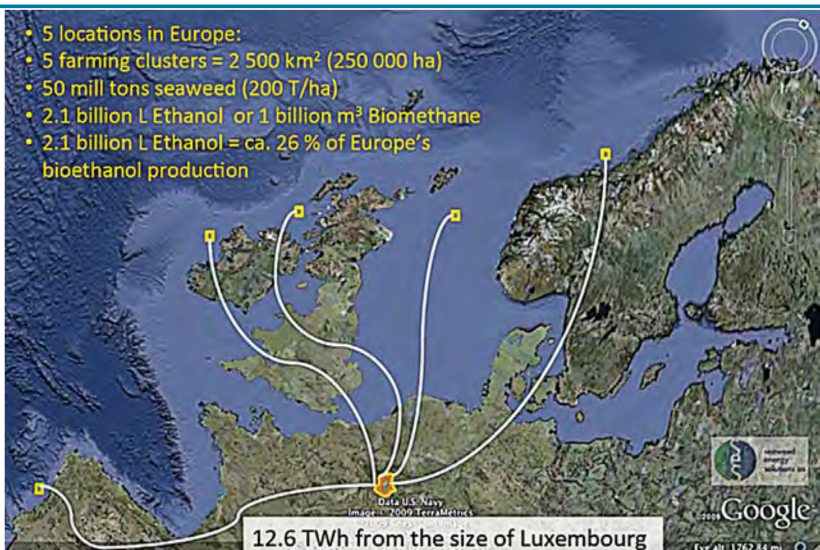


Figure 3.66 - Exemplary set of five seaweed-for-energy farms distributed over European waters: minimal footprint when seen in the large picture (based on GoogleEarth image).

carrier structures to cultivate seaweed in a very large scale, in order to achieve a competitive product for Biofuel conversion.

At the present stage of know-how (Figure 3.66), commercial-sized seaweed could be from 50km2 (5000 ha) large areas, with an expected annual harvest of 200 tons per hectar (resulting in 1 million ton wet seaweed per year).

Amongst the major challenges for turning the required multi-million-ton harvests per year into reality, is to develop suitable, (semi-) automated deployment- and in particular harvest equipment in resemblance to land-based agriculture developments. Both the logistics associated to this dimension and the very strong cost pressure make commercial seaweed farms a serious engineering challenge, in particular due to the high automation required for the harvesting and re-seeding operation. Although in the long term, the vast open and exposed oceanic waters (extreme wave heights >20m) are key areas for cultivation, the priority of development in the present context is a short-term solution focusing on the development in protected waters like e.g. found in the Trøndelag-area (Norway), where SES is developing cultivation techniques in its test area.

3.5.2. WHY FARM THE OCEAN?

To date, both the harvest of natural stocks and cultivation activities have mainly been related to the (higher value) sale of food, pharmaceutical and cosmetic products, especially seaweed cultivation for food has long tradition in Asian countries (see Figure 3.67 and Figure 3.68). However, very labour-intensive manual cultivation methods are used, making such projects unsuitable for Europe.

The worldwide seaweed industry shows strong consistent growth. In 2010 the total supply of seaweed was 19.1 million tons with a raw material value of about 7 Billion USD. 95% of this volume is from cultivated seaweed, predominantly from Asia. Applications are Food, Colloids (Alginate, Agar and Carragean) and others (Chemicals, cosmetics etc.).

Wild seaweed

Wild brown seaweed is being harvested in Norway, Ireland, Iceland, Canada and Chile. Norway is the largest harvest region with about 190.000 tons (wet weight) of the large seaweed Laminaria Hyperborea for alginate production, representing over 70% of the European volume. In addition, about 40.000 tons of Ascophyllum for animal feed and fertilizer are harvested in Norway and 36.000 tons in Ireland. The harvest is highly regulated and limited and the sustainable expansion of wild harvest volumes will come to a halt at some stage.

Traditional seaweed cultivation – current status

Seaweed farming has been carried out in the Far East for many centuries, mainly for the production of sea vegetables for human consumption. In recent decades the cultivation and use of seaweed has greatly expanded for various industrial applications. Even though the cultivation now yields about 18 million tons fresh weight annually, the production methods are highly labour-intensive and not optimal for high volume bulk production. The seaweed industry in China employs about 1 million people and the harvest volume is expected to be in excess of 7 million tons wet weight. Species from all algal classes (brown, red and green) are being cultivated. The large brown seaweed species are best suited for temperate and cold waters, whereas the red algae favour temperate to tropical waters. Green algae may be found in all waters but have so far received insignificant industrial interest.

While the seaweed harvest of wild stocks and existing cultivation activities in Asia may still have considerable growth potential due to increasing demand, mainly in the chemical industry, there is a need to cultivate regionally (i.e in Europe) in very large scale, if seaweed is to be used as biomass for energy. Especially in Norway, large ocean areas in semi-protected areas exist and beside the need for mechanised operations, there

Figure 3.67 – Aerial view on large Kelp farm north-east China [3].

Figure 3.68 - Manual harvest in China [4].

is mainly the need for transparent and efficient attribution of concessions to enable this sector as being a contributor to the renewable energy mix.

Seaweed: the better biofuel

Seaweed as biomass has a number of benefits, especially when cultivated large-scale for biofuel. In the following, the most relevant characteristics are outlined:

- No food versus fuel conflict: Seaweed cultivation does not occupy agricultural land and it does not influence the terrestrial balance of food demand and supply.

- No need for fresh water; being one a most valuable and sometimes scarce resource for humanity, this is an important argument from an economical, technical as well as political point of view.

- No conflict regarding indirect land use changes (iLUC), which is a considerable issue for the terrestrial biomass industry. In the ocean, large areas are available for sustainable growth and economies of scale.

- Higher biomass productivity (faster growth) than any terrestrial crop (dry weight/hectare/year).

- No or minor need for fertilizers: The ocean is naturally abundant with nutrients. In many areas there is an excess level of nutrients from sewage, land run-off, agriculture and aquaculture, which have a positive impact on seaweed growth (which e.g. led to the IMTA – Integrated Multi-Trophic Aquaculture – concept).

- No need for pesticides: Pesticides are costly and involve many environmental issues.

- Carbon fixation: Seaweed absorbs CO2 to a similar or greater extent to land plants per hectare. By farming the ocean we are adding new "forests" to the planet and the standing crop in these ocean farms will thereby contribute to carbon fixation. We therefore also believe seaweed farming will be eligible for carbon credits in the future.

- Low CO2 transport footprint: Energy intensive logistics of energy crops is a major contributor to a high CO2 footprint. CO2 emissions for transportation on land are about 100-250 gram CO2 per ton per km versus about 25 gram for transport of cargo in the ocean.

- Lower transportation costs at sea; few limitations with regards to the size of the transporting means (land based transportation is limited to the width of the roads and height of bridges etc.); cost advantages due to buoyancy (minimal necessity to lift raw material).

- Scalability: The ideal farming system will consist of flexible structural components which can be used in large offshore deployments or as smaller units in near shore farms.

- Synergies / Other offshore energy business: Offshore oil and gas exploration, offshore wind and wave energy all occupy ocean space and synergies can be achieved by sharing areas, maintenance and infrastructure.

- Whereas exposure to extreme events (especially waves) is an issue, more stable temperature and fewer natural disaster issues (such as draughts, frost, fires and floods) than for land crops.

Growing seaweed in farms covering an area of just 0.05% of Europe's ocean areas would yield a yearly production of 75 million tons of seaweed. This biomass could be converted into an estimated 3.7 billion litres of ethanol. As a pioneer in the in the development of cultivated seaweed as an alternative energy source, SES expects to be able to embark on energy scale cultivation between 2020 and 2030. The large brown seaweed that SES is targeting grows best in cold water (temperate zone) as e.g. from Portugal in the South up to the North of Norway. On a global level, the most important regions for this purpose will be USA, Canada, Chile, Argentina, South-Africa, Australia, Russia, Japan, Korea and China. Prior to market entry, the local demand for energy-carriers and other co-products must be carefully taken into account. Some countries have good infrastructure and incentives for biogas production (i.e. UK) while other regions will be more interested in Ethanol (i.e. Norway).

Seaweed properties and cultivation issues

The life cycle of large brown seaweeds is initiated when mature plants (the sporophytes) produce sorus patches, which contain microscopic spores, a process that now can be conducted year round in a nursery. In nurseries, each of the huge number of microscopic spores grows into a microscopic sexual stage, with 50% each of males and females. This rapidly yields the next generation of macroscopic plants which can be harvested and the life cycle is repeated. Spores can be released artificially from "mother plants" all year round, which is an important factor to extend the harvest season and enable multiple crops per year.

To attach to the substrate, seaweed has a holdfast, unlike the roots of terrestrial plants. They absorb nutrients from the surrounding water and have the ability to store the minerals and nutrients in high concentration. This means that the whole plant is exposed (with no roots in the soil) and the whole energy in the plant is readily accessible (typical leaf of Saccharina Latissima see Figure 3.69). This also means more flexibility in terms of the farming structure design as well as the ability to move farms.

The photosynthetic efficiency (fraction of light energy converted into chemical energy) of seaweed is higher than plants grown on land allowing it to grow faster. Natural seaweed forests in temperate waters are amongst the most productive

Figure 3.69 - Typical appearence of an adult Saccharina Latissima plant [5].

ecosystem on earth with rates of carbon fixation exceeding that of tropical rain forests on land.

The bulk of natural seaweed forests are found in temperate to cold waters where the temperature varies far less than on land. In temperate regions, the sea is naturally fertilized each autumn, giving high levels of nutrients throughout the winter and spring, which supports the rapid growth of the seaweeds into the summer. Due to being totally immersed in water with dissolved nutrients, like nitrate and phosphate, every surface area of the whole plant has access to nutrients, so seaweed wastes hardly any energy for uptake and transport of neither water nor nutrients.

3.5.3. STATE OF THE ART OF SES ACTIVITIES

Seaweed Energy Solutions AS (SES) has from the beginning focused on the development of low cost artificial carrier structures to cultivate seaweed in a very large scale, in order to obtain a competitive product for biofuel conversion. Initial focus was the cultivation structure, resulting in two full-scale prototypes suitable for moderately exposed sites, one of which could be further developed to fully exposed sites. Theultimate development goal for energy-scale cultivation is simple, light structures which can survive in fully exposed seas like e.g. the Portuguese coastline. The artist's impression (Figure 3.70) is a possible vision of such structures.

The development work at SES was a result of two collaborative RTD projects with the technical partners Aqualine, Sintef, NTNU, Ciimar, and Stolt Sea Farm Iberia [6], [7]. Besides working on long-term concepts for energy-scale, SES has increasingly focused on enabling fast scale-up in a short time frame. Some promising concepts would require dedicated infrastructure and equipment development. The full-scale prototype successfully tested at Taraskjæret (since early 2013) has been the basis for the development of efficient harvest and deployment sequences within a new public funded project [8]. These are generic activities, focusing on longer term commercial phases and possibly involving the development of entirely new approaches and vessels (2nd/3rd generation). They might call for large ocean-going vessels which enable deployment and harvest in sea states in excess of Hs=2m. As an initial estimate, it can be expected that an evolution from the presently tested structures become commercially viable if manufactured and deployed in quantities in the range of hundreds to thousands (corresponding to several hundreds of thousands of tons 'wet' seaweed harvest per year).

In the short term, focus is given on the use of existing state-of-the-art in adjacent areas, in order

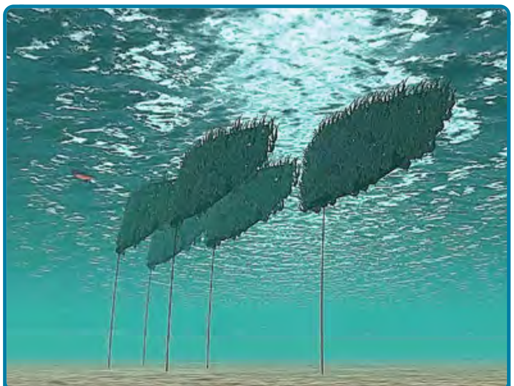


Figure 3.70 – Artist's impression of a seaweed carrier in exposed sea: the structure resembles the movements of marine plants in nature, which can contribute to survivability of structure and plants [5].

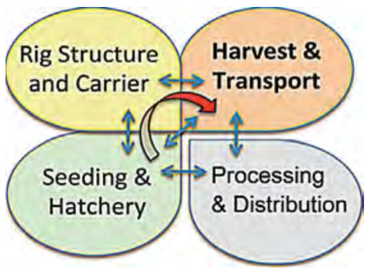


Figure 3.71 - Phases/sectors of production chain for seaweed for energy cultivation. While seeding & hatchery are relatively well controlled and the rig & carrier structure on the expected development path, the mechanised harvest of large-scale farms represents the most critical status of technical development at this stage. For the processing (e.g. fermentation, refinery), techniques are ready for large-scale application with some adjustments [5].

to turn the entire cultivation cycle from seedling production to processed seaweed competitive, especially for the higher value product market, Figure 3.71 depicts the main steps of this sequence.

A challenge in the development of cultivation techniques and harvest strategies is that there is very little information available about the drag forces on the seaweed blades and especially how drag forces are influenced by dense, large-scale exposure to currents, as well as the inclination of the carriers. Uncertainty exists about drag induced by the seaweed on the sheet and resulting hydrodynamic behaviour and tow resistance. Only few research efforts (e.g. [9] have been conducted on this issue to date and these exclusively on single plants or small bundles. The drag on fully grown large carrier sheets will be estimated by field measurements, ongoing laboratory experiments at NTNU (Dept. of Biotechnology) and comparison to simulated scenarios will improve the estimates. Whereas hydrodynamic models for wave-structure interaction are reasonably sophisticated for most of the items if considered separately the interaction of rig-carrier-vessel-deck equipment is a too complex modelling task, which is why field test at real scale is required.

One seaweed plant of the species presently used (Saccharina Latissima) may be in the range of 1.5-2m length and hundreds of grams wet weight when harvested. The plants tend to bundle and grow in relatively short distances (a few centimetres) from bundle to bundle. The plant attaches strongly to the carrier structure (traditionally ropes) by so-called “holdfasts” (similar to roots of terrestrial plants). Growth depends strongly on nutrients and light, which is why only the upper few metres of the water column are interesting for seaweed cultivation in coastal waters.

The combination of physical characteristics (size, weight, stiffness) and degrees of freedom of movements of several connected floating bodies is the main RTD challenge for the development of operational equipment, including vessels. The carrier, although resembling e.g. a fishing net, has to be detached from the rig by a fast clipping system and then hauled in a controlled, probably stretched way on-board the vessel, via lead-ropes. While the carrier is still in the water, it is subject to currents and wave action, dragging and distorting the carrier, which if fully grown, weighs tens of tons in air. Also the vessel is subject to water movements, and only limited stretch may be applied to the carrier while being loaded (material limitations).

Initial harvest field tests of a single carrier have been undertaken in 2013, and valuable measurements could be obtained regarding the drag induced by dense bundles of seaweed (see Figure 3.72 and Video 3.19). However further field trials in full scale are required, and consequently significant amounts of grown carriers will be needed in the next phase trials, which can only occur during the harvest season between May and July.

Future farms consist of several thousands of carriers, causing a rig structure as indicated above to yield several hundreds of tons of wet seaweed (in air) and operations are highly weather-dependant. This should serve as an indication of the logistic and engineering challenge associated.

In order to enable large-scale harvest and deployment processes in the short-medium term, focus must be given to the use of existing state-of-the-art in adjacent areas, both by researching the logistics and the (re-)equipment of existing vessels.

Figure 3.72 - Deployment trial (left) and vessel- based seaweed drag trials (right) of a full-scale carrier in 2013. The seaweed on the right foto corresponds to approximately 15m width and 3m depth of bundled seaweed [5].

Video 3.20 - Underwater view of a net-like seaweed carrier sheet being towed at low speed (when idle, the carrier sheet is 5m deep).

SES research focus has been on the energy market, as this phase of cultivation means a virtually unlimited market. However, there is an existing production as well as emerging new market segments for cultivated seaweed for 'high value products' (cosmetics, medicine, human consumption, animal feeding additives, fertilizer,...) and the application in 'IMTA' (Integrated Multi-Trophic Aquaculture) which will help bridging the gap from pilot scale to commercial farms.

3.5.4. SOCIO-ECONOMIC ISSUES

Regional economics

For nations with ambitions in the blue economy, maritime engineering tasks, the development and manufacture of industrialised seaweed harvest equipment and vessels in the pioneering phase of a potentially large global market, can bring along valuable competitive advantages.

The most significant challenge in implementing large-scale seaweed production is not to solve the technical challenges as such but to find solutions that allow for scaling up towards very low cost large-scale systems. Cutting-edge knowledge will be required in order to find low-cost and possibly 'low-tech' solutions. Such a development enhances greatly the flexibility and bandwidths of products and services offered by a sector, especially having in view the large global export potential of such products and services for seaweed farming.

Energy-scale seaweed farming itself can bring along further advantages on a National level, namely (i) improved energy independency (and/or export potential); (ii) significant potential of job creation in areas like marine biology, maritime technology, biochemistry, materials, production and installation and not lastly marine logistics/transport. To quantify this potential would not be credible at this stage but as an indication may serve the number of 20 million € as the expected annual turnover of a 1 million tons commercial farm, bringing along a capital investment of approx. 200 million €, most of which is likely to be sourced locally. It is predictable that several such farms will arise in the coastal waters of Norway and elsewhere in Europe.

Environmental services

In addition to providing a renewable fuel solution with minimal conflicting issues, society may also find value in the environmental services provided by seaweed farms. By taking up nutrients and carbon dioxide from seawater they would reduce coastal eutrophication and ocean acidification, at least locally. And, by sparing freshwater and land which would otherwise be needed to expand terrestrial agriculture, they would ease the burden we now impose on our terrestrial habitat. Moreover,because seaweeds prosper without land or freshwater a marine agronomy may be less vulnerable than our terrestrial one to the effects of climate change. The most relevant 'environmental services' provided by seaweed are listed under the following:

- Biodiversity: Standing seaweed crops naturally attract marine life and provide shelter and habitat for spawning fish or small organisms, increasing biodiversity. Increased levels of dissolved oxygen help improve water quality in the sea, which combined with habitat provision, assists in increasing fish stocks. Cultivation of seaweed is also a positive counterbalance to diminishing wild seaweed resources. Increased levels of oxygen and provision of habitat lead to increased fish biomass. This in turn supports higher predators and may attract some species of commercial value (food security – over 60 % of world's population are living along the coast. In some developing nations, fish constitutes over 90 % of their protein diet). The added oxygen will allow the fish to survive and grow quicker:

- Biofilter: Seaweed has the ability to absorb pollutants in the water.

- Assist in reducing coastal eutrophication: Seaweed can play an important role in reducing coastal eutrophication (degradation of the marine habitat due to human activities), which is an increasing problem with high economic and ecological costs.

- IMTA (Integrated Multi-Trophic Aquaculture): IMTA has recently become an area of increased focus in many aquaculture regions. Seaweed cultivation can be implemented in proximity to intensive fish farming regions to remove excess nutrients and waste products from the fish farms.

- CO2 storage / fixation: The standing biomass in the farms represent new added "forests" which are continuously sequestering CO2. Seaweed lost during harvest, bad weather, fish grazing etc, enter the detritus food chain or are exported to nearby regions and open sea, all contributing to the cycling of carbon between ecosystem and food webs, being an important nutrient source in the marine environment. Also, a fraction of the fixed carbon may end up at the bottom of the sea, permanently stored, thereby helping in emissions mitigation. The significantly reduced DIC (dissolved inorganic carbon) levels also help counteract ocean acidification.

Potential negative environmental impacts due to a high amount of synthetic materials in the sea, will have to be evaluated however it is not expectable to be of significance in relation to other existing uses. Other threats like floating debris and visual effect can be countered by improved rig design and the ecosystem changes will have to be monitored once the first larger-scale developments exist.

Also the benefits now need to be tested and quantified, and the question for our society is whether the above balance of benefits and drawbacks should be sufficient payback in return for access to the space in coastal waters that seaweed farming would need.

Barriers to the development

Similar to ocean energy, seaweed for energy has still an important development path ahead with respect to some technical issues. Equally analogous is that the long term economics are undeniably promising but there seems to be no sufficient drive on a political and industry level to embark on the high initial investments associated with the establishment of these sectors. Factual subsidies of conventional energy sources continue to be hidden in the tax payers' bill, while emerging, sustainable energy sources are demanded almost immediate competitiveness. Simultaneously, the significant advantages of increased energy independency and decentralised supply, is not accounted for, which in case of seaweed for energy has the additional advantage of being storable biofuels.

In addition to the difficult phase of demonstrating viability for commercial scale, new entrants to the marine environment also face substantially higher obstacles with respect to permissions, even in the early phase of scale testing, where small sea areas are required and almost no impacts can be expected.

A straight-forward approach to concessions, structured along several development phases (sea trials, demonstration and commercial) should exist not only on paper but be implemented in practice in the very short term. Fair regulations should be distinct between the type of installation to be tested and the associated risk level for the environment. It should be directly connected to the level of how demanding certificates and inspections will be.

Further early testing requires substantial public support, which does not always seem to be accessible under practicable conditions.

3.5.5. CONCLUSIONS

In Europe, almost all current seaweed harvest is from limited wild resources, primarily for high-value products (alginate, cosmetics, pharmaceutics, fertilizer,...). As such, seaweed-for-energy cultivation is a new specific area of RTD and development, as in existing practice no precedence for unloading, transporting and harvesting large net-like seaweed carriers exists. At first sight, resemblance to fish trawling and some techniques in aquaculture (fish handling and well boats; mussel farming) do exist, but none of these techniques show as being viable options for seaweed farming. The main reasons for existing limitations are:

- Cost as a major driver for materials and operations: adjacent sectors like fishing and aquaculture deal with different cost levels for their products; while the cultivated seaweed target is set according to achievable prices on the biofuel market, presently far below cultivation costs.

- The physical characteristics (size, weight, stiffness) and degrees of freedom of movements of several connected floating bodies (rig, carrier - without/with growth - and lead ropes, vessel) are unusual combinations that in connection with the environmental forces (current, waves, wind) pose a complex challenge, nearly impossible to simulate on a small scale or numerically.

It is therefore vital to proceed to real-scale tests of a promising cultivation and harvest system that can be further developed and automated in the future. The expected results from present developments represent a decisive step towards making large-scale seaweed-for-energy farming technically proven and economically credible.

Norway is a very likely region to be the first with commercial-scale seaweed-for-energy farming, due to its temperate climate (the large brown seaweed grows best in cold water) and large fairly protected ocean areas, both of which are important characteristics for the early cultivation of most seaweed species. The level of R&D and the maritime industry's capacity suggests that if tackled early enough, the technical challenges can be overcome soon, paving the way for a global business case of substantial dimensions. Once proven in semi-protected waters, more exposed farms will follow and the open ocean will ultimately allow for exploring dimensions very relevant for the global fuel supply.

With respect to the technical viability of such undertakings, one should remember that we drill for oil at several thousand meters depth with high precision. We farm fish in large quantities for a lower cost than wild caught fish, we move in submarines, we build under water and there are structures constructed at sea which can withstand the highest recorded waves. In this context, construction of efficient large-scale offshore farming structures for seaweed should be considered manageable in the medium term.

In addition to their direct impact potential on the economy, large-scale seaweed farms will serve as efficient carbon sinks and their capacity of taking up nutrients (cleaning effect) is proven. Further, seaweed does generally enhance the local biodiversity and natural growth has been declining both in Norway and other European regions. Large cultivated seaweed farms could well contribute to regaining the balance, similar to terrestrial reforestation activities.

Once the above factors are recognised and translated into useful incentives, the cultivation techniques should be at the starting blocks, so to speak 'we are ready when society is ready'.

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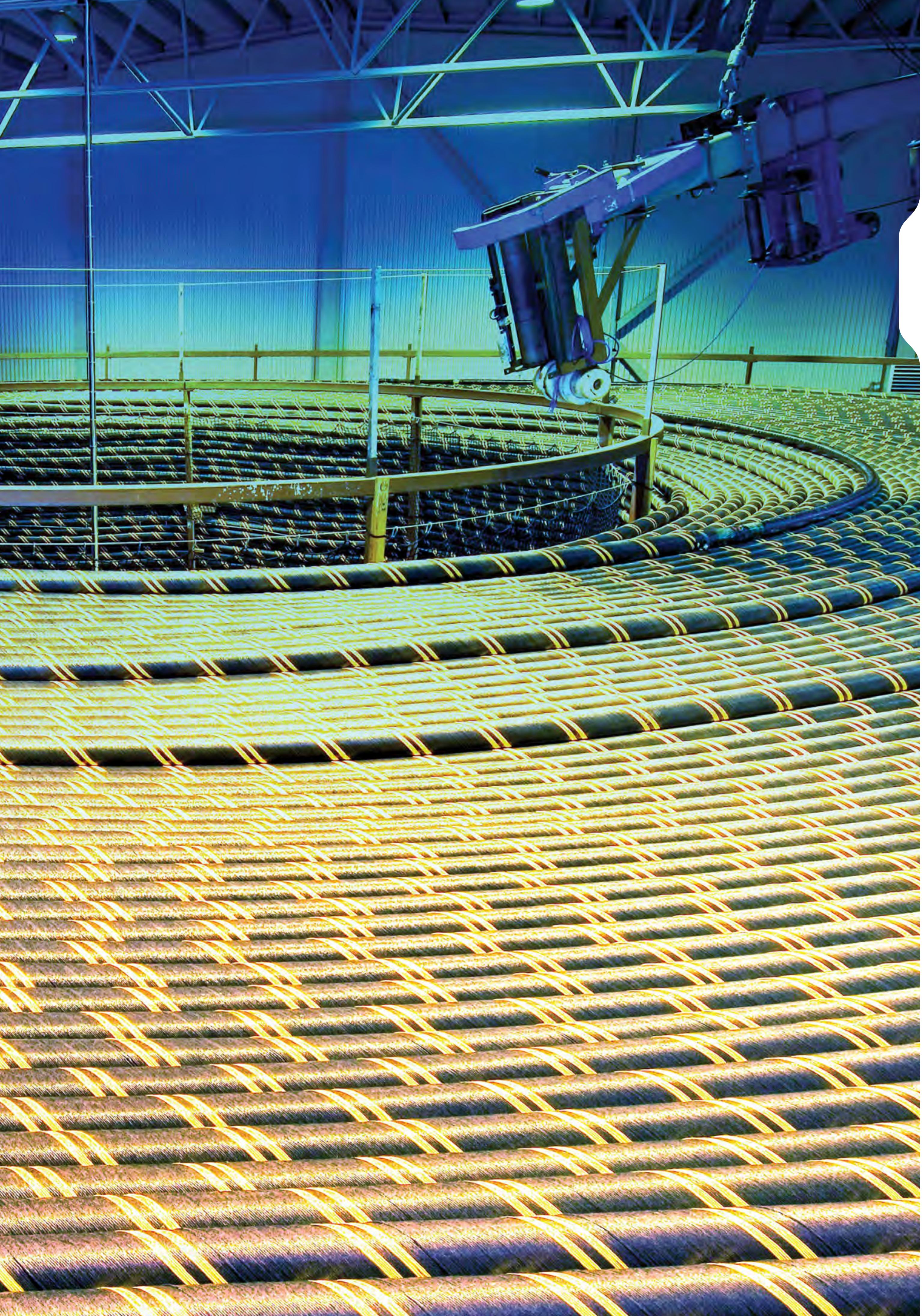

ENABLING TECHNOLOGIES FOR OFFSHORE RENEWABLE ENERGY – REVIEW

4

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4.1. INTRODUCTION

In this chapter we will focus mainly on wave energy converter systems (WECs) but also cover enabling technologies for tidal current systems (TEC). The latter have different challenges and solutions than the WEC systems but also share many of the same related to operation and maintenance.

In the recent years we have also seen a development within offshore floating wind, particularly the full-scale pilot WindFloat outside Portugal and the HyWind project off the coast of Norway, both 2 + MW turbines installed on two different types of floating support structures.

As many of the technologies discussed for ocean wave projects (moorings, foundations, O&M, installation techniques, advanced control systems) as well as many of the challenges are similar for floating wind projects we also include the floating wind concepts in our discussion. It is also relevant as we observe many new concepts combining offshore wind with ocean energy to improve the economics for both.

Furthermore it is now public that Statoil will install five 6 MW HyWind turbines in a floating wind farm at the Buchan Deep outside Scotland UK and the Japanese are installing their first floating wind turbine outside Fukushima.

It is impossible to describe all various solutions which can contribute to enabling offshore renewable energy solutions. Therefore we have selected to first, discuss some of the challenges and key aspects designing and operating these systems to give the reader insight into the key drivers for the development, before we describe some of the solutions which are in the works.

In our view enabling technologies also includes important framework around the ocean energy systems like standards.

The systems we consider are shown in Figure 4.1 and Figure 4.2 taken from the SI Ocean Energy Status report[1]. Where Figure 4.1 gives an overview of types of WECs and Figure 4.2 the different mooring and foundation configurations used.

For TECs Figure 4.3 and Figure 4.4, gives an overview of the foundation types and the various turbine technologies.

4.1.1. SECOND WAVE OF OFFSHORE RENEWABLE ENERGY SYSTEMS

The present focus on offshore renewable energy is a kind of “second wave” on developing systems for energy extraction from ocean waves and currents. The

DEVICE TYPE	CLASSIFICATION (WAVE)
Attenuator	A
Point Absorber	B
Oscillating Wave Surge Converter (OWSC)	C
Oscillating Water Column (OWC)	D
Overtopping/Terminator	E
Submerged Pressure Differential	F
Other-Bulge Wave	G
Rotating Mass	H
Other	I

Figure 4.1 – WEC Types [1].

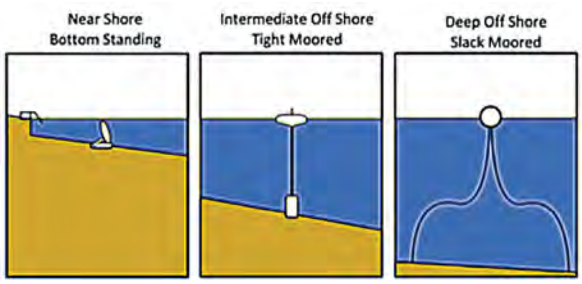


Figure 4.2 – Mooring and Foundation Configuration for WECs [1].

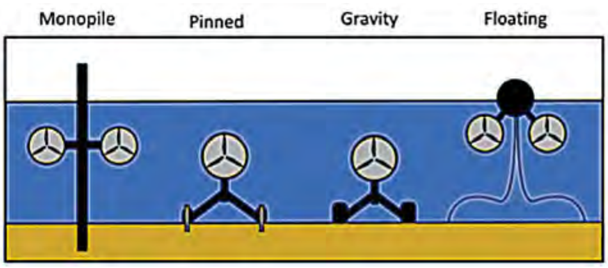


Figure 4.3 – Tidal energy converter foundation types [1].

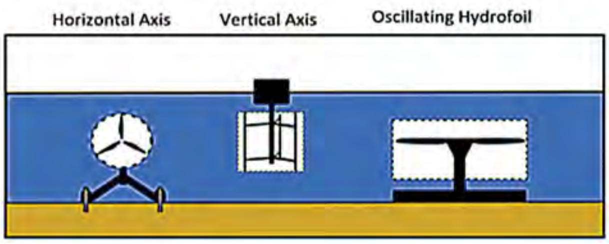


Figure 4.4 – Tidal energy converter swept area [1].

first serious attempt to design systems for ocean energy extraction was in the period around 1980 initiated by the oil crisis in 1973 when the cost of oil skyrocketed. In this period many of the fundamental principles for wave energy extraction were derived. Various full-scale devices, e.g. the Tapchan and the Oscillating water column in Norway by Kværner demonstrated the principles and that energy could be extracted as electrical power. However the projects were abandoned as the systems were damaged basically due to lack of proper structural design and that the oil price returned to normal levels again in the mid-eighties

Since the middle of the eighties the development within marine engineering and research within the marine field combined with the development of new, fast and advanced computer tools means that the development of offshore renewable energy systems can be taken to the next level.

In the same period, the international offshore oil and gas industry moved from shallow water mild climate in the US gulf to the harsh deep offshore waters outside UK and Norway. This fostered new technology and new materials which can benefit the emerging offshore renewable energy industry.

Hence today when the "second wave" of offshore renewable energy systems is coming, we benefit not only from the good theoretical and basic framework established in the eighties but also from a technical and engineering revolution since then. This means that we now are in a better position to handle the challenges we see.

4.2. FUNDAMENTALS AND CHALLENGES

For a researcher within the marine engineering field, the offshore renewable energy systems (specially for extraction of wave energy) are probably the most interesting and challenging topic that can be found. For an engineer who is supposed to design a system that will work and deliver cost efficient electrical energy, it is a nightmare!

The WEC systems should be located in areas with most available energy, which means areas where we would also see the highest waves and roughest seas. The systems should be designed to attract the wave forces, not to reduce them as in traditional design. The systems need to be able to withstand the worst sea states occurring only once or twice a year without damage but the value for production is in the smaller sea states occurring regularly and which have a totally different design paradigm than the extreme sea states.

Extremes are all about strength while energy production is all about reduction of friction and loss.

Figure 4.5 illustrates this effect very clearly. This scatter diagram is for a location in the northern North Sea (the Heidrun offshore oil and gas field outside Norway). This is a 1000 years scatter diagram which shows the weighted available energy (available energy in kW/m multiplied with the probability of occurrence) as a function of the wave height.

The block marked with read is the extreme design sea state for the system; Hs = 18.5 meters, Tp = 17.5 seconds and the deep green, light green and yellow blocks in Figure 4.5 indicates where the energy available for energy production is located. It shows that 47 % of the available energy is in the deep green block, 77% of the energy in the light green block and 94% of the energy in the yellow block, i.e. up to Hs = 7.5. It is in these areas that the WEC design needs to be optimized but it also needs to be able to survive the extreme sea state in the red block.

This is where the challenge for design lays, as it is different design parameters which drive the design in these areas.

Ideally the systems should have at least a 25 years

Weighted average available energy kW/m nothern north sea conditions, total weighted energy available = 65 kW/m

47%
77% Of weighted average energy available
94%

Hm0/Tp	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5	15,5	16,5	[illegible]	18,5	19,5	20,5	21,5	22,5	23,5	24,5	Sum	Cum
0,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0					0	0
1,5	0,0	0,0	0,1	0,2	0,4	0,5	0,6	0,5	0,4	0,3	0,2	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3	4
2,5	0,0	0,0	0,0	0,2	0,6	1,1	1,4	1,4	1,26	1,0	0,7	0,5	0,3	0,2	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	9	12
3,5		0,0	0,0	0,1	0,4	0,9	1,6	2,0	2,0	1,7	1,3	0,9	0,6	0,4	0,2	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	12	25
4,5		0,0	0,0	0,0	0,1	0,5	1,1	1,8	2,1	2,0	1,7	1,2	0,8	0,5	0,3	0,2	0,1	0,0	0,0	0,0	0,0	0,0	0,0	12	37
5,5			0,0	0,0	0,0	0,1	0,5	1,1	1,6	1,8	1,7	1,3	0,9	0,6	0,3	0,2	0,1	0,0	0,0	0,0	0,0	0,0	0,0	10	47
6,5				0,0	0,0	0,0	0,1	0,4	0,9	1,3	1,4	1,2	0,9	0,5	0,3	0,2	0,1	0,0	0,0	0,0	0,0	0,0	0,0	7	55
7,5				0,0	0,0	0,0	0,0	0,1	0,3	0,6	0,9	0,9	0,8	0,5	0,3	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	5	59
8,5					0,0	0,0	0,0	0,0	0,0	0,2	0,4	0,6	0,6	0,4	0,2	0,1	0,0	0,0	0,0	0,0	0,0	0,0		3	62
9,5						0,0	0,0	0,0	0,0	0,0	0,1	0,3	0,4	0,3	0,2	0,1	0,0	0,0	0,0	0,0	0,0	0,0		1	63
10,5							0,0	0,0	0,0	0,0	0,0	0,0	0,2	0,3	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0		1	64
11,5									0,0	0,0	0,0	0,0	0,1	0,3	0,1	0,0	0,0	0,0	0,0	0,0	0,0			0	64
12,5										0,0	0,0	0,0	0,0	0,0	0,1	0,0	0,0	0,0	0,0	0,0	0,0			0	64
13,5											0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0				0	65
14,5												0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0				0	65
15,5													0,0	0,0	0,0	0,0	0,0	0,0	0,0					0	65
16,5														0,0	0,0	0,0	0,0	0,0	0,0					0	65
17,5															0,0	0,0	0,0	0,0						0	65
[illegible]																[illegible]	0,0							0	65
19,5																									
Sum	0	0	0	1	2	3	5	7	9	9	8	7	6	4	2	1	0	0	0	0	0	0	0	65	
Cum	0	0	0	1	2	5	11	18	26	35	44	51	57	60	63	64	64	64	65	65	65	65	65		

Figure 4.5 – Weighted available energy as function of the wave height in the northern North Sea.

life with minimum capital cost and cost of maintenance. The systems are placed in salt water with limited access due to being located at energetic areas in the ocean.

This imposes huge demands on the materials used in the structure and the ancillary systems like mooring systems, generator systems, bearings etc., which calls for new and innovative solutions and materials.

4.2.1. FRICTION, THE KILLER

Power take off (PTO) from waves implies damping the velocity of the motion of the WEC. Classic wave energy conversion methodology says that you should have a low damped system and place the natural frequency close to the exiting frequency of the wave and by this get a resonant motion of the WEC with high velocities as a result.

The PTO then applies damping to the system by extracting the energy "stored" at the oscillations at the natural frequency and the energy produced will be the difference between the black and red curve in Figure 4.6.

The unfortunate of this is that 1) a normal sea state exposes the WEC to a range of frequencies and 2) any friction you have in your WEC extracts energy from the system in the same way.

Point 2 means that low friction systems, like Oscillating Water Columns, are favourable in comparison to Hydraulic based systems which will likely to have high friction in the energy conversion system.

Point 1 call for advanced active systems control.

4.2.2. ACTIVE CONTROL SYSTEMS

Different types of wave energy systems need different types of control systems. Point absorber systems may need control systems which can "tune" the response frequency to various wave periods in order to optimize energy extraction. This is often referred to as latching control where the motion of the point absorber is controlled to allow the point absorber to respond to the period of the wave. Other control strategies can be to maximize the forces during a wave cycle where the response at the natural frequency is less important. Fred Olsen's Bolt1 etc. uses this control strategy.

However, this means that technologies related to control optimization, self-learning computer control etc. will be a very important piece in the puzzle and a key to a potential success of wave energy systems.

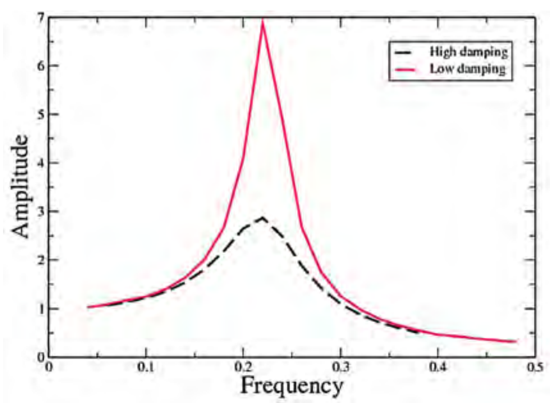


Figure 4.6 – Effect if friction on response.

4.2.3. DRIVERS FOR THE DEVELOPMENT

At present the wave energy conversion systems and tidal power turbines are very costly compared to other renewable energy systems like solar or wind. However, by applying similar learning curves as for other emerging renew able energy industries it is assumed that WEC and TECs when reaching a given level of installed capacity can be an attractive solution in the mix of the future oh the de-carbonized energy system.

As the energy contained in waves and ocean currents is much denser than in wind, it is clear that the systems extracting the energy will inevitably be more expensive than the same structures working with wind. However, one should expect that the weight/kWh produced should be of similar magnitude.

On the other hand, the energy in the waves is extracted from wind and hence, can act as energy storage when the wind stops blowing. Typically it will take hours or maybe a day before the waves calm down after strong wind. Therefore it is important to analyse the energy generation system in an ocean area as a whole when looking at the economics.

When looking at the OWC system in isolation there is a balance between the capital investment (CAPEX) and the operational cost (OPEX), which needs to be addressed when estimating the cost of energy. Optimizing the CAPEX may lead to a higher OPEX and through that, a higher cost of energy produced.

Therefore when it comes to look at enabling technologies for offshore renewable energy devices WECs and TECs it is important not only to look at the technology as such but also look at what can enable the installation and operation of these systems from a broader economic point of view. We will address this in the following:

4.3. ENABLING TECHNICAL SOLUTIONS FOR OFFSHORE RENEWABLE ENERGY DEVICES TECHNICAL

4.3.1. MOORINGS

A key element of floating offshore energy devices

Moorings will be a key element, which can be a substantial cost element for all floating offshore energy devices, floating wind, floating wave energy converter, ocean thermal converters etc., and is often overlooked during the early design of these concepts.

The mooring line configuration can be selected in many forms, but Figure 4.7 from [2] gives a very good overview over a range of various combination of mooring line lay outs; slack, taut, with and without weight and floats.

An example of a slack and taut mooring spread is shown in Figure 4.8, taken from the web site of the University of Strathclyde Engineering in Glasgow [3].

For the typical catenary mooring, heavy chain needs to be involved in the mooring line mock up. This is to provide the distributed weight which creates the catenary that allows the device to stay on location without overstressing the lines.

For a taut moored configuration it is typically necessary that the mooring lines themselves are elastic to provide the necessary freedom for wave frequency motions without over stressing the lines.

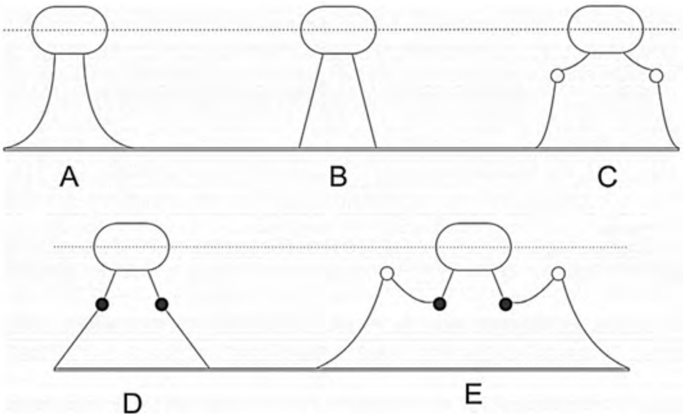


Figure 4.7 – Typical mooring systems for wave energy converters: A) catenary line; B) taut line C) taut line with mid-column float; D) taut line with weights; E) taut line with weight and floats. Each configuration exhibits different dynamic behavior. Scaling the dynamic characteristics of these mooring lines are rather difficult [2].

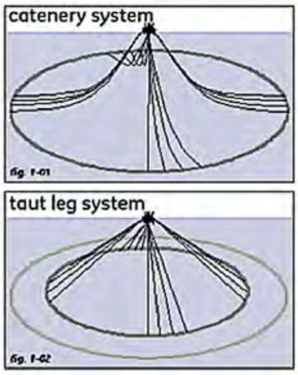


Figure 4.8 – Example of slack (top) and taut (bottom) mooring spread [3].

Lately and specially for drilling rigs, we have seen that a combination of the two types of lines have been used especially for deeper water where the weight of the chain would be taking out too much of the rigs buoyancy which in turn would reduce the available pay load. The part of the sea surface and down close to the sea bed, is made up of a synthetic or fibre rope with high strength and almost zero weight in water and the bottom part which goes from the anchor to the end of the rope is of heavy chain.

This is also a solution, which can be attractive for offshore energy devices, as it will reduce the required buoyancy for the mooring system and hence reduce cost.

To design fibre ropes for offshore use and mooring systems we recommend using either the NDV Posmoor standard [4], the API standards [5], [6] or the ISO standard [7]. As far as we know the ISO standard should cover both the DNV Posmoor and the API standards but all are kept in the text for reference.

When using fibre ropes, it is very important to pay attention to the termination and connections of the rope. We have seen several failures where the connection point to the structure has damaged the rope to the point where it has failed. Furthermore, if passing the rope over a pulley sheave, it is critical that they are designed to work with the rope.

We have also seen failures of the mooring system where various types of shackles have failed due to improper design.

Station keeping and active use for energy production

The moorings are a very important part of any wave energy converter system and over the years there have been several projects where lack of proper attention to the mooring system design has caused the projects to fail!

There are two fundamental uses of the mooring system. The main function of the moorings is station keeping, i.e. keeping the device in place so it does not drift away and ends up on the shore! However, for some wave energy converters, the mooring system plays an active role in the energy generation. This is typically for tight moored structures.

An example is the Fred Olsen Bolt Lifesaver in Figure 4.9.

This concept actually uses both types of moorings. The tensioned mooring works both with the energy capture system working against winches attached to the generators and primary station keeping. The second set of moorings is installed to keep the energy converter at the location if the primary tensioned moorings break.

Arrays

If a large park of Wave energy devices is going to be installed, the mooring system can be a substantial part of the costs. If the park covers a large area, it is also most probable that the water depth will vary across the whole filed which calls for special design of mooring systems for each unit.

One way to drive down the costs is to try to standardize the mooring systems and one possible solution for this is to install an artificial seabed in the area where the various wave energy devices are hooked up. This is described in a patent by Fred Olsen, Øigarden and Strømsem [9], and shown in Figure 4.10. The artificial sea bed is constructed of mooring lines connected to the sea floor by clump weights or suction anchors and where the horizontal forces in the system is taken by chains to anchors at each of the four sides.

The benefit of such a system is that it allows standardized components to move the individual WECs, support for the power cable between the

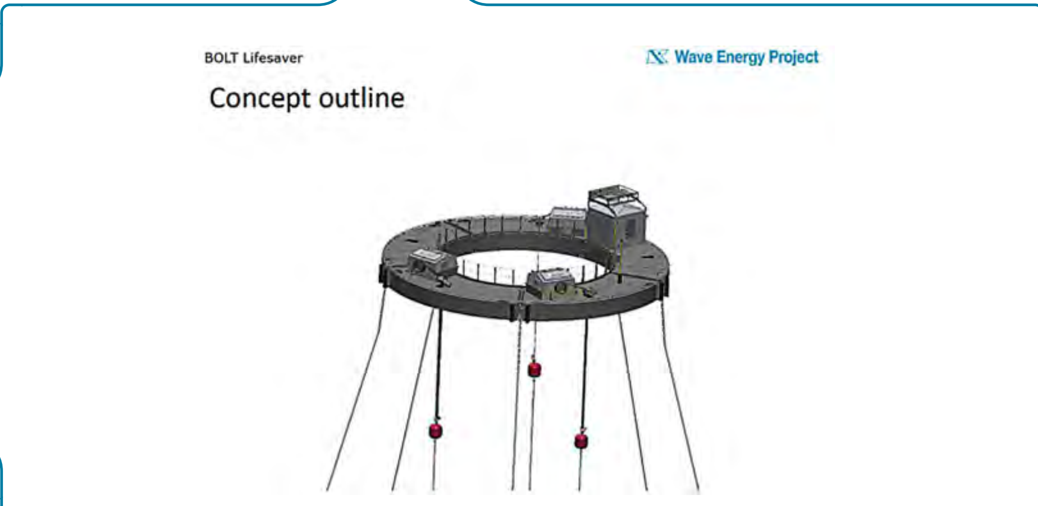


Figure 4.9 – Fred Olsen Bolt Lifesaver [8].

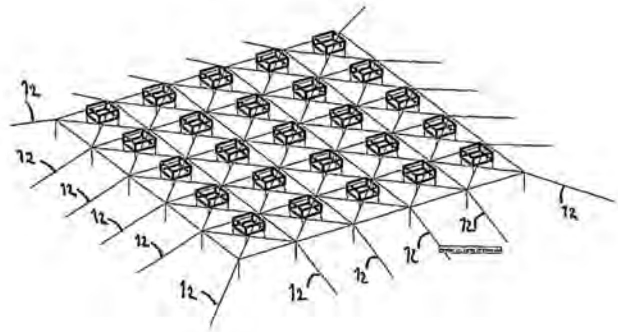


Figure 4.10 – Artificial seabed, one possible solution to drive down the mooring costs [9].

units and also easy disconnect and repair of each of the units by simply unhooking the WEC at the mooring point and floating it to shore.

The 6th framework programme SEEWEC [10], which was run by Fred Olsen Ltd and the University of Ghent in Belgium, worked with arrays and developed models and systems to optimize positioning of large wave energy producers to maximise energy output and improve stability of the production into the grid. Marintek in Trondheim developed in the same project a model to maximise energy output from point absorbers located very close. These are tools which can be used when designing a wave energy array/field development.

4.3.2. FOUNDATIONS, SUCTION ANCHORS, CLUMP WEIGHTS, STANDARD ANCHORS

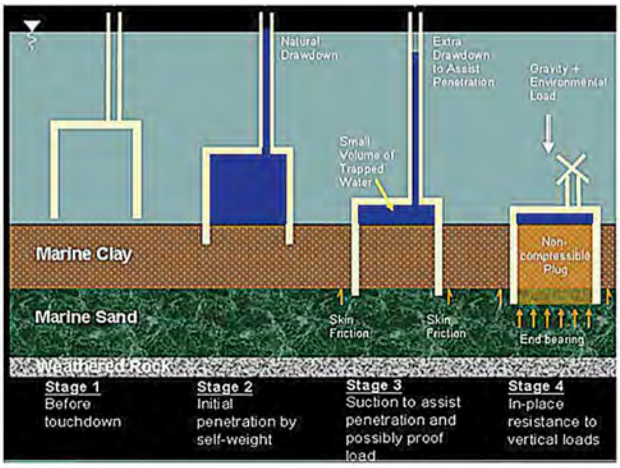
Anchoring of the WEC and TEC can be challenging. For the TECs which would normally be located where the tidal current is large, the current imposes time limits on subsea operations. The current velocity is low only for a very short period of time, twice a day and the challenge is to be able to install the systems either in high currents or fast, where the time window for low current velocity can be used. In such conditions, large clump weights or suction anchors can be a part of the solution.

The suction anchor is simply an up-side down can with an opening at the bottom and where the anchor is dragged into the ground by creating a slight under-pressure at the top, by pumping water out from the top of the can. Once water is being pumped out, the inflow of water along the skirts ensures that the friction against the soil is very small and one can say that the anchor "falls" down in the soil. See Figure 4.11, from the Hong Kong offshore wind farm design[11].

This means that if this is properly done the anchor can be installed very fast and once the valve at the top is closed the anchor has a tremendous holding capacity both for horizontal and vertical loads. Typical suction anchors are shown in Figure 4.12.

4.3.3. ADVANCED BELTS FOR GEARS

As mentioned earlier, friction is a critical factor for conversion of wave energy and many of the systems have a combination of gears and electrical generators. It is known that Fred Olsen on LifeSaver[12], Figure 4.13, is using belts instead of gears to transmit wave forces to the generators. This reduces friction and costs and has enabled Fred Olsen to



Source: Arup

Figure 4.11 – Suction caisson installation steps [11].

Figure 4.12 – Suction anchor.

Figure 4.13 – LifeSaver, an equipment that uses belts instead of gears to transmit wave forces to the generators [12].

install a device which has been producing energy continuously since its installation.

4.3.4. USING ADVANCED MATERIALS TO REDUCE CAPEX AND IMPROVE OPEX

To reduce the friction in bearings and systems for power production it can be necessary to investigate in order to use more exotic materials than normally used. This can be used locally in the bearings and the rest of the structure can be standard steel or the material that is used in the structure elsewhere.

For parts which are very exposed to corrosive action, it can be worth looking to the offshore industry where e.g. Inconel cladding is used in pipe connectors and seals and where the corrosion resistance is very good. Inconel is welded to the material and then the piece is machined to its proper form as shown in Figure 4.14.

GRP is also a material which could be looked upon to provide good solutions for WECs and TECs.

In the SEEWEC [10] project the point absorbers were built using filament winding on a mould and thereafter analysed and impact tested for structural strength. Figure 4.15 shows high-speed camera footage during the impact testing. They were very successful and it was concluded that GRP would be a suitable material for WEC.

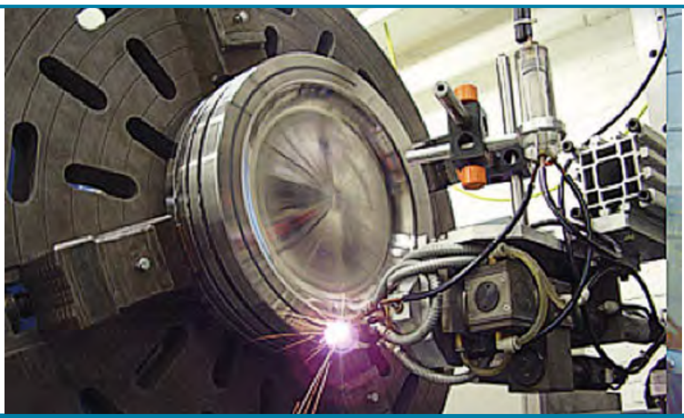


Figure 4.14 – High corrosion resistance component machining [13].

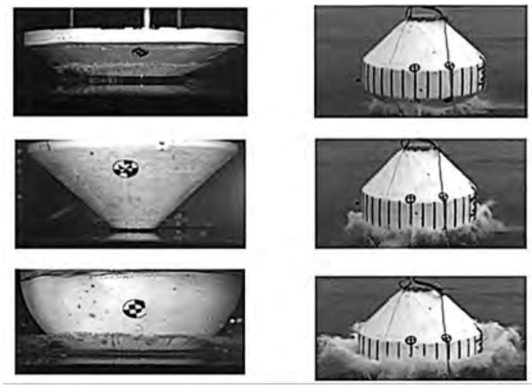


Figure 4.15 – Material design for large scale manufacturing of point absorbing buoys and platform structures. Left: Small scale (1/16) drop tests (resp.: cone 20°, cone 45° and hemisphere); Right: Large scale (1/3) drop tests [14].

Recently we have also seen GRP used in tidal designs like the Norwegian Flumill, where the whole unit is constructed in GRP with the benefit this gives for operational life. See Figure 4.16.

4.3.5. ANALYSIS TOOLS AND MODEL TESTING

As discussed previously the ocean energy systems are very different from ships and other offshore structures. In particular the wave energy systems are designed to attract forces and energy and not to minimise forces but also the tidal current systems have some of the same attributes.

In addition, many of the systems extract energy by moving relative to the waves and are exposed to very non-linear forces from the waves. This creates specific challenges to the analysis tools (software). To predict energy extraction and also derive extreme design loads, the software not only should be able to model the non-linear wave forces correctly but also have to handle the feedback of the wave forces from the (often non-linear) energy extraction system. By keeping in mind that the wave theory (e.g. AIRY theory) is developed for infinitesimal small wave heights which is used to predict large none linear wave conditions it is obvious that this may pose a challenge. Yes other wave theories exist but it is a fact that in many of the frequency domain software packages used for large volume structures, the Airy theory is the basis.

There are other types of software available and by combining results of frequency domain analysis with non-linear time domain software packages it is possible to build models which represent the wave energy converter systems in real ocean waves in a proper way. Typically use of Wamit or Aqua for frequency modelling combined with time domain software like Orcalfex, Flexcom3D for energy extraction and non-linear wave interaction are common options.

Model testing is a very important tool in the process of developing and constructing the ocean energy systems and these systems create new challenges to the model construction.

On of the main challenges is that the energy extraction part of the ocean energy systems and the ocean energy system itself often need to be modelled using different modelling laws. Typically the overall ocean energy system is modelled using the Froude model law and if the energy extraction system is, say a hydraulic system, this may need

Figure 4.16 – Flumill's TEC, fully constructed in GRP [15].

to be modelled using the Reynolds model law, as friction may be the dominant factor.

The issue is that the energy extraction system cannot be tested separately from the overall system since the energy extraction system influence the way the overall system behaves which in turn influence the energy extraction.

4.3.6. STANDARDS AND CERTIFICATIONS, IMPORTANT ENABLERS

For the emerging ocean energy industry it will be very important that a series of technical standards are developed which allows projects to achieve the necessary technical quality. This will also be very important for financing, as it will be extremely difficult to make the projects bankable if no commonly accepted quality level is available.

International standards used in the offshore oil and gas industry, as well as the maritime industry, can be a starting point for the work but as the ocean energy devices are of a very different nature compared to ships and platforms, it will be necessary to develop a series of specific standards.

On the technical side, standards on ocean energy are being prepared under the IEC TC 114 including so far [16]:

DNV has a risk-based certification process for tidal and wave energy converters. This process is defined in their OSS-312 Certification of Tidal and Wave Energy Converters. The certification is not only related to safety and environment but to functional requirements that are of key importance for the success of marine renewables.

The certification process is a gradual process which evolves at the same level as the technology evolves. This is reflected on the different certification deliverables, as part of the initial steps of the certification process and its function of the results from the technology assessment and failure mode identification and risk ranking; i.e. it is a direct function of the criticality and associated risks for the success of the technology.

Further it is referred to as the solid basis of standard developed for the offshore industry (DNV/ISO/API) where the mooring standards referred to earlier in this chapter is a part of.

4.3.7. CABLE TECHNOLOGIES

One essential component not discussed so far is the power cable. The cross section of a power cable taken from BPP cables [17] is shown in Figure 4.18.

INTERNATIONAL TECHNICAL COMMISSION IEC TC 114	
Reference	**Title**
PT 62600-1	Terminology
PT 62600-2	Design requirements for marine energy systems
PT 62600-10	Assessment of mooring system for marine energy converters
PT 62600-100	Power performance assessment of eletricity producing wave energy converters
PT 62600-101	Wave energy resource assessment and characterization
PT 62600-200	Power performance assessment of eletricity producing tidal energy converters
PT 62600-201	Tidal energy resource assessment and characterization
PT 62600-102	Wave Energy Converter Power Performance Assessment at a Second Location Using Measured Assessment Data.

Figure 4.17 – List of documents for wave power devices from IEC TC114 [16].

Figure 4.18 – Cross section of a power cable from BPP cables [17].

This is an AC dynamic power cable where the tree power leads is shown in the middle. Then the two yellow plastic sheets with the tensile wire layers in between. The two tensile wire layers give the tensile strength which allow the cable to be hung off from a floating platform as well as it allows the cable to bend without being damaged.

The power cable from an offshore energy device is typically AC, which is necessary to control the ocean energy device. Then the power for the various energy devices in the area is typically collected into an AC substation and if the power is not too high or the distance to shore is not too long, the power is transmitted to shore via an AC cable.

However, if the distance is long and/or the power is very high the AC on the substation has to be transformed to DC and transmitted via DC lines to shore, where it is changed to AC.

Two slides (Figure 4.19) from a presentation, held by M.Bahrman P.E, ABB Grid Systems at Maui in October 2011[18], have two excellent figures which illustrate the two solutions. The AC link is shown first.

For fixed installations as fixed offshore windmills the power cable and the power cable technology is fairly well known as static power cables in the sea has been used for many years.

However, connecting a dynamic a power cable to a floating device like a floating windmill or a floating WEC/TEC which is a another ball game completely.

First of all, the power cable needs to be a dynamic power cable. This influences the armouring in the cable as well as the protective sheeting. It will need a tougher outer plastic sheet able to take abrasion on the seabed touch down as well as it will need a bending stiffener/restrictor at the connection point at the unit.

The bend stiffener is typically a specially designed piece is installed outside the power cable close to the connection point. The bend stiffener is connected to the structure and provides a gradually increasing stiffness from the tip to the connecting point, hence allowing the bending moment in the power cable to be taken without over bending the cable.

Figure 4.20 from SRP Subsea Riser Products [19], illustrates how a bend stiffener is mounted where the thickness increase gradually towards the connection point.

4.3.8. SUBSTATIONS

As mentioned under the last section the substation is used to collect the energy from several devices in a field to transmit the power to shore or to a second substation.

A picture of a typical substation is taken from the London Array web page [20] and shown in Figure 4.21.

A substation will, in addition to the transformer and the interconnectors to all the energy producers in the field, contain a helideck to ease access

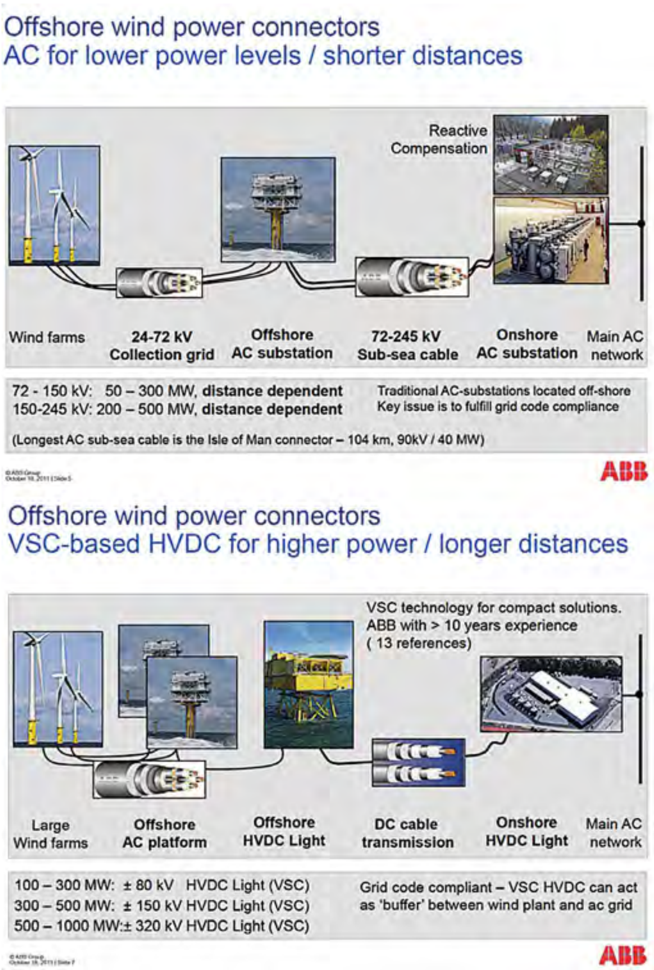


Figure 4.19 – Different solutions (AC and VSC-base HVDC) for power transmission [18].

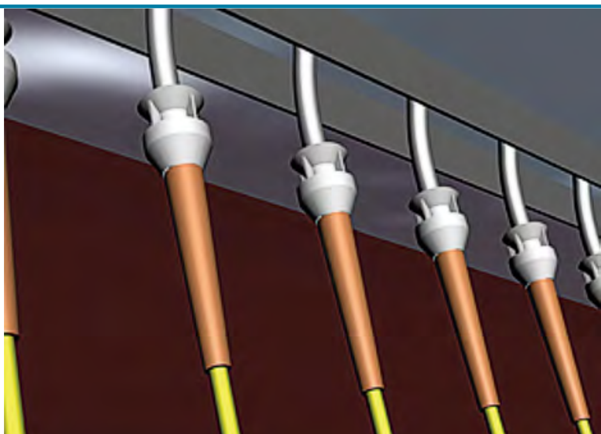


Figure 4.20 – Mounted bend stiffener [19].

Figure 4.21 – Offshore substation [20].

for maintenance and repair even in heavy seas and bad weather.

Offshore access to offshore energy devices and equipment is a challenge and as the substation is a very key element for delivering of power it is important that this can be accessed at almost any time.

We will later show some examples on specific vessels and equipment which are developed to improve offshore access.

4.3.9. CONNECTORS

If the offshore energy device was easy to disconnect and bring to shore for maintenance this would probably reduce the operation and maintenance costs of the device as it would minimize work offshore and speed up maintenance and repair of the devices.

Therefore a subsea wet connector would be very handy for these uses. It would allow a quick disconnect of the device from the power cable.

Indeed we see several companies working and developing such solutions and the example in Figure 4.22 is taken from MacArtney[21], in Denmark, who has developed a 11 kV wet mate connector to be used for offshore wind, wave and tidal devices.

4.4. OFFSHORE FLOATING WIND

Portugal is pioneering with the Principle Power WindFloat project where the 2.2 MW floating platform was installed on 30 November 2011, off the coast of Aguçadoura, Portugal and by 15 April 2012 at 15:19:31 Lisbon Time, the WindFloat 1 had reached Production of 1GWh of Energy.

Figure 4.23 shows the platform with the wind turbine and the various features of the WindFloat.

The Japanese after their Fukushima accident also turned to offshore floating wind and have initiated a project where they will install three floating windmill concepts and one sub-station in the area outside Fukushima, in order to test technology and develop solutions.

Figure 4.22 – MacArtney 11 kV (7.6 MW) Wet Mate Connector [21].

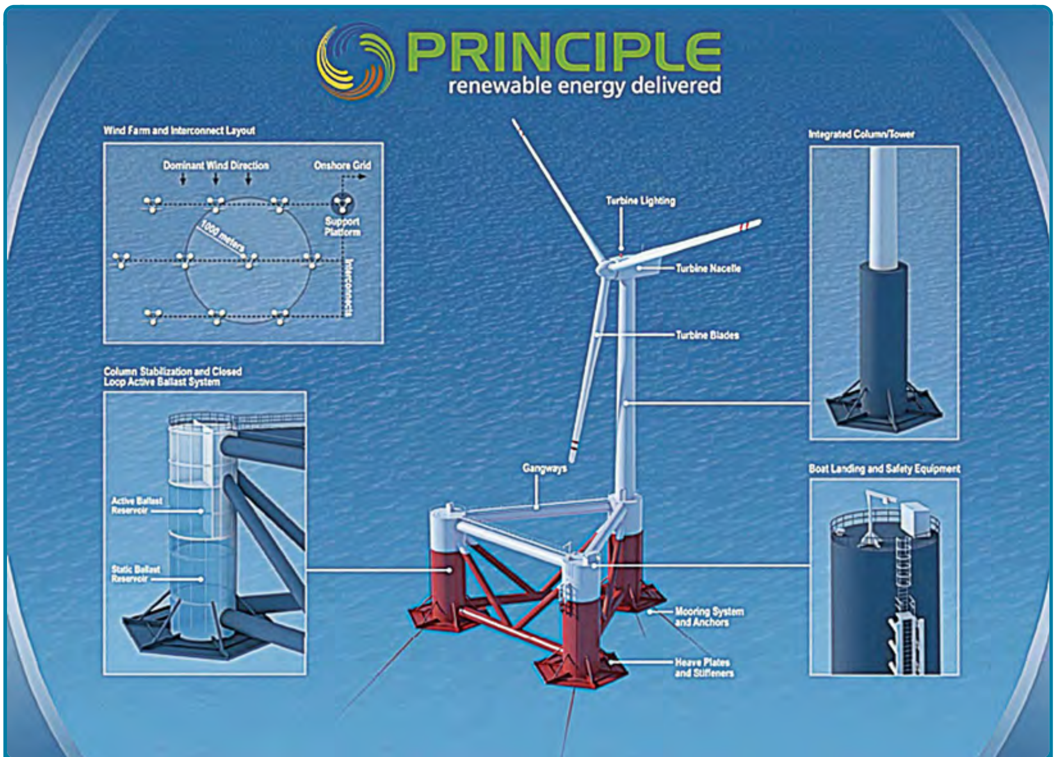
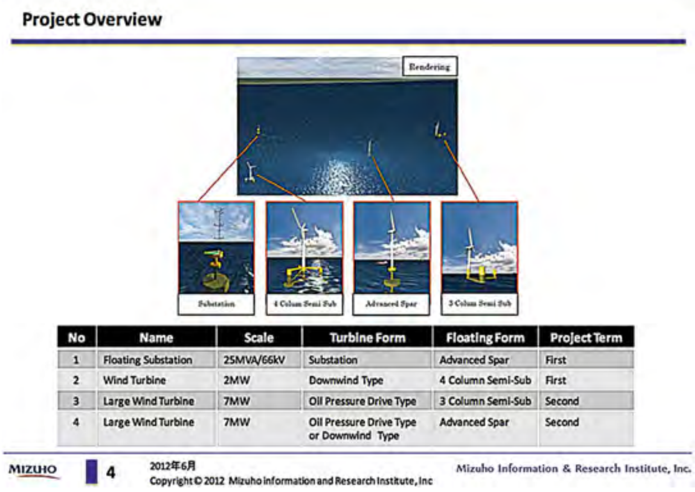


Figure 4.23 – WindFloat brochure [22].

The project is very briefly outlined in a presentation held by the Japanese research institute Mizuho (Figure 4.24).

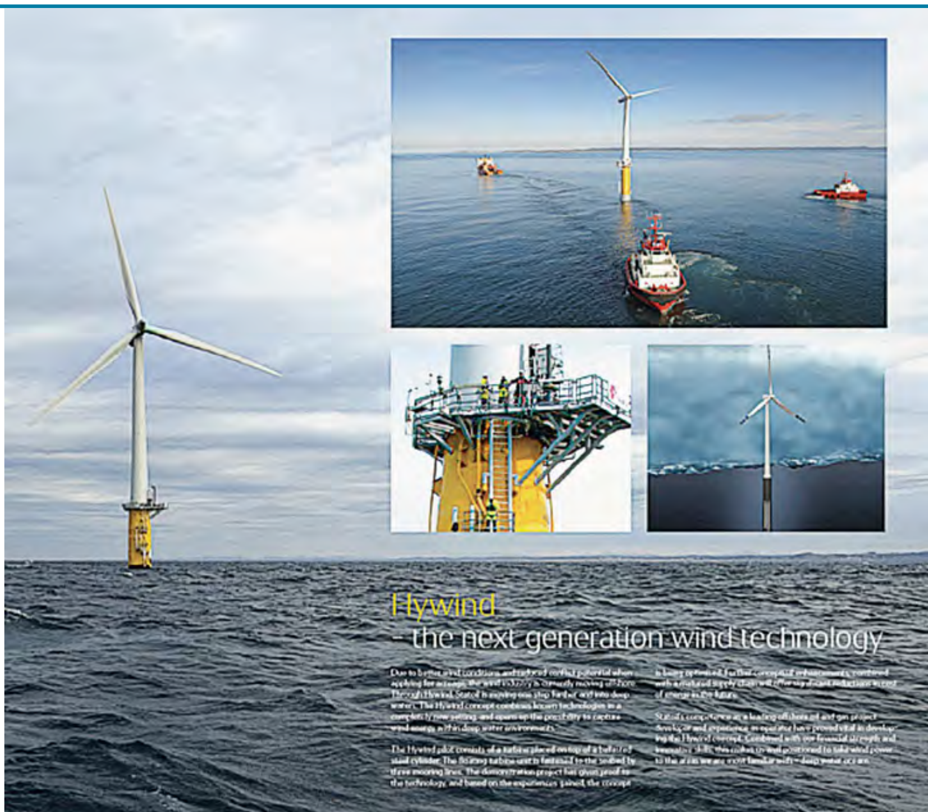
The project will be built in two stages where stage 1 with the substation and the 2 MW wind turbine is being installed this year.

Finally we have the Hywind project by Statoil in Norway with the 2.3 MW monotower floating concept deployed off the coast of Karmøy, which has shown excellent production, much higher than land based wind and where a commercial project is being kicked off outside Scotland during these days. Figure 4.25 shows the concept described in Statoil's own brochure[23].



No	Name	Scale	Turbine Form	Floating Form	Project Term
1	Floating Substation	25MVA/66kV	Substation	Advanced Spar	First
2	Wind Turbine	2MW	Downwind Type	4 Column Semi-Sub	First
3	Large Wind Turbine	7MW	Oil Pressure Drive Type	3 Column Semi-Sub	Second
4	Large Wind Turbine	7MW	Oil Pressure Drive Type or Downwind Type	Advanced Spar	Second

Figure 4.24 – Offshore floating wind project outline in Fukushima.



4.5. VESSEL CONCEPTS

As mentioned access to offshore energy devices can be very challenging and to provide the highest possible uptime it may be required to access the devices in relatively heavy seas and high winds.

In order to improve the offshore access we see that ship owners start to develop dedicated vessels that go fast and give a more stable platform for personnel transfer in higher seas. For example, Grovfjord Mek. Verksted (GMV) built an aluminium catamaran vessels customized to service offshore wind farms (Figure 4.26)

They are now also developing larger catamarans for tougher weather.

Marine aluminium is building a telescopic gangway to connect supply vessels with offshore windmills (Figure 4.27). The goal is to ensure safe access for maintenance even in rough weather.

Personnel transfer is not the only challenge. Installing offshore energy devices are also an area where advanced vessels will be needed in the future.

Here, it is possible to use many of the vessels and methodology developed for offshore oil and gas. The new bow developed on the Ulstein vessels shown in Figure 4.28, gives the ship better motion characteristics than traditional bows and can very useful when installing and accessing offshore energy devices.

It may also be desirable to have "greener" vessels working with installation, operation and maintenance of offshore energy parks, as it may be desirable to reduce the total carbon footprint of the farm. New vessels running only on LNG, like the Edesvik Viking Lady, shown in Figure 4.29, can be used.

As the offshore energy production systems will increase in numbers we should expect several new solutions for a more efficient and specialized vessel to be used.

Figure 4.26 – GMV's Aluminum catamaran vessel customized to service offshore wind farms.

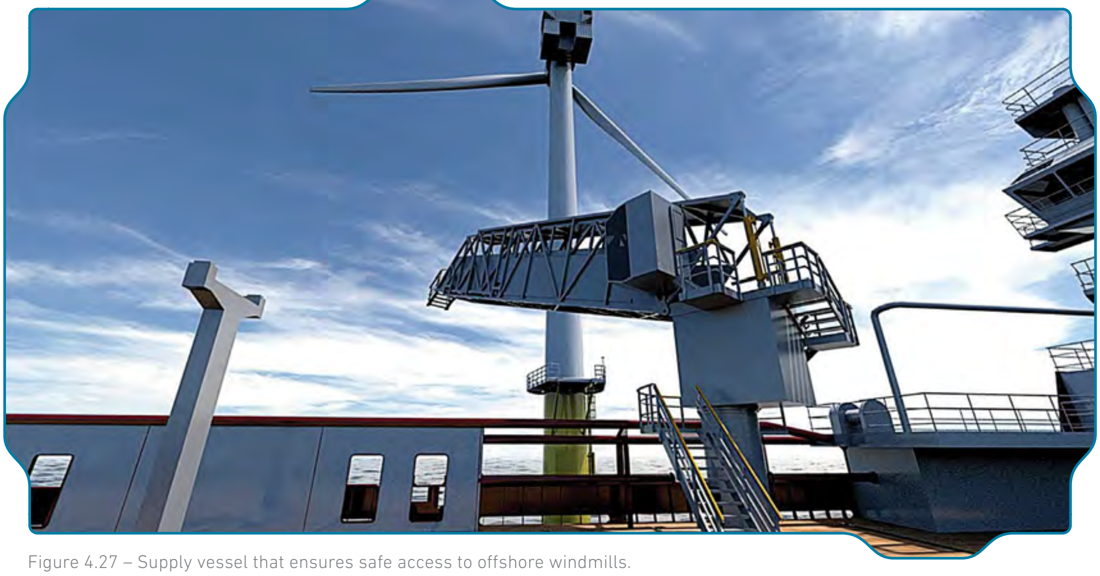


Figure 4.27 – Supply vessel that ensures safe access to offshore windmills.

Figure 4.28 – Ulstein's vessel with useful motion characteristics for installation and to access offshore energy devices.

Figure 4.29 – "Green" vessel.

4.6. NEW EXISTING SOLUTIONS

From [1] we have picked a couple of new existing solutions for tidal energy. One is the Norwegian developed Flumill (referenced earlier) and the other is the Swedish developed Minesto Deep Green tidal kite design.

The Flumill tidal energy converter (Figure 4.30) is influenced by the design of a helical excess flow control valve used in the gas industry. Glass reinforced plastic (GRP) is used for the construction of the helix and buoyancy allows the system to be towed to the location of deployment.

The Flumill system is able to align passively into the flow and the device is capable of accommodating offset tidal flows where the ebb and flood flow directions are not perfectly bi-directional. The rotational speed of the outer edge of the helix never exceeds the speed of the water flow, so there is no cavitation of the water. This also means that marine life will be able to safely negotiate around the device without risk of harm from fast moving blades.

Counter rotating helical screws allow torque loading on the foundation to be cancelled out, ensuring a hydrodynamically stable device design. The device is self-regulating in strong tidal flows.

A prototype of the smallest commercial Flumill device has been deployed at the EMEC nursery test site in the UK and plans for a fully grid connected, larger diameter device is being installed for testing in Rystraumen near Tromsø.

The Minesto Deep Green tidal kite (Figure 4.31) design has the potential to unlock deep-water sites with a lower velocity which is currently considered economically feasible.

By fixing a turbine and generator into a nacelle underneath a wing structure, the wing can use lift to accelerate the device through the water at speeds of up to ten times the flow speed of the surrounding water, therefore increasing the relative velocity of water entering the turbine.

The device can be tethered to the seabed and rudder control surfaces at the rear of the device will allow it to be steered in a figure-of-eight path. In 2012, a one-tenth-scale prototype was deployed in Strangford Lough, Northern Ireland, UK.

Plans to up-scale the technology could lead to a range of devices between 120kW and 850kW depending on the flow speed into which the turbine will be placed. Anticipated water depth range for the 150kW device is 50-65m. This could increase to between 90m and 120m for the 850kW variant.

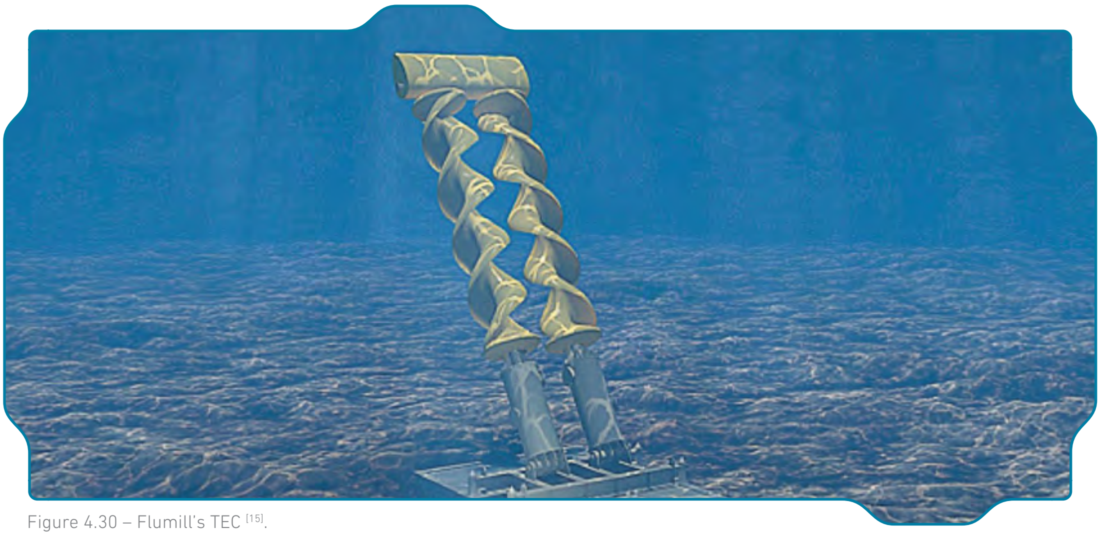


Figure 4.30 – Flumill's TEC [15].

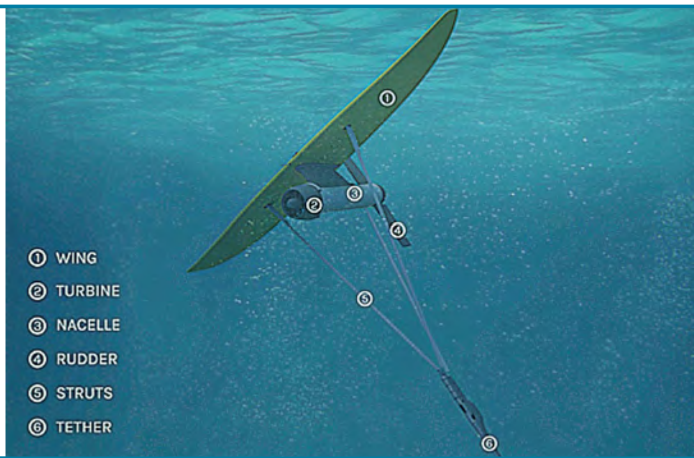


Figure 4.31 – Minesto's Deep Green tidal kite [24].

4.7. ENABLING SOLUTIONS BY TECHNOLOGY COMBINATION OR CO-LOCATION

There are several projects on the way looking at possibilities to use offshore renewable energy systems together with other uses in the same ocean area and/or the same physical infrastructure. The idea being that the total value of the complete combined solution as a whole is higher than the sum of various uses in isolation. This approach would enable the deployment of offshore renewable energy devices in areas where the energy production alone would not be cost efficient.

4.7.1. COMBINING WIND AND WAVE ENERGY DEVICES SHARING OCEAN SPACE

One such combination which springs to mind is to install wave energy converters into an area with fixed or floating offshore wind.

In [25] and [26] the benefits are discussed and it is concluded that co-location of wind and wave energy devices increase the capacity value of the farm and reduces hours of zero output and the variability of the aggregate power output.

This is partially due to the fact that wave energy converters will produce energy partially out of phase with the wind energy production it will be a huge benefit for the operator, as a requirement for energy storage or balancing power to the grid, will be reduced. This effect is clearly demonstrated in Figure 4.32 where the combination of 25 % installed effect on wind and 75 % installed effect on wave for a real environmental condition is combined. It is seen that the total capacity of the combined farm is smoothened out and that the combined capacity factor go as high as 50 %, which for wind or wave alone would not be possible.

It is also stated that since offshore wind and WECs do not occupy the same space in the sea and sharing common infrastructure such as transformer platforms, transmission cables and not in the least, crew maintenance could potentially give large economical savings.

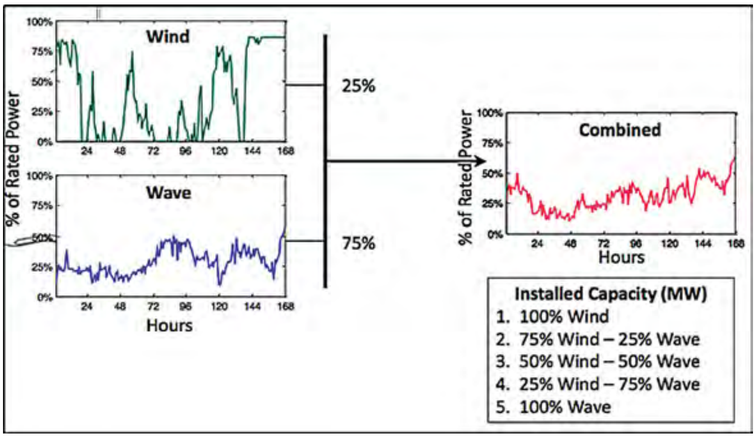


Figure 4.32 – Combination of wind and wave power analysis.

4.7.2. COMBINING WIND AND WAVE ENERGY DEVICES AND OTHER SOLUTIONS

The MARINA platform (Marine Renewable Integrated Application platform) project within the 7th EU framework programme is established to develop the basis for and use of multi-purpose platforms for marine renewable energy (MRE) combining wind and waves [27]. The project will at the end deliver proposals for new multi-purpose MRE platform designs, validated by advanced modelling and tank testing at reduced scale. The next step will be to build and test a pilot installation.

MERMAID: Innovative Multi-purpose offshore platforms: planning design and operation (EU-FP7 project) [28], will develop concepts for the next generation of offshore platforms, which can be used, for multiple purposes. The project does not envisage building new platforms but will theoretically examine new concepts, such as combining structures for energy extraction, aquaculture and platform related transport. Figure 4.33 gives an idea for the expected outcome of the project.

TROPOS: The Tropos Project [29] study solutions will explore the relations and integration into the platform of a broad range of sectors including energy, aquaculture and related maritime transport.

The renewable energy mix, which will be studied, will be wind as well as ocean energy technologies like wave and ocean thermal energy converters (OTEC). The system will be optimised at three different areas; Mediterranean, sub-tropical and tropical latitudes; The project aims to develop novel, cost-efficient, floating and modular multi-use platform designs (Figure 4.34), which enable optimal coupling of the various services and activities;

H2OCEAN [30], is a project aimed at developing an innovative design (Figure 4.35) for an economically and environmentally sustainable multi-use open-sea platform. Wind and wave power will be harvested and part of the energy will be used for multiple applications on-site, including the conversion of energy into hydrogen which can be stored and shipped to shore as a green energy carrier and a multi-trophic aquaculture farm.

The unique feature of the H2OCEAN concept, besides the integration of different activities into a shared multi-use platform, lies in the novel approach for the transmission of offshore-generated renewable electrical energy through hydrogen.

This concept allows effective transport and storage of the energy, decoupling energy production and consumption, thus avoiding the

Figure 4.33 – MERMAID project concept [28].

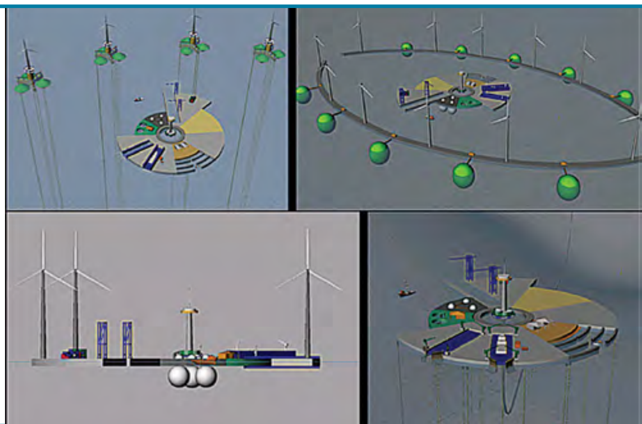


Figure 4.34 – TROPOS multi-use platform design [29].

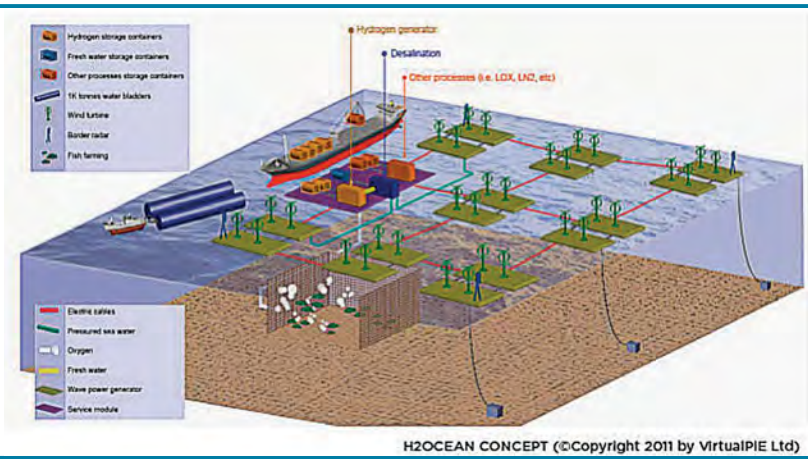


Figure 4.35 – H2OCEAN Concept [30].

grid imbalance problem inherent to current offshore renewable energy systems.

Additionally, this concept also circumvents the need for a cable transmission system, which takes up a significant investment share for offshore energy generation infrastructures, increasing the price of energy.

4.7.3. CO-LOCATION WITH AQUACULTURE

An attractive solution to reduce cost and increase the profit from a wave energy development site is to co-locate the wave energy systems with aquaculture. Looking at the proposal of the artificial sea bed (shown under moorings), it is clear that there will be no trawling in this area hence the wave farm can act as a sanctuary for fish or fish farming. It is seen at the platforms in the North Sea, that close to the platforms there are a lot of fish and that the fish use the platforms as a reef.

By combining fish farming with wave power it is both possible to preserve fish areas but also the energy generated from the WECs can be partially used in fish farming.

The report in [31] has looked at problems and benefits and has presented a co-location matrix as shown in Figure 4.36.

The GWIND gyro stabilized floating wind turbine [33] (Figure 4.37), being developed in Norway, is such a device which is planned on being used with fish farming.

4.7.4. GENERATOR OR PRODUCING POTABLE WATER DIRECTLY

One of the features of wave energy is actually that, the devices can generate large forces with slow motions. This is actually a useful, if trying to produce potable water from desalination. Initially, the idea Fred Olsen had for his wave energy converter, was to produce fresh water for the Canary Islands. In many ways this makes a lot of sense as the production of fresh water is becoming more and more important in many areas of the world and instead of using petrol and/or electricity, a

		Aquaculture			
		Onshore finfish	Onshore finfish	Shellfish	Processing
Renewable Energy	Offshore Wind	Neutral	Positive	Neutral	Neutral
	Wave	Neutral	Positive	Neutral	Neutral
	Tidal	Neutral	Positive	Neutral	Neutral
Subsea cables and pipelines	Eletricity	Neutral	Neutral	Neutral	Neutral
	Oil/Gas Pipilines	Conflict	Conflict	Neutral	Neutral
	Telecomms	Neutral	Neutral	Neutral	Neutral
Inshore fisheries	Nephrops	Neutral	Conflict	Competition	Neutral
	Scallop dredge	Neutral	Conflict	Conflict	Neutral
	Demersal	Neutral	Conflict	Competition	Neutral
	Pelagic trawl	Neutral	Conflict	Neutral	Neutral

Figure 4.36 – Sectoral interactions matrix and definitions and colour coding of interactions options (reproduced from [32])

Figure 4.37 – GWIND gyro stabilized floating wind turbine [33].

Figure 4.38 – EnergyBuoy, an equipment to produce fresh water [34].

wave energy converter could very simply produce fresh water directly.

One of Fred Olsen's engineers are presently exploiting this possibility and have built and are in the process of testing a device in Norway [34]. The "EnergyBuoy" (Figure 4.38) will produce pressures up to 80 bars outside the Canary Islands, which can be used directly to produce fresh water.

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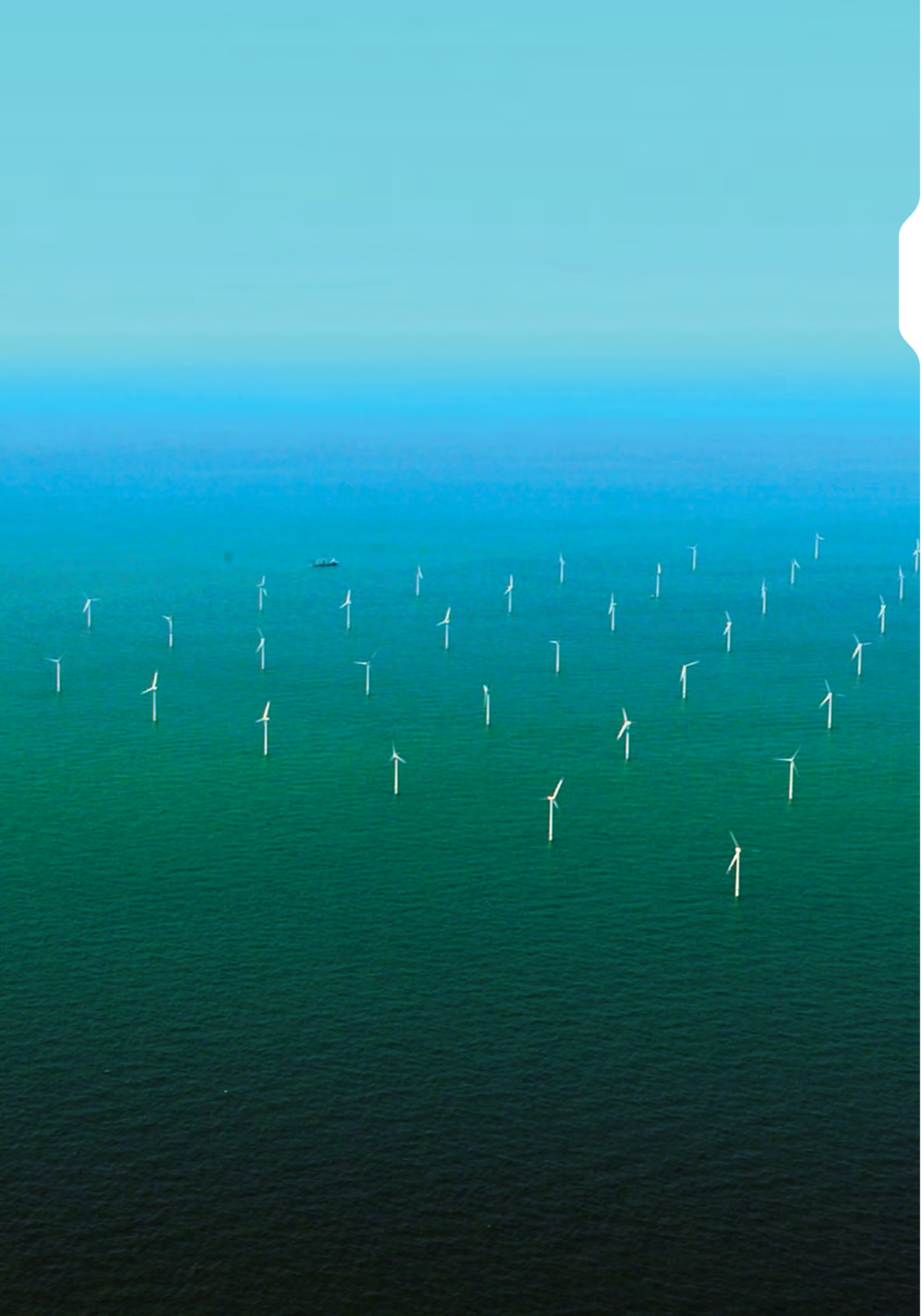

MARKET DEVELOPMENT

5

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5.1. INTRODUCTION

There are several reasons for offshore renewable energies to develop but the development of the market potential depends on a number of factors including technical and non-technical aspects. The size of the market for offshore renewable energies will not only depend on the available of offshore energy resources and the maturity of the technology in terms of reliability, efficiency and ability to overcome technical constraints. It will also depend on the evolution of energy demand and the access to the grid to reach the consumption centers, the competing uses of the sea and, of course, the competitiveness of offshore energy projects against alternative energy options in the region, taking into account, not only the cost of energy but also environmental and social aspects.

Taking all this into account, this chapter summarizes the actual stage of market development of different offshore technologies, their actual costs and expected evolution towards grid-parity, the actual support mechanisms to promote technology and market development and finally the size of the prize, the total addressable market.

5.2. ACTUAL STAGE OF MARKET DEVELOPMENT

As it has been discussed in the previous chapters, offshore renewable technologies are very diverse and are at very different stages of development. Even the most advanced, offshore wind technology, is still not able to compete today in price against other more mature technologies in the electricity markets but it is expected to do so in the future. Still, there is an increasing deployment of energy projects normally due to both public support mechanisms which incentive investment in technology development and investors' appetite to take a share in this emerging sector. This section focuses on the number of projects deployed in the recent years, while section 6.3 discusses the actual support mechanisms in the leading countries.

While onshore wind is already a mature technology after a few decades installing and operating commercial scale farms, offshore wind is still a relatively new application (most utility scale offshore farms only account for a few years of operating and have not reached even half of their expected lifetime). As such, there are still some aspects to be addressed in terms of technology and supply chain development which are actually hampering offshore wind costs to decrease. However, in terms of installed capacity, offshore wind deployment in Europe (Figure 5.1) is at the start of the curve with exponential market growth in installed capacity (in Europe the cumulative capacity in June 2013 was 6 GW expecting to increase to 35-40 GW by 2020 [1]).

Yet, the other offshore renewable energy technologies are at an earlier stage of development. Tidal energy technology has rapidly advanced into TRL8 after demonstrating the continuous operation of a few full-scale prototypes in the last years. The Siemens-MCT Seagen project in Northern Ireland has been in operation since 2008 and with a very high availability and capacity factor in the last couple of years (it achieved a cumulative production of 7 GWh in April 2013 according to MCT, with most of it in 2012-13).Andritz-Hammefest has also demonstrated to have a reliable technology with the results of its part-scale 300kW prototype with more than 98% availability and the start of tests on their full-scale prototype at EMEC. Other big OEMs such as Alstom or Voith are also developing their tidal technologies. In total, the global cumulative installed capacity in 2013 was around 16-18 MW[1] , basically corresponding to single device demonstration projects. However, first pre-

1 This includes actual projects in the water but also past projects that are already decommissioned.

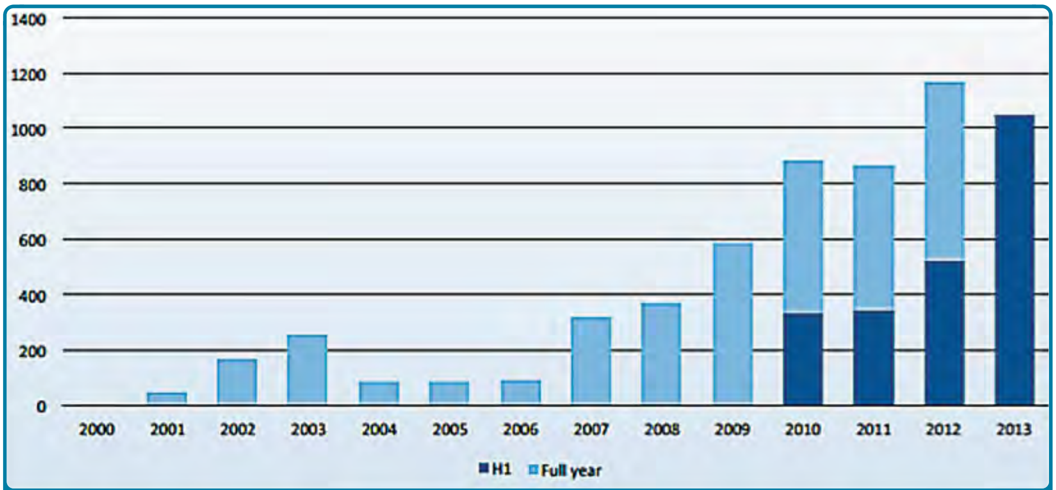

Figure 5.1 - Annual installed offshore wind capacity in Europe (MW). In dark blue installed capacity during the 1st semester [1].

commercial arrays are expected to be deployed by 2015-16 and have obtained significant funding in Europe. If they prove to be successful, the market is expected to increase rapidly . The fact that the most energetic tidal sites are concentrated in a small number of locations puts more pressure on project and technology developers to position themselves as soon as possible in key markets such as UK, France, Canada, the US or Chile and eventually trigger the market faster than in other sectors.

Wave energy technology is nowadays one step behind tidal technology (TRL 6-7). The total installed capacity is similar to that of tidal energy (around 14 MW at the end of 2012, Figure 5.2) but most demonstration projects haven't proved continuous reliable operation with GWh scale production. The most advanced technology in terms of energy production is OWC onshore[1] but this is a technology very site specific which will unlikely have a large market share in the future. Several offshore technologies are being tested at different scales and a few pre-commercial arrays are being planned but reliable continuous operation including extreme wave conditions needs to be demonstrated first. Leading technology developers such as Pelamis or Aquamarine still face some technical challenges and may still need a few years to reach technology demonstration.

There are other new concepts being developed which are worth looking at. Some wave developers are looking into smaller devices targeting niche markets such as salmon farming (e.g. Albatern) before moving into commercial scale farms. Smaller devices have a competitive disadvantage against large utility-scale farms in the long term but in the short term, this strategy allows technology developers to gain experience with a deployment of several small devices (compared to the demonstration of one or a few large devices). Also small devices are easier and cheaper to deploy and maintain, lower project risks and are suitable for niche markets with higher energy costs (e.g. Salmon farming energy is supplied by diesel generators with a LCOE of around 400$/MWh). This is the natural market development path followed by, in other technologies such as wind or solar PV, which were first developed for small isolated systems. In tidal energy, there are also some developers, such as Verdant Power or Tocardo, who are targeting at other markets for deploying several small scale devices (run-of-river or inshore tidal application).

1 Especially the Mutriku project in the Basque Country, which was finally commissioned in June 2011 produced around 200MWh during the first year and is supposed to have operated with more than 90% availability in the second year (Wavegen-Voith communication).

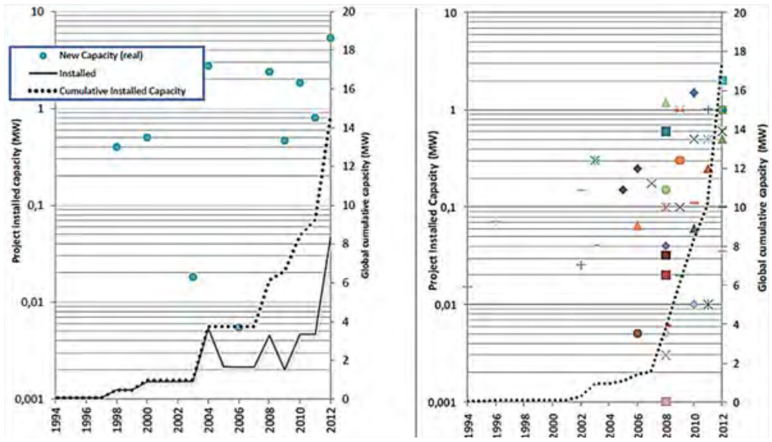

Figure 5.2 - Wave (left) and tidal (right) installed capacity between 1994 and 2012 [2].

OTEC and osmotic power are at an earlier stage of technology development (TRL4-6). A few OTEC small demonstration projects have been developed at small scale. The largest plant up to now is a 210kW plant which was operated in Hawai between 1993 and 1998 (commercial scale OTEC demonstration is expected to have up to a few hundreds of MW). Today, the activity is focused in Hawaii and France, where DCNS and Ifremer are developing demonstration projects of 5-10MW which could be operational in a few years.

In the case of salinity gradient, the activity today is basically focused on two companies in northern Europe: Statkraft, which installed a 5kW plant in Norway in 2009 and REDStack, a Dutch start-up which developed the RED system and installed a 4kW plant in the same year. Not much information is available but the published data seems optimistic. However, as in OTEC, there is a need of larger demonstration projects in order to assess with some level of confidence for the potential competitiveness of these technologies. Statkraft aims to install a 2MW plant in the coming years, the first, to plant a large scale in 2020 and in 2030 to commercialize the technology.

5.3. COST OF ENERGY AND FUTURE PERSPECTIVES

Offshore technologies typically face harsher conditions than competing onshore technologies, leading to higher CAPEX and OPEX. However, they also access more energetic resource levels which can turn into a higher energy production or capacity factor. Technologies such as OTEC or Salinity gradient are totally dispatchable, while others such as tidal, wave or offshore wind aren't but are more constant and predictable than other onshore renewable options.

As it has been described in the previous section, there is a divergence in the level of maturity between offshore technologies which also impacts their costs; prototypes costs are significantly higher than the cost of production of units in series and also scale is a key factor in achieving competitive energy costs of energy.

Still, the levelized cost of energy (LCOE) of the most mature technology, offshore wind, is not yet fully competitive against other energy options. The costs of offshore wind in the UK have increased substantially since the first commercial scale wind farms were deployed in the early 2000s, driven both by underlying cost increases (commodity prices rises, currency fluctuations) and by more specific factors such as supply chain bottlenecks, sub-optimal reliability and the move to deeper water sites.

Recent wind farm projects have indicated that costs have stabilised at around £140 per MWh [3], which is above market prices. However, costs are expected to decrease to around 100£/MWh by 2020 (improvements are expected due to larger scale, supply chain development, optimized manufacturing, installation and O&M procedures, improved efficiency, etc.) (Figure 5.3). Also, some important comments should be made at this point: First, the cost of energy depends on the level of resource and the characteristics of the location so LCOE should be assessed on a project basis (not on a technology basis)[1] . Second, the target cost of energy will also vary from region to region, energy is local and energy prices in different regions with different energy sources vary significantly[2] . Moreover, some external costs in electricity production are not internalized on the prices, which could modify the rank of the most competitive energy options[3] . Taking all these aspects into account, offshore wind may be a competitive option already today in certain regions.

1 It is very site dependent the cost of energy of wind farms in low wind sites may be twice the cost for high wind sites.

2 In some regions the alternative may be installing solar PV farms or onshore wind while in other regions some type of conventional plants (coal, nuclear, etc.).

3 Costs on the environment, health, energy security or other aspects are difficult to quantify but several studies indicate that in some conventional plants could be as large as 80-300€/MWh depending on the technology and location [13], [14], [12]. Offshore renewable are also expected to bring external costs in some cases (e.g. grid reinforcement), but are normally lower that then alternative external costs.

In the case of wave and tidal energy, it is not appropriate to talk about the actual cost of energy as the technology is not ready to produce consistently. It is preferred to estimate the expected LCOE of the first arrays, once they are able to produce with high availability, for their design lifetime and when O&M costs are better understood. A good starting point is to look at the CAPEX or mass to power ratio of the actual projects. Prototype costs for wave and tidal arrays are typically in the range of 10-30M€/MW. However, the latest published costs for the first 10MW tidal arrays expected to be deployed in the near future are 70 M£/MW, which is around 2,5 times the actual CAPEX of offshore wind farms in the UK. However, in terms of mass-to-power ratio, some tidal prototypes are at the same level as offshore wind (around 300 t/MW) and have the potential for further optimization (Figure 5.4). Assuming this CAPEX and the expected operating costs, capacity factor and availability the LCOE of these first tidal arrays may be 300-400 €/MWh according to the latest report[4] [4]. Of course the cost of energy of these arrays will be especially dependent on the level of industrialization of the manufacturing and installation process, the depth of the sites and access to grid, the energy resource and the availability and O&M costs of the technology.

4 This report was issued after extensive consultation with leading technology and project developers.

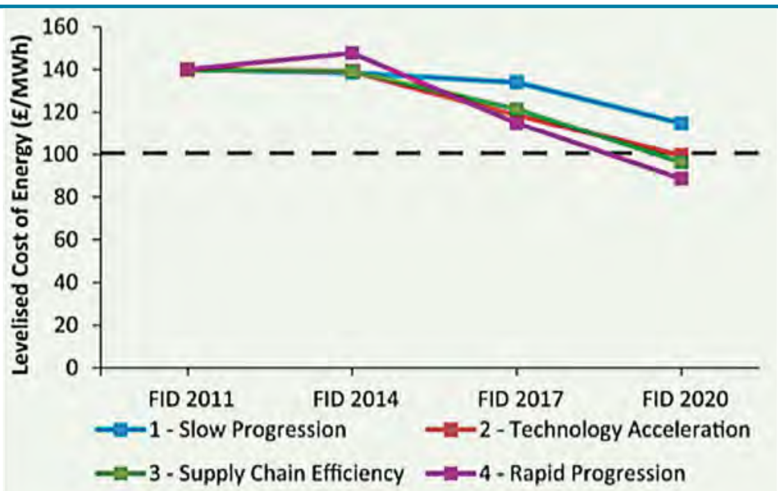

Figure 5.3 - Expected LCOE evolution in the UK under the four industry 'Stories' [3].

The costs of first wave energy arrays are expected to be higher than for first tidal arrays (Figure 5.5). Actually the expected costs of both wave and tidal arrays have increased in the last years. This is due to the better knowledge of the challenges facing offshore energy farms and the need for more reliable designs and strategies[1] . Leading wave energy devices still need to decrease its steel weight-to-power ratio by a factor of two in order to reach tidal or offshore wind values. However, wave technology has a bigger cost reduction potential due to several factors: wave energy concepts are novel and have a large space for optimizing their design allowing for cost reduction and increased energy yields. They are also more adequate to incorporate new materials (such as composites, rubbers, concrete) which could reduce significantly the steel weight (potentially undertaking tidal and offshore wind in steel-to-power). They also have a large addressable market which could allow for a cost reduction in mass manufacture and deployment of units compared,for example, to tidal energy, which has a smaller market potential and some aspects of the design (not all) have been adapted from wind technology and have less margin for optimization.

However, this starting point for wave and tidal is promising taking into account their early stage of development with just a few MW of installed capacity[2]. In the long term the expected LCOE for both wave and tidal energy are expected to decrease potentially reaching competitive levels when a few GW have been deployed (Figure 5.6). However, these projections are constantly varying and it will be crucial to update them, especially after the results of the first arrays. The target cost of energy for utility-scale application of these technologies may be that of wind, as these locations with strong wave and tidal resources normally have also a high wind resource. As some of the costs are influenced by scale (e.g. installation, electrical connection, mooring/foundation costs, etc.), wave and tidal utility scale farms will necessarily be composed of multi MW units in order to be competitive against 5-10 MW wind turbines. Second-generation tidal turbines are already targeting 2MW or more but some wave energy devices (not all) will struggle to reach these levels unless they are cost-effectively aggregated into clusters. For isolated applications small devices may also be competitive as the target cost may be that of small diesel generation or alternative energies available locally (solar PV, small wind turbines, biomass, etc.).

1 In fact, technology developers with new concepts at lower TRL claim very competitive LCOEs but this is typically due to the subestimation of costs and inexperience offshore, and an excess in confidence.

2 Solar PV had cost of energy over 400€/MWh only a few years ago and after several GW of distributed generation had been installed globally. With the high demand of utility scale plants the cost has decreased to levels below 100€/MWh but of course solar PV technology involves high-tech materials with a larger cost reduction potential. Yet some innovative materials such as electroactive polymers under study are a promising opportunity for applications such as wave energy (http://www.polywec.org/).

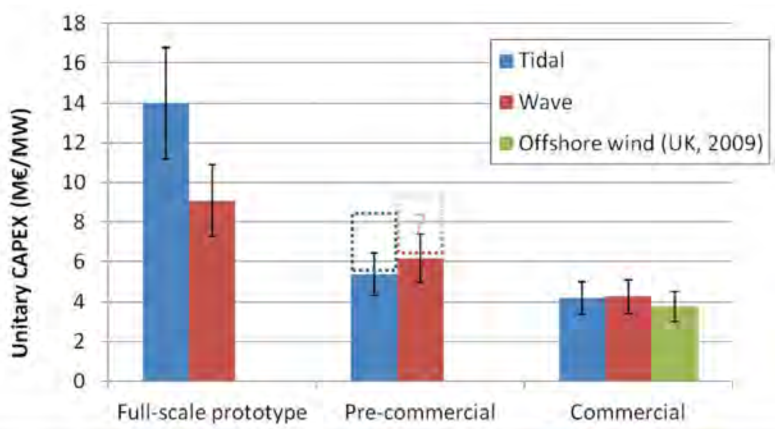

Figure 5.4 – Expected evolution of CAPEX from various sources ([5], [6] and [7]). In dashed lines the most recent values of expected CAPEX for the first arrays under development [2].

The costs of energy of OTEC or salinity gradient technologies are more uncertain than those of wave or tidal, as there are only very few demonstration plants and at a scale much smaller than the targeted size of commercial plants. There are few publications on the expected LCOE of these technologies. OTEC expert Luis Vega indicated a LCOE of 440€/MWh for a 5MW decreasing to 155€/MWh for 100MW plants [8]. In the case of salinity, Statkraft expect a LCOE of around 120€/MWh for its first large-scale plant to be installed in 2020 expected to decrease to around 70€/MWh after 30 plants have been deployed [9]. There are both promising targets but only after pre-comercial plants of a few MW of capacity are installed and operated the real potential will be well understood.

5.4. SUPPORT MECHANISMS TO ENHANCE TECHNOLOGY AND MARKET DEVELOPMENT

There are several mechanisms which help new energy technologies to gradually enter the market while they aren't still fully competitive, enhancing technology development towards what is known as "grid-parity" against established technologies.

Some countries have established favorable conditions for the development of offshore renewable energy projects, which has attracted the attention of technology developers, large industrial companies, utilities and investors.

Different support mechanisms are required in the different stages of technology and market development (Figure 5.7). In the demonstration phase, in which technologies, is typically preferred to obtain constant public support in terms of investment and a R&D grant, access to testing infrastructure to help develop their technology as well as simplified licensing processes. In the early commercial phase production incentives such as feed-in-tariffs (FITs), green certificates or bonus over market prices[1] are typically put in place in order to close the gap between the higher cost of

1 Feed-in-tariff are typically preferred by developers as it reduces the uncertainty in prices by providing a guaranteed fixed energy prices for the project lifetime, making the projects more easily bankable.

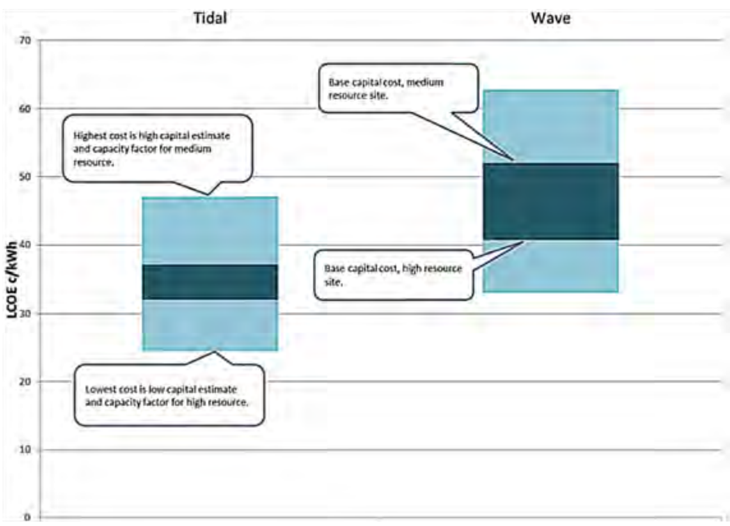

Figure 5.5 – Expected LCOE of early tidal and wave arrays depending on different cost estimates and resource levels [4].

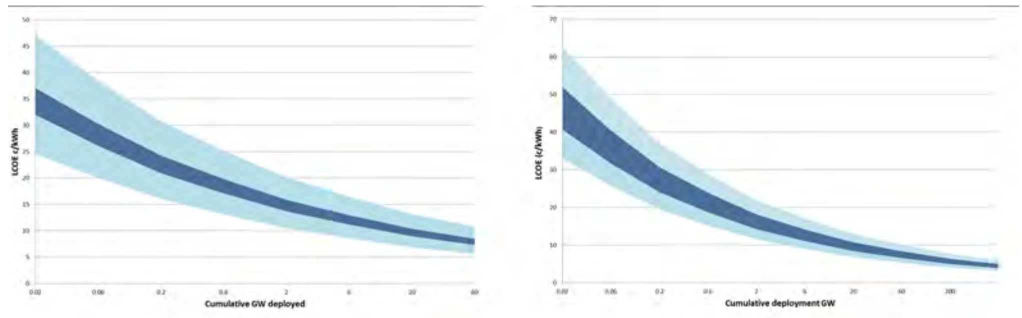

Figure 5.6 – Evolution of LCOE (in c€/kWh) for wave and tidal energy projects [4].

energy and market prices. In the pre-commercial phase in between demonstration and commercial stages, both capital support (technology push) and production incentives (market pull) are required. This transition from prototype testing to commercial demonstration, known as the "valley of death", is where most ocean technologies get stuck, as it strong public and private investment are at high risk.

Offshore wind development in Europe is booming due to the strong support of a few countries such as the UK, Denmark, Germany, Belgium, Netherlands and Sweden, which have put in place attractive revenues support mechanisms (FIT or green certificates depending on the country of around 140-200€/MWh and in some cases, together with capital support incentives, such as tax benefits or capital grants). The leading country is clearly the UK with more than 3,6GW of cumulative installed capacity in 2013 and a target to reach 18GW by 2020. Between 2011 and mid 2013, more than 2,5GW of new capacity were installed, proving that the 2-ROC incentive, together with an active role from the public administration (e.g. the Crown Estate leasing rounds) have stimulated the market.

After several years of funding support for prototype demonstration, the first pre-commercial tidal arrays are being developed in the UK thanks to the strong support given by the British and Scottish governments as well as the EU, through its capital grants and production incentives[1] , by licensing the seabed and making plans to strengthen the grid. It is likely that additional funds will be available to finance these and other projects. Other countries which have beemheavily investing on tidal current in recent years are Canada and France (with strong capital support). Countries like the USA, Ireland, South Korea, Chile and China are also supporting these technologies but to a lesser extent.

The UK (especially Scotland) is also the most attractive market for wave energy at the moment, with similar support to that of tidal energy which has facilitated the installation of several prototypes. However, first pre-commercial parks are taking longer to develop than planned, due to delays in technological development in recent years, although the potential market is much larger. Other countries with very active support in recent years in the development of the waves are Ireland[2] , Australia the US and to a lesser extent China, Scandinavian countries, Italy, Japan, New Zealand, Chile, Spain and Portugal[3] .

For OTEC, potential markets are those territories located between the tropics. The US, France and Japan have some activity today but there aren't

1 The European NER 300 fund has allocated € 40M 10MW for two projects in the current and other British MEAD £ 20M to the development of two other parks 10MW. Also the British and Scottish government support wave and tidal energy with a production incentive of 5ROCs, equivalent to about 32c €/kWh, which will be soon substituted by a FIT type mechanism with an expected price of XXX €/MWh.

2 The WestWaves project in Ireland, which is expected to be first pre-commercial wave park 5MW, has received € 20M European NER 300 fund. Ireland has a subsidized rate of 22c € / kWh for waves.

3 Spain and especially Portugal but have actively supported their policies, are on stand-by due to their financial situation. Both countries are developing areas for test waves (BIMEP and Oceanplug).

Market drivers	Demonstration	Pre-commercial	Commercial
R&D support	High	Medium	LOW
Capital support	Very High	Very High	LOW
Revenue support	Medium	Very High	Very High
Licensing support	Very High	Very High	High
Testing facilities	Very High	High	LOW
Resource Intensity	Medium	High	Very High
Market size	LOW	Medium	Very High

Non-driving factor — Driving factor

Figure 5.7. Factors which stimulate the market for the various stages of technological development [2].

strong specific incentives for this technology. French demonstration projects in their islands overseas have applied for European NER300 funds, but have not been awarded yet.

As for the salt gradient, there are no specific incentives today. The two most advanced prototypes have been installed in Norway (Statkraft) and The Netherlands (REDStack), probably with some public support. Other countries that have shown some interest are Japan, South Korea and Italy.

5.5. TOTAL ADDRESSABLE MARKET AND FORECAST SCENARIOS

Of course, all this private investment and public support for technology and market development wouldn't occur if there wasn't a market potential behind it which will eventually pay-back the investment.

Conventional fossil fuel price increase[1] and climate change agreements will lead to a progressive substitution of conventional power plants for alternative technologies in the next decades, such as renewables and nuclear energy. The large deployment of relatively recent renewable technologies such as onshore wind, solar PV has led them to be already competitive against conventional power prices in locations with good resource. Still there will be a back-up need in order to cope with their intermittency, which will probably be done by conventional power, storage (large hydro and other technologies under development) and demand-side management.

In the last years the newly installed capacity of renewables (especially wind and solar PV) has exceeded the new installed capacity of conventional fossil fuels[2] . Still, the contribution of renewable technologies (excluding hydro and biomass) to the global energy demand is still very small (in 2009, they accounted for 2% of the global electricity demand and 0,4% of the global primary energy supply). Hydro power is still the largest renewable contributor to power (16% of power demand and 2,3% of primary supply) but the development of new projects is very limited (most best sites are already developed and there are strong environmental issues). Biomass is the leading renewable contributor of primary energy supply (10% of global supply) but being the majority traditional biomass used in cooking and heating and not for power (Figure 5.8). Also the competition for other uses of the land will difficult the massive use of biomass for energy supply and will eventually need to move offshore. On top of this, energy demand in 2050 is expected to be more than twice that of 2008[10].

All this factors indicate that there will be a need of massive deployment of renewable energies in

1 The substitution of conventional fossil fuel fired plants will not occur because of fossil fuel depletion but because the diminishing accessible reserves lead to increasing complexity and costs to extract them, which will lead to higher costs than competing energy technologies.

2 Of the approximately 300 GW of new electricity generating capacity added globally over the two-year period from 2008 to 2009, 140 GW came from RE additions

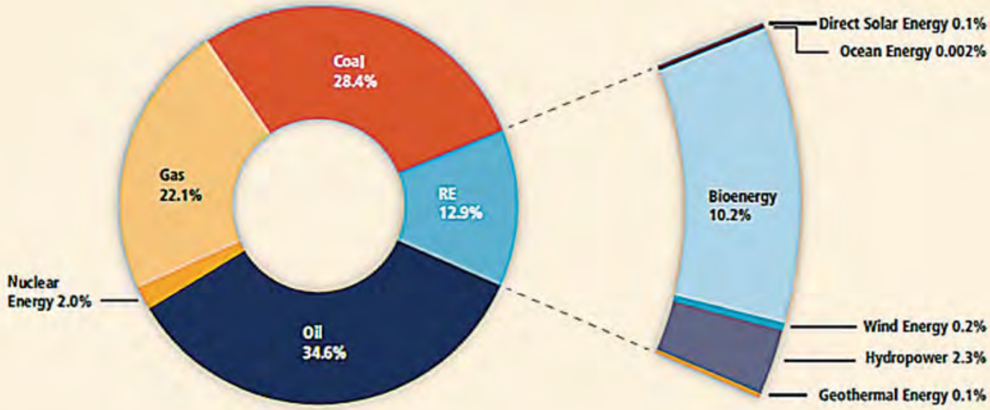

Figure 5.8 – Shares of energy sources in total global primary energy supply in 2008 (492 EJ) [10].

the next decades. Still the size of renewable energy sources is large enough to meet the demand. Solar energy represents by far the largest energy resource, followed by ocean and wind energies (Figure 5.9). Also the increasing population and pressure on land, is already forcing the displacement of activities offshore and this is also happening with RE.

The different geographic distribution of RE resources, the intermittency of most of them and the need to reach the consumer at a reasonable cost will lead to a combination of portfolio of local RE energy sources in most regions with some back-up capacity and probably active demand-side management.

As it has been discussed in the previous sections, offshore renewables will need to be competitive in the long-term against other competing technologies in the same interconnected region (different regions will likely to have different competition technologies and different prices). Those areas with best resource potential and more attractive market conditions are likely to be developed first. Attractive market's conditions, in the short term, are those with support mechanisms in place but there are also others, where energy prices are high (without the need of subsidies (e.g. some countries and isolated regions or consumers)).

Renewable source	Annual Flux (EJ/yr)	Ratio (Annual energy flux/2008 primary energy supply)	Total reserve
Bioenergy	1,548[d]	3,1	-
Solar Energy	3,900,000[a]	7,900	-
Geothermal Energy	1,400[c]	2,8	-
Hydropower	147[a]	0,30	-
Ocean Energy	7,400[a]	15	-
Wind Energy	6,000[a]	12	-
Annual Primary energy source	Annul Use 2008 (EJ/yr)	Lifetime of Proven Reserve (years)	Total Reserve (EJ)
Total Fossil	418[b]	112	46,700
Total Uranium	10[b]	100-350	1,000-3,500
Total RE	64[b]	-	-
Primary Energy Supply	492 (2008)[b]	-	-

Figure 5.9 – Renewable energy theoretical potential expressed as annual energy fluxes of EJ/yr compared to 2008 global primary energy supply [10].

In the long-term, global high energy needs will eventually open a very large addressable market for offshore renewables which could eventually be capped only by their economically extractable potential (the exploitation of all those areas which offer a competitive LCOE against alternative solutions, of course taking into account competing uses of the sea and environmental constraints) (Figure 5.10).

Offshore wind is already experiencing and exponential growth and forecasts expect it to achieve 30-40 GW by 2020 in Europe. After that, it is expected to continue to grow steadily in order to reach probably several hundreds or even a couple of thousands of GW by 2050. The deployment of other offshore renewables is more uncertain and will depend on the demonstration of their competitiveness.

Recent tidal energy forecasts expect around a few hundred MW by 2020, although it seems more realistic that only several tenths corresponding to the first pre-commercial arrays, will be deployed by then. After that, a rapid development of commercial size farms, in the best sites, is expected to occur, potentially reaching around 10 GW by 2050 [11].

A similar market growth is expected for wave energy, with some delay for the first arrays to be deployed but eventually catching up due to the larger resource potential. While in 2020 there will be a moderate installed capacity of a few demonstration projects and perhaps a couple of pre-commercial arrays, in 2050 the deployment could be significant (50-300GW[1]) if the technology proves reliable and competitive.

The future market development of less mature ocean technologies such as OTEC and salinity gradient is unknown. The best attribute of these resources is that they are constant and dispatchable, unlike other renewable resources. While OTEC resource potential is very large, most of it is located far from shore and will not be accessed unless competitive energy storage and transportation is developed. Its market penetration is likely to be limited to energy demand in tropical markets and to the accessible resource in these areas. In the case of salinity, a favorable aspect is that the distance to demand is short but the global resource potential is very limited (a technical potential of around 1600TWh, of which only a small percentage may economically be extractable)[10].

1 There is large variability between sources but in any case there is a large market potential of tenths or even a few hundred GW if the technology is successful [11] [15] [16]

Negative / Positive

TYPES	Theoretical resource	Intensity	Variability	Predict-ability	Avg. distance to demand	potencial market 2050
WAVE	Med-high	High	High	High	Med	50-300GW
TIDAL CURRENT	Med-Low	Very high	Med	Very high	Med	10-30GW
OTEC	High	Low	Very low	Very high	High	<10GW(300GW)
SALINITY	Med-Low	Low	Very low	Very high	Very low	<10GW
OFFSHORE WIND	Very high	High	Very high	Med	Med-Low	500-5.000 GW

Figure 5.10 – Summary of the main characteristics of ocean resources and long-term potential market [2].

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OFFSHORE RENEWABLE ENERGY SUPPLY CHAIN

6

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After completing his Masters of Environmental Law at the University of Cape Town, David moved to the UK and found work at the Construction Industry Research and Information Association producing industry guided best practice for the construction and maintenance of major infrastructure. After delving into nuclear and renewable energy, David recognised his passion for energy policy and was lucky to gain employment at RenewableUK. As Wave and Tidal development manager, David worked hand in glove with the world leaders of marine energy, representing the UK industry to government, media and a wide range of other stakeholders. He sat on the Department of Energy and Climate Change led Marine Energy Programme Board Management Group, the European Ocean Energy Association's Board of Directors and was awarded the International Tidal Energy Summit's Outstanding Achievement award for his contribution to various lobbying campaigns, particularly around the UK's Electricity Market Reform.

6.1. INTRODUCTION BUILDING THE BRITISH OFFSHORE RENEWABLE ENERGY SUPPLY CHAIN – PERSPECTIVES FOR PORTUGAL

The offshore renewable energy industry presents a bright spot in an otherwise bleak economic landscape. Particularly in Europe, offshore renewable energy provides the opportunity to capitalise on rich marine engineering heritages and reinvigorate currently underutilised complex manufacturing bases.

Individual nations are scrambling to position themselves for the windfall of a potentially gigantic global market while the European Commission looks to entrench supply chains with its members states economies and ensure its members secure maximum share of the value that offshore renewable energy yields.

By their very nature, the areas of highest offshore renewable resource tend to be remote and often peripheral economically, yet offshore renewables can revive ailing coastal communities with jobs and skills. The positive socio-economic benefits are becoming ever clearer and the European Union has driven development of the industry with a comprehensive package of support for innovative offshore wind, wave and tidal projects.

The UK enjoys a world leading position in the three primary offshore renewable energy sectors with more capacity than the rest of the world combined in each of offshore wind, wave and tidal. The way that the UK government has supported the sectors must be praised as the Renewable Obligation has driven sustained growth while incentivising only the most cost effective projects.

As a result, the UK now have a flourishing offshore renewable energy industry delivering almost 20000 jobs and billions of pounds of inward investment. While the UK offshore renewable energy policy has been amongst the most successful in the world up until this point, the global economic downturn has created a hostile investment climate as utilities tighten the purse strings and slow investment into the renewables market.

A comparison of the development of the UK and Danish onshore wind sectors

The UK onshore wind industry is established as an excellent source of low carbon and affordable renewable energy. It currently employs over 6 600 full time employees spanning a range of activities (Figure 6.1).

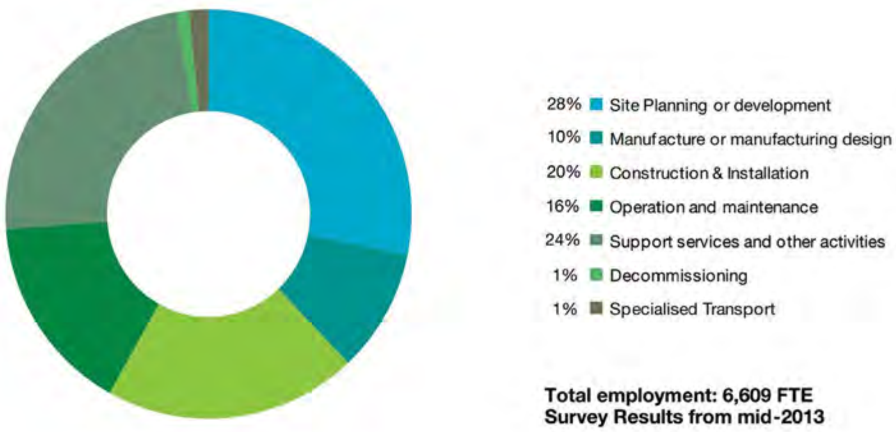
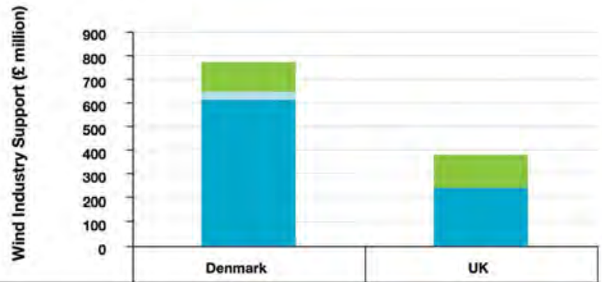


Figure 6.1 – Direct employment in the UK onshore wind sector [1].



	Denmark	UK
R&D	122	141
Capital Grants	31	0
Production Incentives	615.4	240

Figure 6.2 – Comparative policy support offered to wind energy industry in Denmark and the UK (1980 - 2000) [2].

Interestingly the bulk of the socio-economic benefits of the onshore wind industry are to be found in employment in the site planning or development, construction and installation and operation and maintenance categories.

However, many of the top tier component manufacturers are Danish companies. This is due to shortcomings of energy policy in the 1990s, when onshore wind was on a rapid cost reduction pathway. Relatively small amounts of investment from the Danish government enabled it to take up a dominant position in the manufacturing of wind turbines, securing huge amounts of business and investment for Danish companies (Figure 6.2).

This is a primary example of national governments putting decisive policies in place to build a home market and therefore enabling its companies to export high level skills and innovative technology. Policy support needs to be robust and coherent to ensure that government can develop an indigenous industry and postion its companies to provide services and products across the global market.

Key lessons:

Supportive frameworks to be put in place to guide offshore renewable energy industry through stages of development.

OEMs to be encouraged to engage with industry.

R&D institutions to prioritise solutions aimed at bridging innovation gaps.

Industrial companies make investment decisions on the basis that intense upfront capital investment will bring long term rewards. It is important that Government policy sends a signal of ambition to the market, providing confidence that there will be an industrial scale, established market providing risk reflective returns to investors. Companies will only manufacture in the UK if there is long term confidence in the UK's ambition to deploy in volume. In the absence of strong political signals to that effect, the risks and therefore the costs, of the significant investment are too high.

There is significant pressure on utilities and Original Equipment Manufacturers (OEMs) to reduce costs rapidly to ensure grid parity with other, more established forms of electricity and thus maximum value for money. However, there is a drive for member states to secure a high proportion of local content. These are two of the primary drivers behind the formulation of offshore renewable energy policy but they can often be in direct competition as the local option is often not the most cost effective.

The UK renewable energy policy has been effective at deploying projects and there is now an extensive experience base established in the nation. While the UK and Portugal are very different nations, with differing skills and vulnerabilities, Portugal is behind the UK in terms of offshore renewable energy deployment and should look for lessons in the UK experience. This chapter seeks to distill the most valuable of these lessons and link them to the current situation in Portugal.

6.2. OFFSHORE WIND – DELIVERING ON POTENTIAL

Offshore wind has enjoyed a momentous period in the UK, redefining the way the country considers energy generation (Figure 6.3). The three largest offshore wind farms in the world, Walney, Greater Gabbard and the London Array, were all commissioned in UK waters during 2013.

The offshore wind industry is on an increasingly exciting growth trajectory, delivering investment, jobs and manufacturing opportunities to the UK economy. In September 2013, RenewableUK realised Working for a Green Britain and Northern Ireland 2013-23 [1], a follow up to the 2010 report which sought to track employment across the wind and marine sectors. RenewableUK worked with Cambridge Econometrics, The Warwick Institute for Employment Research and IFF Research to develop an extremely credible and robust evidence base to track current employment levels and project future potential. The 2013 version noted a marked increase in current employment levels across all the generation technologies RenewableUK represents. Among these, offshore wind was a remarkable performer and already directly employs almost 7,000 individuals in the UK and has the potential to employ in excess of 20,000 individuals by 2023 under the higher growth scenario (Figure 6.4).

Analysing the employment opportunities available in offshore wind, it is clear that operations and maintenance offers the greatest level of growth, while construction and installation also makes up a significant proportion. This is good news for local areas as these types of activity require large numbers of semi-skilled to highly skilled tradesmen often on long term contracts.

Wind Projects Currently in Operation

Reference	Round	Project	Current Phase	MW	Number of Turbines	Foundation*			Grid Connection
						Monopile	Jacket	Gravity	
1	1	Blyth Offshore	Operational	4	2	•			HVAC
2	1	North Hoyle	Operational	60	30	•			HVAC
3	1	Scroby Sands	Operational	60	30	•			HVAC
4	1	Kentish Flats 1	Operational	90	30	•			HVAC
5	1	Barrow	Operational	90	30	•			HVAC
6	1	Beatrice Demonstrator	Operational	10	2		•		
7	1	Burbo Bank	Operational	90	25	•			HVAC
8	1	Lynn & Inner Dowsing	Operational	194	54	•			HVAC
9	1	Rhyl Flats	Operational	90	25	•			HVAC
10	1	Gunfleet Sands 1	Operational	108	30	•			HVAC
10	2	Gunfleet Sands 2	Operational	65	18	•			HVAC
11	1	Robin Rigg A&B	Operational	180	60	•			HVAC
12	2	Thanet	Operational	300	100	•			HVAC
13	2	Walney (Phase 1 & Phase 2)	Operational	367.2	102	•			HVAC
14	1	Ormonde	Operational	150	30		•		HVAC
15	Demo	Gunfleet 3	Operational	12	2	•			HVAC
16	2	Greater Gabbard	Operational	504	140	•			HVAC
17	2	Sheringham Shoal	Operational	317	88	•			HVAC
18	2	London Array (Phase 1)	Operational	630	175	•			HVAC

Figure 6.3 – Currently operational offshore wind farms in UK water [3].

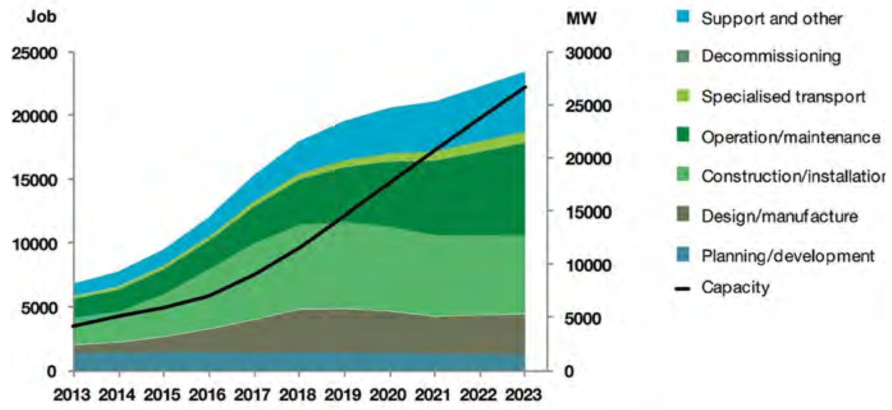


Figure 6.4 – Direct employment in offshore wind activities [1].

The development of a local skills base capable of providing services to offshore installations is essential if a nation is to reap the benefits of jobs, local trade and inward investment associated with from the expansion of the industry.

However, local contractors and consultants may look enviously at the experience gained and lessons learnt in the continental onshore wind sector, which has equipped companies like Siemens, Vestas and Areva to dominate the offshore wind turbine supply chain. It is important to remember that this is just one part of the market and an array of niche capabilities and products remain open for exploitation and, if done in a way which supports local skills' development, subsequent exportation as new markets emerge.

Knowledge sharing in offshore wind:

The Offshore Wind Project Timelines document has proved to be of incredible value to the supply chain as they provide indicative timings of development phases for all offshore wind projects in UK waters. Additionally, the timelines provide information about Invitation to Tender and Financial Investment Decisions (where available). The project stemmed from a recommendation found in the Offshore Wind Industrial Strategy, the Offshore Wind Project Timelines are produced annually by RenewableUK with the support of the Offshore Wind Industry Council.

Share Fairs: Initially an initiative from oil and gas, Share Fairs are being introduced to the Offshore Wind Sector. Share Fairs are opportunities for supply chain companies to learn about upcoming projects and opportunities directly from Project Developers and OEMs. These events will aid supply chain companies with details of prequalification, specific timelines for the overall project as well as procurement timelines and processes. Share Fairs take the idea of "meet the buyer" events further by encouraging Developers to take advantage of a public platform and engage with supply chain companies and vice versa. Most recently, offshore renewables and the recent Offshore Wind Industrial Strategy have recognised Share Fairs as an initiative of high value for signalling opportunity and aid the development of an indigenous UK supply chain for offshore wind. Share Fairs are now expected to be a regular feature for the offshore wind community supported by the Offshore Wind Industry Council and RenewableUK.

Both the Share Fair and Project Timelines are examples of industry led initiatives aimed at providing clarity of projects and opportunities to the lower tiers of the supply chain. Examples of initiatives where opportunities are clearly visible and accessible to companies in the supply chain could serve as areas of reference for the wave and tidal energy sector. As an industry on its path to commercialisation and potential for future industrialisation, it is key that best practice is implemented if supply chain visibility is to be achieved and the UK receives maximum socio-economic benefit from an indigenous source of power.

Thus, an interesting development in the policy surrounding offshore wind relates to levels of local content. The UK and Scottish governments are working hard to ensure that supply chains and the skills base are geared up to deliver a vibrant UK based industry. As part of this initiative, the industry is working in a more open fashion and working hard on sharing information and project data.

Just one of the areas which has benefitted from a surge of activity is vessel design and boatbuilding including new types of crew transfer and installation vessels. British companies are building cutting edge specialist vessels for offshore wind and ports are working harder than ever to service the existing fleet. The opportunity for these companies to take advantage of a business opportunity has been demonstrated across coastal areas in the UK, showcasing the capability of UK based companies to grow, create jobs and sustain their businesses via activity in offshore renewables.

Currently, the biggest drive in the offshore wind industry is the imperative to drop costs at a highly accelerated pace. Right now it is succeeding by increasing the capacity of each individual turbine and moving closer to attaining the cost nirvana of mass production, while at the same time pushing the boundaries of innovation to reach ever-increasingly energetic resources. However, the industry faces a steep drop-off in the levels of support it can expect over the next few years as governments look for value for money in the face of a collective tightening of belts. This trend is often at odds with the pressure for local content as project developers have to look for the cheapest option to squeeze costs.National governments can enable the development of the industry by making a long term commitment to the industry. The investment community looks for predictability when making decisions and the right market signal from government can provide the confidence they need to invest. By enabling the industry through the cost reduction phase, supportive nations will be well positioned when the industry is ready to expand its horizons to those in earlier stages of renewable energy development.

Key lessons:

Governments can create an enabling policy environment to ensure that domestic companies can capitalise on world leading positions in order to capture socio-economic benefits.

Development of a local market is essential to build up capability early in the offshore wind's development cycle and ensure ability to export skills services and products as new markets emerge.

Reliable long term signals of government support will encourage investment and enable local market.

Skills programmes to be put in place to ensure a sustainable supply of skilled individuals to service offshore installations.

Collaborative working, knowledge sharing and participation in industry forums, enables local contractors to leverage their local supply chains and to build up capacity more quickly.

6.3. THE MARINE ENERGY OPPORTUNITY

The UK is the undisputed leader in the marine renewable energy industry and has more prototype wave and tidal energy technologies operating in its waters (Figure 6.5) than the rest of the world combined. The progress of the UK industry to date has been made on the back of stable support from the UK and Scottish Governments, the creation of world leading proving infrastructure such as the European Marine Energy Centre and the excellence of the UK's rich marine engineering heritage. This has resulted in the UK being home to the world's leading technologies.

Currently, the industry is in the all-important demonstration phase, where testing of prototype devices and improved understanding of the marine environment has provided proof that the technology is capable of extracting energy from

	OPERATOR	DEVICE	RATING (MW)	COMMISSIONING DATE	LOCATION
TIDAL	Andritz Hydro Hammerfest	HS1000	1	2011	Fall Warness, EMEC
	Tidal Generation Limited (Alstom)	DeepGen 1MW	1	2013	Fall of Warness, EMEC
	Marine Current Turbines (A Siemens Business)	SeaGen	12	2009	Strangford Lough, Noerthern Ireland
	Minesto	Deep Green	0,5	2013	Strangford Lough, Noerthern Ireland
	OpenHydro	Open Center turbine	0,25	2008	Fall of Warness, EMEC
	Scotrenewables Tidal Power	SR250	0,25	2011	Fall of Warness, EMEC
	Voith Hydro Ocean Current Technologies	Hy Tide 1000-13	1	2013	Fall of Warness, EMEC
WAVE	Aquamarine Power	Oyster 800	0,8	2012	Billia Croo, EMEC
	Fred Olsen	Bolt"Lifesaver"	0,25	2012	FaBTest, Cornwall
	Pelamis	Pelamis P2	0,75	2010	Billia Croo, EMEC
	Pelamis	Pelamis P3	0,75	2012	Billia Croo, EMEC
	Seatricity	Oceanus	1	2013	Billia Croo, EMEC
	Wello	Penguin	0,6	2013	Billia Croo, EMEC

Figure 6.5 – Currently operating wave and tidal devices in UK waters [4].

the harsh marine environment at a meaningful scale. The industry is now targeting commercialisation, which will be achieved when multi-device, multi-megawatt arrays are deployed in numerous locations in UK waters and contributing a significant amount to the UK's energy demand.

The UK has a strong history in engineering and this traditional strength has carried forward into the marine energy industry. Tidal energy leaders Marine Current Turbines and Tidal Generation Limited were both created in the South West of England and OpenHydro was designed and developed from its Northern Ireland headquarters. Wave energy pioneers Pelamis Wave Power and Aquamarine Power all had their genesis and remain headquartered, in Scotland.

While the British have been prolific inventors, in the past there has been a failure to capitalise, with commercialisation of products often led by overseas markets, thus attracting the technology supply chains. We are seeing a similar trend in the tidal industry with the home-grown technologies of MCT, T GL and Open Hydro all having been purchased by foreign owned OEMs. While the entry of the OEMs into the market has contributed greatly to the credibility of the industry and reaped enormous inward investment, it has deprived the UK of its opportunity to export turbines to other markets and forced it to look elsewhere in the supply chain for value.

Up until this point, both the UK and Scottish governments have been central to the development of the industry by providing the vital legislative, revenue and capital support the industry needed to grow and move closer to full commercialisation. The fact that much of the global activity in the wave and tidal sector has occurred in UK waters has resulted in a high level of UK content in the demonstration phase of the industry's development and the leading technologies being developed in the UK.

Case Study - Marine Current Turbines:

Marine Current Turbines Ltd (MCT), now owned by Siemens has a pedigree in the tidal energy sector which can be traced back to IT Power Ltd in 1993. Marine Current Turbines Ltd was established in 1999 and has been at the forefront of tidal technology demonstration through the Seaflow project in Devon, installed in 2003 and decommissioned in 2009; and the SeaGen S 1.2MW system (Figure 6.6) installed in Strangford Lough, Northern Ireland which has now generated over 8.5GWh and operated for more than 11,000hrs.

Figure 6.6 – MCT's SeaGen with its crossbeam raised [5].

MCT was originally based in Basingstoke but relocated to Bristol in 2004. Between 2004 and 2012 the headcount of the MCT team expanded from 10 people to 30 people and outgrew the original office accommodation. In February 2012 MCT was fully acquired by Siemens AG and relocated to Bristol and Bath Science Park in October of that year. The team in Bristol is now 50 strong and expanding.

In addition to the office space, MCT has acquired factory space in St Philips, Bristol, which will be able to accommodate production volumes of the power conversion components for the SeaGen platforms way into the 2020's.The new 25,000 square feet facility will be the base for the development of next- generation drive trains used in SeaGen - the world's first and largest tidal turbine developed by MCT.

The facility will be the first of its kind in the UK and will be used by the MCT team to assemble and test the first drive trains. The Bristol facility will be used for series production of the systems which will be deployed on the multi-turbine arrays e.g. in the Skerries and Kyle Rhea by 2016 and on other arrays beyond that.

MCT is working closely with the UK supply chain to provide fabrication, assembly and installation services for the first demonstration projects with intent to develop strategic relationships with the proposed contractors for the larger UK market.

Through the acquisition of MCT and the associated investment in infrastructure and expansion of the MCT team, Siemens has demonstrated its commitment to the tidal sector and the development of the UK tidal market. Siemens has helped to develop the business, including investment in new facilities and a doubling of the workforce.

Providing capital support grants to the industry has proved extremely effective at building the UK market as bringing the technology to market has resulted in an immense amount of added value. Every £1 of public funding has been shown to leverage £6 of private investment and this trend is set to continue as the Marine Energy Array Demonstrator facilitates the commissioning of projects of values in excess of £50 Million on the back of a £10 Million government grant.

The creation of this home market has enabled the UK to gain valuable experience of developing marine energy projects. Again drawing on the Working for a Green Britain and Northern Ireland 2013-23 report [1], we noted the speed at which the marine energy industry is expanding as employment in the sector has more than doubled since the last Working for a Green Britain study, standing at 1,724 FTEs (Figure 6.7) compared to the 800 FTEs recorded in 2010.

From Figure 6.7, we see that activities directly relating to deployment of marine devices account for 66% of employment in the sector,

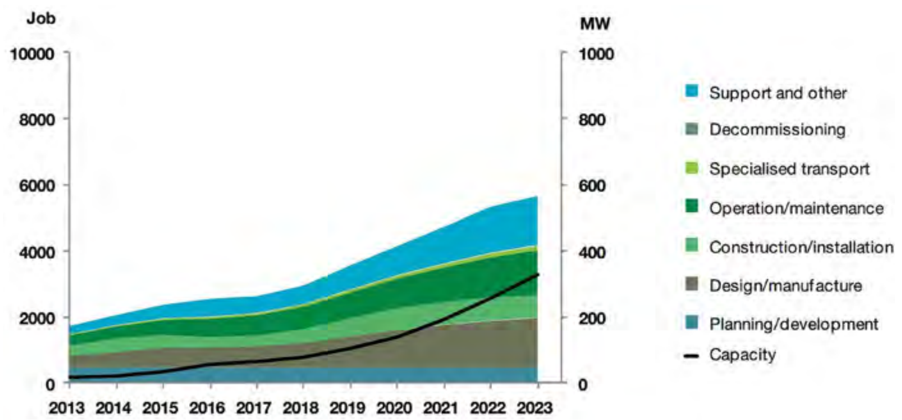


Figure 6.7 – Direct employment in marine energy activities [1].

with a further 16% working in operation and maintenance. This is to be expected from a sector which is currently focused on the installation of demonstration devices and the first small proving arrays. Interestingly, if we look at the medium scenario in more detail, we see a large expansion in employment in operations and maintenance activities. This is to be expected given the high level of UK expertise in these areas and the tendency to employ local workers on marine operations. Another beneficiary of increased marine energy deployment will be the manufacturing sector, which will benefit from greater volume of orders and the bespoke requirements of marine energy.

Case Study: Aquamarine's Lewis Wave Power 40MW Nearshore Wave Array

The Lewis Wave Power project received full consent from the Scottish Government to develop the 40MW wave farm back in May 2013 - making it the world's largest fully-permitted wave energy site. The onshore planning which was approved by the local council Comhairle nan Eilean Siar in September 2012.

Aquamarine Power has been at the forefront in working with local suppliers and organisations in pioneering this project, which has the potential to bring significant economic and social benefits to one of Europe's most remote communities. Aquamarine Power is chair and is the lead industry partner, of the Hebridean Marine Energy Project (HebMEF), working closely with Lews Castle College (part of the UHI) to develop local academic skills and establish research programmes into the potential of the Outer Hebrides for wave energy. HebMEF were successful in securing nearly £1 million funding from the Scottish Funding Council to conduct research into wave resource measurement, grid optimisation studies and studies on the interaction between wave energy machines and wildlife. As part of this process Aquamarine Power provided match funding, project support and trained UHI postgraduates in wave modelling techniques to provide the College with a long lasting academic legacy and capability in wave resource assessment.

From the beginning, the company has taken care to be as open as possible about its desire to develop their world-leading technology in Lewis and has endeavoured to use local expertise and suppliers wherever possible. During the development stage around £0.5 million has been spent within the Highlands and Islands and across Scotland to undertake environmental monitoring and impact assessment, wave resource assessment and legal services, along with direct spend in the Lewis economy on travel and subsistence costs.

Aquamarine Power were proud sponsors and keen participants in the Energy North "Realising the Potential" supply chain conference held at the Borve House Hotel in 2012, near our development site, where they outlined their procurement process and the range of services and supplies we require for their future build out plans. They recognise that the success of our project hinges on the development of the local supply chain to meet our operational needs. For example, they have spent over £5 million in the Orcadian local economy during the installation of the first two Oyster devices (Figure 6.8) and have worked with over 40 local companies as part of their commitment to sourcing much of the services and expertise they require locally. We recognise that the installation, maintenance and operation of 50 Oyster devices in Lewis will require greater local support, which presents a significant opportunity for the local economy.

Developing a strong local market develops highly exportable skills such as design, development and operations. Orkney has already experienced a prototype industry expansion and export boom with worldwide sales of expertise by local, private firms entirely disproportionate to the size of the population. It is vital that we act now to ensure these skills are developed for the continued growth of the industry. The report indicates that the UK's global lead in marine energy is fragile and is highly influenced by policy support, as demonstrated by the difference in projections for the low and high growth scenarios:

- In the low scenario, diminished UK-export opportunities, where policy support to help develop the technology is weak, leading to a lower rate of development in the sector and less opportunity for the UK to consolidate its expertise and market position;
- In the high scenario, stronger policy support to develop the UK's position as the market leader in marine energy, with correspondingly stronger demand for UK expertise and its manufacturing base.

This suggests that the UK marine energy sector, if properly supported by Government, can contribute meaningfully to UK plc by providing exportable skills and services. By demonstrating longstanding commitment to the UK marine energy industry, the Government has enabled the industry to flourish and put itself in a position to secure dominance of the global industry.

Based on a detailed supply chain sub-sections analysis, the Carbon Trust estimates that the UK could be expected to capture c.25% of the global market value and is uniquely well positioned to capture market share of the world's marine renewable energy market and a majority of the sub-component supply chains.

Currently, overall UK competitive advantage is estimated to be high or very high in nearly all of the sub-systems areas and the UK is likely to have high supply chain ownership for structure and prime mover sub-sections as well as installation and O&M aspects due to its current high number relatively mature of device developers. This is thanks to a strong research and development base, a strong share of device developers and the

Figure 6.8 – Aquamarine's Oyster 800 device, just after being fabricated [6].

existence of the oil & gas and offshore wind industries.

While the UK's current lead is undeniable, its future dominance is not assured and there are numerous other countries vying for the global marine energy prize. The recent announcement that the French Government will invest €200 Million into a number of pilot projects indicates just how driven other countries are to overtake the UK's lead. We've also seen the development of port and manufacturing facilities at the Port of Cherbourg, which is a significant upgrading of France's capabilities and which will service the projects planned at Paimpol-Bréhat and Raz Blanchard. This is good news in that it allows technology developers to increase volume facilitating cost reductions that do not solely rely on progress in the UK market.

However, it is important that the UK maintains comparative advantage and capitalises on the progress we have seen to date by securing manufacturing facilities and jobs associated with securing a UK based marine energy value chain. This can only be done with the support of the UK and Scottish Governments which have the power to bolster confidence in a future market by sending a clear signal of intent. It is hard to envision OEMs justifying building capital intensive factories and maintenance facilities without total confidence that industrial scale projects will be installed. Government and industry need to work together to overcome the barriers that undermine confidence and develop a coherent plan that encourages investment in crucial infrastructure. Thus, the need for the UK is to ensure that it continues to lead the market through strong market signals which encourage on-going investment from the private sector. Without this signal of support, the UK's current lead could slip and allow other economies to benefit from the substantial progress of the industry.

Key lessons:

Marine energy needs a strong market signal to thrive which is best given by strong and consisitent revenue support coupled with targeted capital support.

Capital support is extremely effective at leveraging private finance and attracting project developers to a nation's waters.

A thriving home market creates jobs and generates exportable capabilities.

6.4. STRENGTHENING THE VALUE CHAIN

To fully capitalise on the opportunity that the offshore renewable energy industry presents, it is important to understand the capabilities and shortcomings of the domestic value chain. An assessment of the value chain can indicate a number of areas to concentrate on (Figure 6.9).

It is important that nations respond proactively and robustly to threats to its value chain. By identifying threats and pathways to commercialisation of parts of the value chain, the Government can take targeted measures to ensure retention of value and encourage increased involvement of domestic companies. However, the most effective action that the Government can take is ensuring that the UK companies can gain experience of marine energy projects through the creation of a stable and robust market. This will enable capture of the value of marine energy projects, throughout the value chain.

6.4.1. RESEARCH AND DEVELOPMENT

As a new and extremely challenging industry, the offshore renewable energy industry needs to retain a strong research and development focus. Project development requires the development of new techniques and technologies to design, build, install,

Research and development	Feasibility assessment, design and planning	Manufacturing and fabrication	Installation	Operations and maintenance	Decommissioning
• Technology development • Hydrodynamic and resource modelling • Geological understanding • Financial risk modelling	• Environmental consenting and licensing • Legal, financial and insurance services • Electrical and civils design expertise • Project design and management	• High value fabrication of power take off • Offshore structures and support structures • Energy transmission infrastructure • Components and monitoring equipment	• Novel installation and stationkeeping • Dedicated vessels • Cable laying and reinforcing • Onshore assembly • Offshore civils • Transportation	• Recovery and repair • Environmental monitoring • Integrity, reliability and performance evaluation • Marine operations	• Offshore disassembly • Refurbishment • Disposal • Environmental and legal compliance • Transportation

Green: Significant UK lead. Actions needed targeted on protecting UK lead

Amber: Opportunity at risk. Actions needed targeted at securing UK participation

Red: UK losing opportunity. Proactive interventions needed targeted at improving involvement of UK companies

Figure 6.9 – An analysis of the UK's offshore renewable energy value chain [7].

operate, and maintain devices in hostile environments at an affordable economic cost with minimal environmental impact.

The UK has an unrivalled proving infrastructure, yet the challenge is in commercialising this capability and ensuring that the UK derives maximum benefit from its resources. A strong R&D capability provides the basis for which industrial development can grow on but it is only the first step on the pathway towards commercialisation of a product or service.

Key Lesson:

The Government is to provide incentives for utilising world leading facilities and offers continual upgrading to ensure retention of cutting edge R&D expertise.

6.4.2. FEASIBILITY ASSESSMENT AND PLANNING

Development of innovative offshore renewable energy projects requires a wide range of activities and skills. The various predevelopment activities lend themselves to local work and, as a result, UK consultants are leading the world in environmental and design expertise. The experience we have built up in this area should be exploited and used to enable UK content across the emerging global market.

Much of the UK's more general prosperity is built on the financial, legal and insurance services sectors. Once again, we are seeing British companies leading the field in the development of innovative and supportive products in this area. It is important that the UK fosters this ability and ensures that our world leading financial and legal sectors are able to capitalise on the global market.

Case study – MeyGen's 86MW tidal project: Economic investment from the FEED and Consenting phases at Highland, Scottish and UK levels

MeyGen Limited, a Scottish registered company was awarded an agreement for lease by The Crown Estate in October 2010 for the development of a 398MW tidal energy project in the Inner Sound in the Pentland Firth and Orkney Waters region. The award coincided with the creation of a UK based team with the sole purpose to develop the Inner Sound site with financial backing from its shareholders, GDF SUEZ, Morgan Stanley and Atlantis Resources Corporation. The project is being developed in two phases. The first phase (86MW) was consented by the Scottish government and The Highland Council in 2013 within which a demonstration array (up to 9 MW) is planned to reach a Financial Investment Decision (FID) in Q4 2013.

The company's approach to developing the project was to have a small, in house multi-disciplinary team working with consultancy partners to deliver the project design basis through a Front End Engineering (FEED) process such that a technical and commercial proposition could be made to Shareholders at the end of 2012. In tandem with this process MeyGen carried out site investigations and environmental monitoring in order to inform the design as well as establish a baseline for the Environmental Impact Assessment (EIA). After the results from the FEED were approved, the procurement phase was sanctioned and a contracting strategy developed.

From its inception, MeyGen recognised the capability which the Scottish Highlands region and Caithness in particular could contribute to the project. The rich offshore oil and gas heritage married with the high end engineering & fabrication capabilities that have developed due to the Dounreay nuclear power station provided the business with confidence that there is a bedrock of knowledgeable resource in which to expand. The key support on installation techniques has been from a rapidly expanding, Falmouth based SME which demonstrates the breadth of UK involvement. Moreover, the world class skills and experience that UK and Scottish based consultancies and universities have in solving marine engineering challenges as well as being able to navigate through the rigorous consenting regime have massively contributed to the projects' success thus far.

Figure 6.10 summarises the project process and the breakdown of private investment spend over the past 3 years.

Note: Funding quantum is inclusive of company overheads.

Key Lessons:

£95K per MW consented, engineered, risk assessed and costed with demonstration project close to FID.

All funding to date has been from international shareholder private investment with no direct government contributions to date.

Total 97% UK content with approximately £1.3

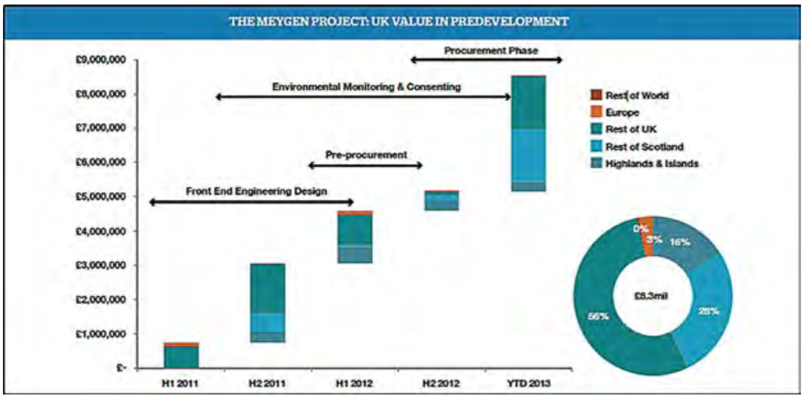


Figure 6.10 – MeyGen's UK value in predevelopment phases [8].

Million spent in the Scottish Highlands and Islands region.

UK based companies who have contributed are at the cutting edge of this sector. This has already led to an exporting of this expertise to other markets around the world.

The macro-economic signals from UK and Scottish governments have been core to investor confidence.

Key Lesson:

Governments should identify areas of strength and ensure participation of key strategic companies.

6.4.3. HIGH VALUE MANUFACTURING

The UK is renowned for producing high quality, high value, advanced engineering projects and solutions, which the offshore renewable energy industry relies upon, as these devices will have an expected life cycle of several decades. Manufacturing of wave and tidal energy devices is specialised and, as such, requires specialised manufacturing facilities.

Another approach is to use existing facilities and British manufacturers, especially those already involved in offshore wind, have already benefitted from involvement in the marine energy industry. However, this would require these companies to deviate from their existing activities and in the absence of volume this is unlikely to happen.

Case Study – Harland and Wolff

Situated within the heart of Belfast Harbour, Harland & Wolff (H&W) is a world famous shipbuilder which has successfully diversified into the Renewable energy sector and that has a proven track record in marine energy device fabrication and design. The company's vast experience in marine construction has allowed it to build up specialisms in a number of marine areas including offshore marine energy.

A diverse engineering business, it has specialist capabilities in marine engineering and design, offshore wind farm fabrication and ship repair. With an experienced and widely skilled design office, vastly experienced manufacturers, skilled tradesmen and commissioning engineers, H&W can assist developers' advance their concepts from prototype to full production manufacture.

In 2006, the company helped to fabricate and design the prototype wave energy device, Wavebob.

In 2007, it was responsible for the assembly, storage and offloading of the Seagen, the world's first commercially success full scale tidal energy generator owned by Marine Current Turbines.

In 2010, Harland & Wolff also manufactured a pre-commercial tidal turbine for ScotRenewables which is currently deployed for testing at EMEC. Harland and Wolff Engineering Manager Fred Black stated "our input was to assist their engineers develop the design to make it production friendly. This makes it cheaper to manufacture and enhances quality."

ScotRenewables' Chief Technical Officer Leader Mark Hamilton said H&W was chosen; "...to construct the SR250 prototype because of their outstanding pedigree in the field of ship-building, offshore oil & gas and more recently offshore renewable energy..."

It has also manufactured the world's first commercial Universal Foundation which uses innovative suction technology to secure the foundation to the seabed which has successfully been used in the offshore wind sector.

Key Lesson:

Existing manufacturing capability should be fostered and encouraged to engage with offshore renewable energy industry.

6.4.4. INSTALLATION

The offshore renewable energy industry will require dedicated vessels as current designs are not optimised for operating in the highly energetic environments that the industry necessitates. We have seen some highly creative designs and partnerships that have taken the industry forward significantly. However, the availability of appropriate vessels is extremely limited and the marine energy industry faces competition from more established industries such as offshore wind. Supporting the development of new vessels is a crucial step that can be taken to entrench the marine energy supply chain in the UK.

Ship building is another traditional UK strength and is a readily exportable industry. New classes of vessels are already being developed and new designs should be supported through a well funded and coordinated programme. The potential for UK export is not limited to physical shipbuilding but encompasses the high value elements of design and licensing which may be exported for construction elsewhere.

Recommendation:

Future funding programmes and competitions to prioritise ship design and building.

6.4.5. OPERATIONS AND MAINTENANCE

Much of the value of a offshore renewable energy project comes through installation, operations and maintenance. It is here that UK companies are leading the field. It is this area that will yield greatest benefit globally too. Installation, operations and maintenance are significant costs and UK companies' innovations and techniques are bringing down the costs rapidly. It is essential that the UK fosters this IP and utilises it to ensure we can roll out services globally.

Offshore Marine Management

Offshore Marine Management (OMM) is a marine management solutions company, which supply a range of services from cable solutions, personnel and vessels. Based in Bristol, the company works within the subsea telecoms, offshore renewables, oil and gas industries. From the initial design to installation, OMM can provide solutions for cables, accessories and terminations. Their personnel agency has a network of consultants available and supply project managers, specialist vessels operatives, CAD and GIS wranglers, ROV operators and divers. The company also has a database of vessels for charter. OMM offers training in offshore management and related skills through their own academy in Bristol and Cambridge. The Offshore Marine Academy uses their own courses and external resources to give qualifications and experience to work offshore.

OMM's experience with working on offshore wind projects has been throughout the UK and Europe. For the BorWin1 HVDC system in Germany, Offshore Marine Management provided guard vessels, route clearance and inspection of gas and pipeline crossings. In the UK, OMM were contracted to work on the Rhyl Flats, Gunfleet Sands and Scroby Sands offshore wind projects as joiner/ tester, supply management support and the main contractors for cable repair respectively.

Recommendation:

Installation, operation and maintenance skills as well as IP, to be fostered and protected to ensure global rollout for domestic solutions.

6.4.6. DECOMMISSIONING

Decommissioning presents an opportunity for the future. While real experience of decommissioning is limited and is only likely to be gained in the future, the UK's marine operations sector has the potential to capitalise on the opportunity it presents. By gaining experience of working in tidal flows and energetic wave climates, the UK marine sector will be well positioned to capture this component of the value chain.

Recommendation:

The Marine operations sector to gain experience facilitated through the creation of a stable domestic market.

6.5. ALIGNING STRATEGY AND POLICY

As a promising but not fully mature technology, offshore renewable energy requires an integrated Government strategy to guide it through the development phases. To capitalise on the massive opportunity presented by offshore renewable energy, the government needs to promote joined up thinking and to develop a coherent approach to developing the sector. Industrial strategy, energy policy and the work of enterprise bodies should reflect a structured and logical approach to developing the industry. The strategy should include sustained financial and political support, streamlined legislation and regulation and the creation of a fit for purpose infrastructure network, supply chain and skills base.

The development of the UK industry to date has stemmed from stable and significant policy support from the UK Government, Scottish Government and various enterprise bodies. Support is not just of a financial nature but also encompasses incentives for knowledge sharing and technology support to enable the industry to cross the innovation gap. Confidence in long-term prospects for the sector encourages the supply chain to invest, crystallising cost reductions earlier than otherwise possible.

It would be of great benefit if the Government could work to a set of overarching principles, designed to guide the development of policy. A coherent set of principles could include the following:

An overarching strategy is essential if a nation is going to capitalise on the emergence of new technologies and policy makers have a range of tools open to exploitation including capital, revenue and R&D support. These three pillars of policy support are an essential part of all technology development programmes and it is difficult for new technologies to flourish without them.

Key Lesson:

Government department and agencies to work together to develop an integrated and targeted industrial strategy, capable of creating an enabling environment in which a local offshore renewable industry can flourish.

6.5.1. CAPITAL SUPPORT

The UK Government has supported the industry as it has moved through the development stages, providing substantial revenue support, capital support and Research and Development (R&D) facilities to drive the development of the sector. Programmes such as the Offshore Wind Accelerator(OWA), Marine Renewables Proving Fund (MRPF), and Wave And Tidal Energy: Research, Development and Demonstration Support (WATERS) have enabled technology development companies

STRATEGY	strengthen confidence by laying out a comprehensive strategy for the commercialisation of marine energy
CAPITAL SUPPORT	Improve confidence by demonstrating Government suport for early stage arrays
	Enable projects by limiting investor exposure
	Catalyse supply chain by ensuring project volume
REVENUE SUPPORT	Promote genesis of a novel industry by enabling marine energy projects
	Provide certainty of a future market by laying out a long term strategy
	Secure manufacture and skills base by supporting adequate volume
R&D SUPPORT	Facilitate innovation by coordinating research and development organisations
	Target productive areas by engaging with industry
TRANSMISSION INFRASTRUCTURE	Enable infrastructure delivery by supporting needs case
	Offset high charges by setting appropriate island CfD
	Deflate liabilities by providing securities
VALUE CHAIN	Build capacity by improving industry volumes
	Secure value by enabling skills development and innovation
	Capture benefits by encouraging UK manufacturing
CONSENTING	Accelerate predevelopment by fast tracking consent and minising administration
PORTS	Facilitate development by encouraging growth and developing strategy
SKILLS	Plug skills gap by including marine energy in a coherent overarching skills strategy
SEABED RIGHTS	Create addressable market of project sites through seabed options and leases

Figure 6.11 – A coherent strategy for developing the offshore renewable energy industry [7].

to take the most promising concepts to higher levels of technology readiness.

The announcement of the £13million worth of technology support grants to Pelamis and Aquamarine from the Scottish Government's Marine Renewables Commercialisation Fund has added further impetus to the advancement of wave energy technology development and enabled these leading companies to carry their projects forward.

Given the investment made by Governments in development of marine energy, it is crucial that the return for this is delivered by helping arrays become viable. The UK Government has led the way in enabling the world's first marine energy arrays with the Marine Energy Array Demonstrator, which is helping to get the Skerries and MeyGen projects commissioned. The Department for Energy and Climate Change (DECC) demonstrated a clear understanding of the industry and a willingness to cooperate by holding extensive consultation on the terms of the grant programme.

Generally, capital support for offshore wind targets innovative technologies helps bring down the cost of energy. Recent UK programmes have providing funding for development of new types of foundations and components. In particukar, floating offshore wind concepts are being pushed by national governments and the European commission as the answer to the problem of installing projects in increasing water depths.

Recommendation:

Funding bodies to provide schemes targeted at innovative technology and areas that can bring down the cost of energy rapidly and open new areas for expansion.

6.5.2. REVENUE SUPPORT

Revenue support is a key tool for developing renewable energy projects as new technologies struggle to compete with more established technologies. In the energy sector, coal has had over 100 years to mature and drive down cost while offshore wind has only been in developing in earnest for less than 15 years.

Enhanced revenue support can have a monumental effect on new industries. In the UK, following successful proof of concept, the Department of Energy and Climate Change saw fit to upgrade the level of revenue support granted to the tidal stream energy industry to 5 Renewable Obligation Certificates (ROCs).

This catalysed an influx of Original Equipment Manufacturers (OEMs) into the industry. The OEMs' contribution of engineering and manufacturing capability, along with their ability to back up warranties has added a great deal of credibility and bankability to the industry. It is essential that engagement with these engineering giants is maintained and new entrants are encouraged to invest in technologies.

It is clear that OEMs require confidence that a market will emerge and revenue support policies should be designed with this in mind. An especially important point to convey is that the future market will be sizable and supported until such a time when support becomes unnecessary.

On closer inspection, the lack of OEM's in the wave energy sector poses certain challenges. While some point towards the technology readiness as the primary hurdle, OEM appetite could be improved by a stable and viable support framework, noting the specific challenges of developing technologies suitable for challenging wave climates. Elements of such a package would include an appropriate level of support to generate risk reflective IRRs, sufficient volume to enable cost reduction and a longer term strategy to maintain OEM interest.

Key lesson:

The Government to strengthen confidence in a future market by providing sufficient and stable long term revenue support of industrial scale is essential to investment.

6.5.3. R&D INSFRASTRUCTURE AND SUPPORT

The UK has a world leading research and development network with organisations which take a forward looking approach to the development of the sector. It is important that these organisations target the most relevant areas and work to prioritise UK companies in their work.

While the three primary UK R&D organisations, the Technology Strategy Board, the Offshore Renewables Catapult and the Energy Technology Institute have offered effective, targeted R&D support schemes, there is a need for these bodies to work in a more coordinated fashion. They should target areas prioritised by industry and that can make an impact for the current phase of industry progression.

IMPROVE PROJECT INVESTMENT	Adquate strike price, providing risk reflective returns
	Protection from competitive allocation
	Access to a sufficient volume of CfDs
PROVIDE LONG-TERM MARKET SIGNAL	Strategy for shedding project cap
	Agree achievable cost reduction trajectory(based on deployment levels, not time)

Figure 6.12 – Revenue support objectives and means [7].

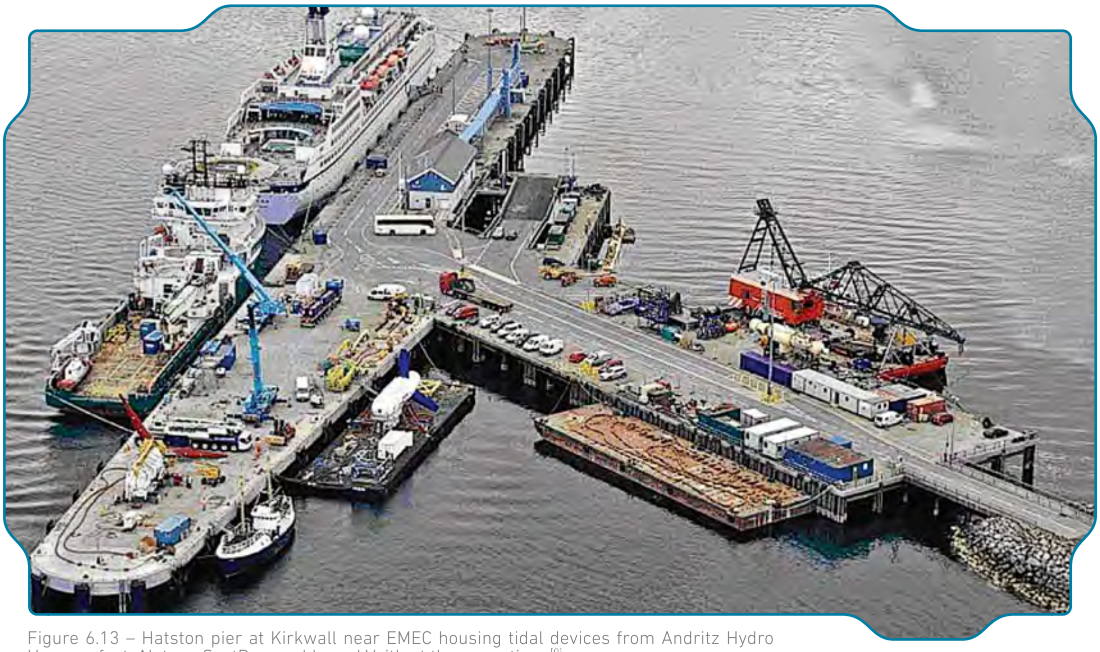


Figure 6.13 – Hatston pier at Kirkwall near EMEC housing tidal devices from Andritz Hydro Hammerfest, Alstom, ScotRenewable and Voith at the same time [9].

In addition, a vibrant and diverse proving infrastructure is needed to advance new concepts towards maturity. In the UK, facilities such as the National Renewable Energy Centre in Blyth and the European Marine Energy Centre in the Orkneys have proved invaluable to testing and maturing new concepts. Without the infrastructure which has been developed in the UK, it is highly unlikely that the UK would have been able to move to a position of such dominance.

Key Lesson:

The Government and R&D institutions are to drive a coherent and well-funded programme to support innovation and maturation in the industry. This is best achieved through each body having very specific and complementary roles.

Case Study – The European Marine Energy Centre (EMEC)

EMEC has been particularly successful in providing a proving ground for pioneering wave and tidal projects (Figure 6.13). It is fully contracted and has been instrumental in proving the technology can work in challenging wave and tidal environments. Celebrating its tenth anniversary this year, EMEC was established with the aim of emulating the Risø wind turbine test centre in Denmark which facilitated the test of wind turbines and helped establish the standards and protocols that have enabled wind power to grow from a few MW in the eighties to a market worth in excess of £50bn per annum today. The centre provides grid connected berths for testing both large scale wave and tidal energy devices and two test sites for testing smaller scale prototypes. From one client in 2004 EMEC now has a total of fourteen full scale test berths contracted to different organisations. EMEC employs a total of 22 staff and is self-supported by fees from device developers as well as research contracts and consultancy. To date ~£33m has been invested in the Centre by the Scottish Government, Highlands and Islands Enterprise, The Carbon Trust, UK Government, Scottish Enterprise, the European Union and Orkney Islands Council. Public investment has also been made in harbour developments in Kirkwall, Stromness and Lyness (Hoy) from Orkney Island Council deploying oil fund monies with additional ERDF support and HIE funding office units for the use of EMEC's clients; this has gone alongside private sector investment in vessels and forward operations bases. EMEC has developed a number of international collaborations with organisations in Japan, USA, Canada, Taiwan and South Korea. A steady stream of international visitors and foreign media come to Orkney to see the work undertaken at EMEC contributing to the local economy. Device developers have established operations in Orkney, with locally based employees. The supply chain has also invested, with companies located both in and out of Orkney creating offices and workshops and investing in workboats, dramatically increasing the resources available compared to a the previous decade. A recent Economic Impact Assessment[1] carried out for Highlands and Islands Enterprise (HIE) identified that the Gross Value Added into the economy associated with EMEC to the end of 2011 was £149m – a 4.5 multiple of the initial sum invested in EMEC. The economic analysis calculates that in the period 2003 to 2011 activity at EMEC supported the average equivalent of 119 jobs in Orkney and 262 across the UK – a figure that is still fast growing. Indeed recent work for Energy of Orkney by Aquatera has identified 221 employed in marine renewables related activity in Orkney alone in areas such as machine testing, environmental consultancy, marine operations, maintenance, design and research. This is a valuable contribution to a community with a population of 20,000 in particular because the employment is high value, often graduate work, scarce in remote communities and in addition because it is expertise that is being exported bringing global revenues to the islands.

1 EMEC Economic Impact Assessment for HIE by Steve Westbrook, Economist, 21 May 2012

6.5.4. BUILDING VALUE CHAIN CAPACITY

As a young industry, the offshore renewable energy supply chain is still developing. The biggest issue for the supply chain is current uncertainty, caused by contracting deployment forecasts and broader policy uncertainty. High costs of capital are also causing problems for the supply chain. Overall, the supply chain does not currently have the confidence in the future market to invest large sums of money into capital intensive R&D and infrastructure.

This is a problem for the sector as there is a substantial benefit to moving early and the UK has an opportunity due to the expertise companies have already been built up. Project developers only want to build their supply chains once and it is important that UK companies are encouraged to capitalise on their expertise and commit to the sector. This will enable export of UK products and skills.

These problems are compounded when viewed in the context of competition with established industries such as Oil and Gas, which are able to place volume orders and can consume the capacity of the supply chain. It is essential that offshore renewable energy projects move quickly towards volume so that they can engage the UK supply chain and ensure retention of value for the UK.

Key lesson:

Build value chain competitivity by fostering the development of a robust domestic market.

6.6. CONCLUSIONS

The emerging offshore renewable energy industry holds huge potential for growth. The opportunity to export home grown technology and skills could yield significant benefits for the UK economy, delivering manufacturing, jobs and inward investment.

However, it is important that the UK government sends a strong signal of support to the industry to improve confidence in the prospects of a future market and encourage the development of facilities and skills. The best way of doing this is to provide an adequate level of revenue support, backed up by appropriate capital support and an overarching strategy for the commercialisation of the industry.

By demonstrating this level of commitment, the UK government will catalyse the genesis of a novel industry and deliver a range of socio-economic benefits to the UK economy. The opportunity is there to be taken it is a matter of applying coherent and coordinated policies to capture it.

Collaborative and coordinated working is another crucial component of renewable energy development. Sharing knowledge enables companies to cut costs faster and developing an integrated and targeted strategy ensures that value for money is achieved.

If the Portuguese government puts in place measures to develop the domestic industry and ensure retention of local content, it can effectively contribute to the burgeoning offshore renewable energy industry. This would ensure that Portugal capitalises on its substantial human and natural resources and positions itself to export skills and technologies across the emerging global market.

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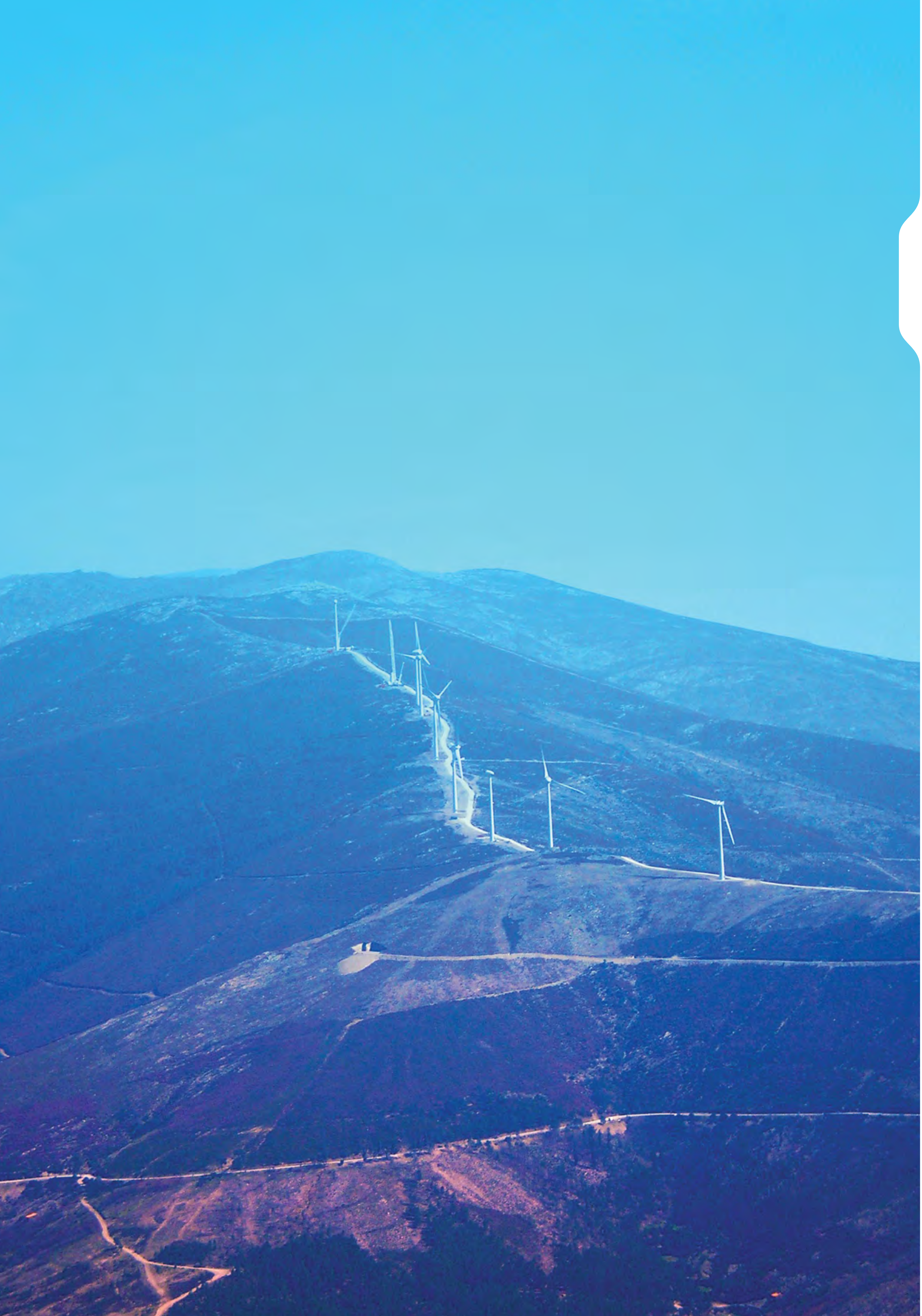

PORTUGUESE PRODUCTIVE CAPACITY: CURRENT SITUATION AND PROSPECTS

7

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She obtained her Master of Science in Environmental Engineering from the Technical University of Lisbon in 2008. After that, she obtained her Executive Master in Sustainable Energy Systems from MIT Portugal in 2011.

7.1. BACKGROUND

Portugal has been seen for a long time has a small country, just raised by the sea. But the beauty of its natural resources is not their only benefit...

Our country has learned how to take advantage of its endogenous renewable resources in order to produce a commodity which is a key driver for the human development – electricity.

As Portugal does not have any known reserves of natural gas and oil and as the exploitation of coal was spotted in late 90's of last century, it quickly became aware that there would be a need for enhancing energy independence, in order to avoid geopolitical constrains, massive importations of fossil fuels, whose price is volatile and to avoid promoting greater damage on the environment so that future generations could be able to sustain itself.

It all began with hydropower, by the end of the 19th century, when the first small hydro power plant (SHPs) started exploiting the power of the water for electricity production. Along the way, the electricity mix evolved; in the last decade it evolved in an impressive way, being recognized worldwide. Water from the rivers, wind, sun, waves, heat of the earth and biomass are being used to produce electricity.

If in 2000 only 3% of the electricity produced in Portugal came from renewable sources (excluding large hydro), in 2012 this value was 27%, being Portugal the fifth European country with a higher penetration of renewable electricity (RES-E) in the consumption and the second in what concerns wind power [1].

In fact, the most relevant kick-off for this development took place 25 years ago, in 1988, when a Decree-Law opened the electricity production to the private sector, for SHPs. Before this a monopoly was in place – all the chain (production, transmission, distribution and commercialization) was detained by a single company.

Ten years later, the electricity production for the private sector was opened to other technologies – a big step towards the expansion of a new activity: the electricity production under a special regime based on renewable energy sources (from now on designated as PRE FER).

An impressive growth was registered, being very consistent; only in the last two years did it became steadier.

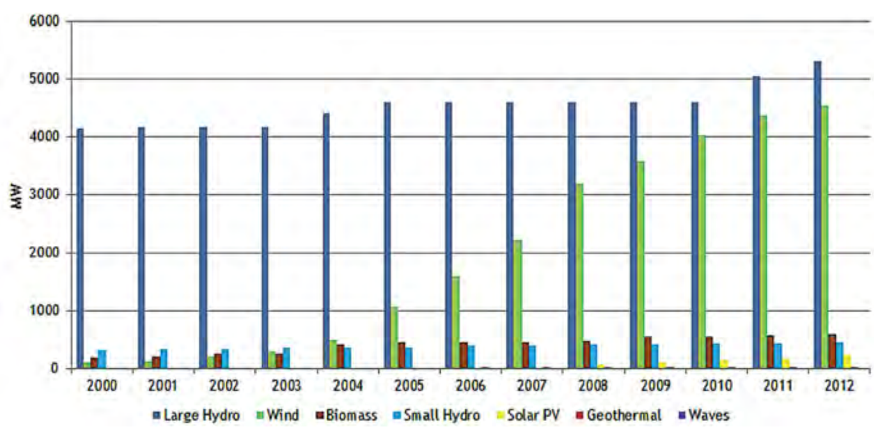

Figure 7.1 - Evolution of the installed capacity in RES-E in Portugal [2].

The evolution of the installed capacity in RES in Portugal between 2000 and 2012 shown in Figure 7.1, shows clearly its development, especially from wind power which multiplied by more than 40 times the installed capacity in this period. It is also possible to observe the emergence of other technologies, such as biomass in its various forms, solar and SHPs that from 1991 developed under the new published legislation.

In Figure 7.2 increasing weight of the PRE FER is shown during the period of 2000 to 2012, which was multiplied by 10 – from 3% of domestic consumption in 2000 to 27% in 2012 [1].

The development of this activity was possible due to the energy policy supported by the European Commission and to the national will to follow the best examples in Europe and to take a leadership position in this matter. The benefits of this leadership should be unquestionable.

First of all, the decrease of the external energy dependency of about 6 - 7% from the average 85% registered in the period 1995 to 2005 (Figure 7.3), which is itself a very important fact for the national economy [3].

Linked to this structural benefit, it is important to recall the relevant savings in fossil fuel imports induced by PRE FER (Figure 7.4 and Figure 7.5). In the period between 2005 – 2012 these savings were 3 539 million euros (M€) and to this value, the value saved in the acquisition of allowances of 600 M€ - more than 4 000 M€ must be added. In the same period the support for renewables was 3 034 M€, in other words, the support in this period amounted to 379 M€/year and the savings that brought the Portuguese economy were 488 M€/year [4].

A holistic vision also takes into account other macroeconomic impacts which should be added to the equation: more than 6 500 direct jobs were created, 8 500 M€ of investment in the installed capacity (70% of which is foreigner), 500 M€ of investment in the solar and wind industry, 200 M€ paid as a financial counterpart to the State in the last tenders for capacity allocation and 96 M€ of direct contributions from the Municipalities [4].

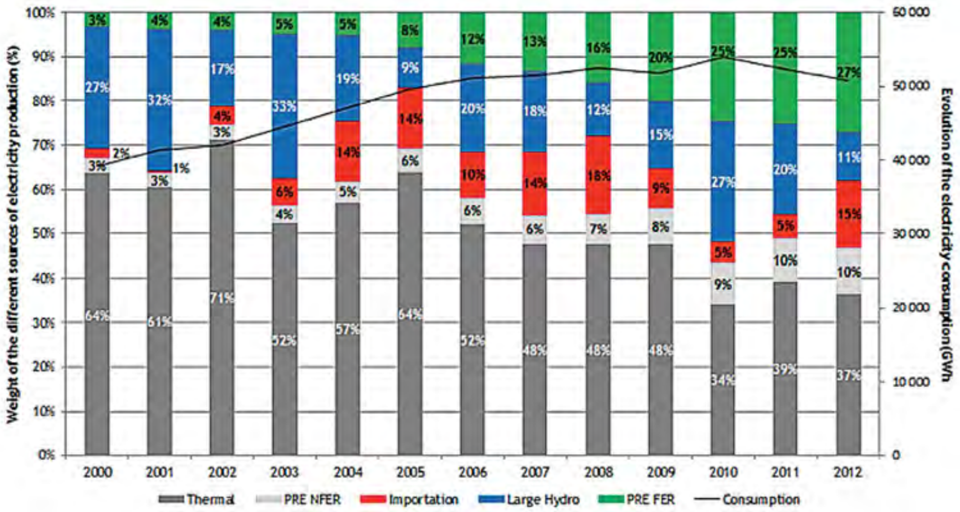

Figure 7.2 – Evolution of the electricity consumption and from the weight of the different sources of electricity generation in the Portuguese mix [1].

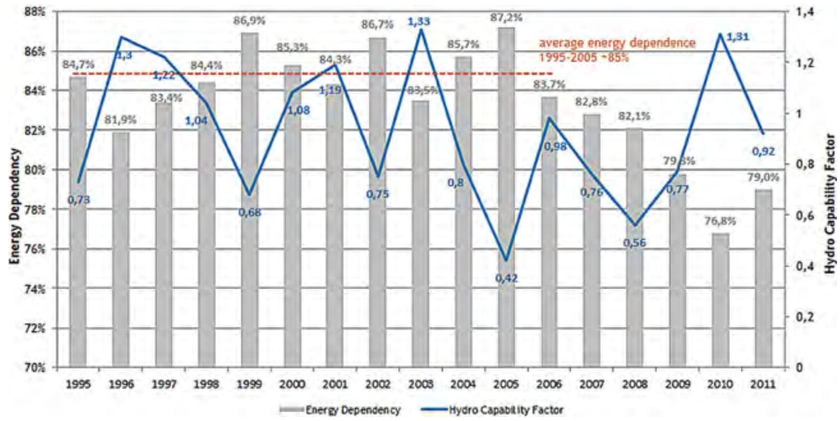

Figure 7.3 – Evolution of the Portuguese energy dependency and its relation with the hydro capability factor [3].

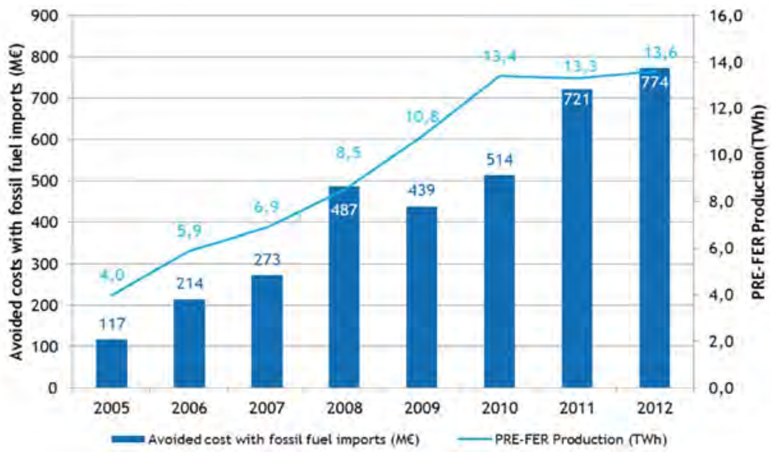

Figure 7.4 – Impact of the electricity from PRE FER in fossil fuels imports [4].

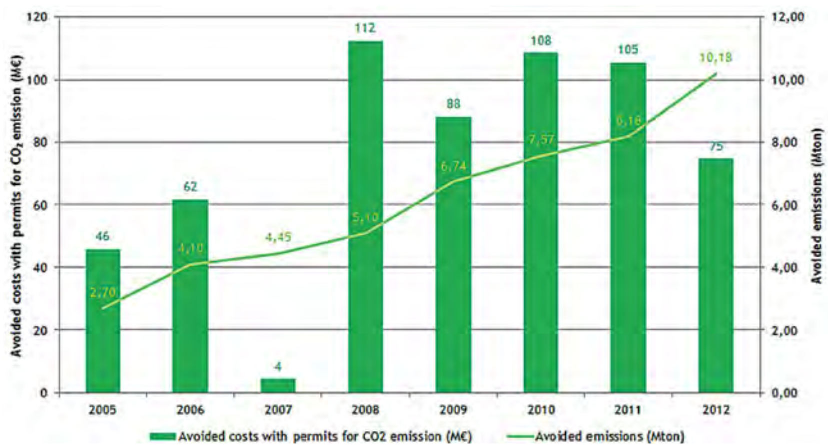

Figure 7.5 – Impact of the electricity from PRE FER in the reduction of the GHG emissions [4].

“ 7.2. CURRENT SITUATION AND PROSPECTS

Although there was a remarkable expansion registered in terms of RES-E in Portugal, the current development is slowing down very suddenly. The actual economical and financial climate in Portugal is shaping this sector:

- A reduction of electricity demand is being registered, which is leading to a situation of excess of capacity for electricity generation in our country;

- The Iberian Peninsula does not have enough interconnections for electricity exportation to the rest of the Europe, and so it is not possible to remunerate adequately the surplus of electricity not absorbed by the Iberian Market;

- A climate of regulatory instability is installed, regarding capacity allocation, remuneration issues and licensing procedures, keeping away foreigner investment and jeopardizing the access to financing;

- There is now an installed idea that RES-E is not affordable because it is too expensive.

In fact, the national panorama leads us to choose more urgent matters rather than the important ones. And in the urgency of dealing with the actual economical and financial crisis in Portugal, important and structural matters for our nation are being jeopardized.

Currently, Portugal does not have a clear energy policy. The only structural document remaining is the National Renewable Energy Action Plan (NREAP) - a document foreseen in article 4 of the RES Directive (Directive 2009/28/EC) which states out Member States' national targets for the share of energy from renewable sources consumed in transport, electricity and heating and cooling by 2020, taking into account the effects of other policy measures related to energy efficiency on final consumption of energy and adequate measures to be taken in order to achieve those national overall targets.

During 2013, the original NREAP, delivered to the European Commission by the previous Portuguese Government in the summer of 2010, was revised through the Cabinet Resolution 20/2013, in light with the current situation of the country, lacking ambition on the development of RES in Portugal, giving the wrong signals both to the market and to investors.

Portugal is now facing the possibility of staying on the platform watching the train of renewables move away. Although there is a considerable potential in terms of endogenous resources, exploiting it, is not presently a concern. And this is happening with offshore energy...

Portugal has a considerable coast extension and is even investing in expanding its continental platform. The sea is nowadays a national target. This means, more potential resource to exploit.

Wave power and offshore wind have already given the first steps in Portugal.

In the case of wave power, Pico's wave power plant in Pico (Azores) was the first experimental power plant, with 400 kW of installed capacity, based on the concept of oscillating water column. More recently, Peniche Wave Park was installed, based on the WaveRoller technology (Figure 7.6) and with an installed capacity of 300 kW. But other prototypes have already been tested in Portugal throughout the last decade, showing the interest of national companies in these projects.

Regarding offshore wind, so far, Portugal only has the WindFloat Project (Figure 7.7), installed near Póvoa do Varzim. Currently in demonstration phase, it is composed of a single wind turbine, with 2 MW of installed capacity on a floating platform anchored at 50 metres depth and is intended to prove the concept of installing wind farms in deep waters. To the date, the results have been rather satisfactory; it is expected that this project will culminate with the installation of 150 MW of offshore wind, based on devices similar to what is

Figure 7.6 - WaveRoller device being positioned [5].

Figure 7.7 - WindFloat Project [6].

currently being tested.

Portugal has specific characteristics that are advantageous for the investment on offshore energies:

- Existence of natural resources, deep water close to the shore, sandy bottom, no significant currents, mild weather, amongst others;

- As 80% of electricity consumption takes place on a 50km coast line, Portugal has the electricity grid necessary to absorb the electricity generated offshore;

- There are also several docks and shipyards along the coast;

- The existence of a Pilot Zone available for testing new technologies, with simplified procedures for the installation of prototypes, pre-commercial and commercial devises and with corridors for connecting the pilot area to the substation on land;

- R&D&I institutions with experience and international recognition;

- Qualified and competitive workforce in many relevant areas.

However, there are countries, such as Ireland and the United Kingdom, with a higher resource potential, better financial and political support, a more mature supply chain and more experience in offshore which may appear more interesting for future projects. So, in order to bring potential investors in offshore energy to our country, it is urgent to take measures to make Portugal into a country where it is worth investing in.

In terms of future prospects for offshore energy in Portugal, the panorama is not the brightest.

The reviewed version of NREAP decreased substantially the ambition of expanding these technologies until 2020: a decrease from 250 MW foreseen in the initial version to only 6 MW in the reviewed document for wave power and from 75 MW to 27 MW for offshore wind.

If NREAP does not represent itself a limit for the expansion of RES-E sector, but rather a minimum threshold for achieving the Portuguese target by 2020, it is fair to say that it gives the worth signal possible to the market. It affirms that Portugal is not willing to harvest the benefits of investing in these technologies.

Presently there are several well identified barriers in the deployment of offshore energy in Portugal:

- High capital intensive technology, in a climate of financial and economic crisis;
- Competition with other more mature technologies in times of excess of capacity and financial constraints;
- Overcoming the demonstration phase and passing to commercialization with reliable production;
- Difficulties in operation and maintenance activities in offshore;
- Lack of access to data for resource assessment and description of possible areas of implementation (system of waves, winds, currents, ...);
- Administrative processes being long and unpredictable;
- Maritime spatial planning and conflict with other forms of exploitation of marine resource;
- Absence of interconnection points with the grid and high costs related to this interconnection.

In order to overcome the present barriers and to prepare for a brighter future in offshore energy, it is important to build a stable framework as a starting point and to give a clear investment signal, to gain the trust of the potential investors. The energy sector has long investment cycles and investment decisions need as minimum uncertainty as possible, in order to lower investment risk. This framework will help to achieve the financial support needed.

Regulatory stability is essential for the energy sector; moreover when dealing with technologies in an early stage of development, as in offshore energies.

With a stable regulatory framework it is than necessary to supply a proper initial support, since these are technologies in an early stage of development in order to be able to compete with the existing ones. That is what happened with fossil fuels, which despite having reached maturity, continue to receive subsidies: a study of the World Watch Institute states that worldwide in 2010 the total subsidies for renewables account for only 8% of total of fossil fuel subsidies.

An initial support is essential to promote the development of technologies and reducing their costs. It should be gradually withdrawn as the technology becomes mature and comparable with other technologies in terms of cost and reliability. The maturity of the technologies will allow to gradually move away from support mechanisms into a fair and properly functioning energy market - a competitive market which is open to all energy technologies equally, restoring healthy price signals and enabling for the full benefits of real competition.

The continued deployment of renewables improves the security of energy supply and reduces the exposure to volatile fossil fuel prices, both in terms of minimizing the importation costs and the impact of its prices in the energy prices. Our competitiveness is too important to rely on external factors such as unstable oil and gas markets and volatile fossil fuel prices.

Competitiveness drives innovation, technological leadership and job creation and will bring down our electricity bills. At the same time it will ensure a reliable, low-cost supply of clean electricity for citizens and industry.

Continuous investing in RES will allow for long-term cost reductions in renewable energy technologies to continue by enabling industrialisation and economies of scale and to reap the benefits of an energy policy which favours clean and indigenous energy sources and technologies.

Finally, it is vital that transnational networks, connecting Iberia Peninsula to the rest of Europe are developed in a short-term, so that the natural resources abundant in the south of Europe, can be properly exploited, reaping benefits for the entire continent by helping to ensure a security of supply for Europe.

7.3. CONCLUSIONS

Portugal is a country with a strategical advantage in what concerns endogenous renewable energy sources – the resources exist and are abundant and the know-how was successfully developed and is nowadays highly appreciated worldwide.

As a member of the European Union, Portugal is committed to the goals of the EU in matters of energy and climate. Not only by 2020 - a 20% of renewables in energy consumption, a 20% increase in energy efficiency and a 20% reduction in greenhouse gases emissions by 2020 – but also by 2030 – targets are still being discussed - and 2050 – a decarbonisation goal of 85% to 90% of the economy.

To achieve such an objective, it is necessary to analyse the various alternatives in a macroeconomic perspective and to define a long-term strategy. The strategy will have to adapt to the economic reality but cannot miss the long-term goal, one that will bring economic development, better quality of life and honour European commitments.

Offshore energies may be a part of the solution taking into account the natural conditions of our coast. It is up to us to leverage a new sector and to harvest its benefits.

Offshore energies may enclose a set of benefits to Portugal, as a new industry will be developed, capturing investors' attention, creating employment and generating benefits for local/regional communities.

One thing is already certain: renewables are a "no-regrets option". A solution, helping to deliver clean and affordable energy at the same time as it increases our security of supply.

And that is why our motto is and will be for many years to come,

Portugal precisa da nossa energia*

(*Portugal needs our energy)

7.4. REFERENCES

[1] APREN, "APREN analysis from data from REN, EEM and EDA".

[2] APREN, "Projecto e2p - Energias Endógenas de Portugal".

[3] APREN, "Data from DGEG and EDP".

[4] APREN.

[5] APREN, image provided by Eneólica, for APREN's Yearbook 2013 Image credits: Eneólica.

[6] APREN, image provided by EDP Inovação, for the e2e Project. Image credits: EDP Inovação.

ROADMAP

8

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8.1. INTRODUCTION

Portugal has immense ocean energy resources and a worldwide pioneering position in the marine renewable energy sector and therefore a huge potential for the commercial exploitation of deep-sea wind and wave energies in the Atlantic Ocean. These energy types may strongly leverage the development of a national cluster for offshore renewable energies.

These Portuguese capacities were highlighted by some deliverables of a national project called OTEO – Offshore Technology Energy Observatory. The OTEO project aims to contribute to the transformation of Portugal into a country which uses the energy potential of its coast and that plays a relevant role in the production and export of basic and support technologies in the marine renewable energy sector in Europe.

A strategy and an action plan that maximizes the national supply chain must be prepared immediately to foster for this development. In Chapter8.4 a technology roadmap is presented which includes a vision, identifies actions, milestones and costs and proposes continuous revision processes.

The definition of a roadmap differs strongly from country to country and between activity sectors. Recent documents were published in Portugal: two roadmaps for the marine sector were concluded and another, for the floating offshore wind, is under development.

The first document, "Principles for a Roadmap Preparation", had, as its main objective, to begin a Portuguese roadmap process. The conclusions can be found in Portuguese in [1].

The second one was "A Roadmap for Offshore Renewable Energies in Portugal - Conception, Monitoring and Roadmap's updating: Application to the Development of Marine Energies in Portugal". The objective of this project was to bring an engineering systems' approach to the development of a novel design methodology of roadmaps for renewable and clean energy systems which encompass uncertainty management, monitoring and update tools. The deliverables can be found in [2].

The main goal of the third document - the Demow-Float Project, under the European FP 7 Framework -, is to develop a roadmap for the industrialization of pre-commercial and commercial phases of floating offshore wind technologies. It has been developed based on the experience gathered by the Windfloat prototype.

Being totally different from each other, it is appropriate to clarify the roadmap concept that shall be adopted. The option chosen was to follow the guidelines of the International Energy Agency (IEA) proposed in the document "Energy Technology Roadmap, a Guide to Development and Implementation" published in 2010. This methodology is described in Chapter 8.2.

The preparation of the Portuguese roadmap is subject to the transposition of the European Commission' (EC) Directives to the Portuguese legislation. In the case of marine renewable energies, the EC estimates a large-scale installation of a few technologies and, therefore, promotes a rapid growth of the employment growth in the sector.

The construction of the roadmap shall take into account the most promising conditions raised by the European Community and Portugal. These positive perspectives are presented in Chapter 8.3. However, being basically a technology roadmap, other issues outside technology must be considered in its preparation.

An action plan following IEA's guidelines is proposed in Chapter 8.4. It aims to cover the OTEO Roadmap's objectives and to answer some of the questions raised in Chapter 8.2 by those guidelines. Other questions remain open to further discussion.

8.2. IEA CONCEPT OF AN ENERGY ROADMAP

OTEO's roadmap was built based on the International Energy Agency's Roadmap' [3] concept with a few adaptations. According to the IEA, a roadmap is a strategic plan which describes the steps an organization needs to take in order to achieve stated outcomes and goals. It clearly outlines links amongst tasks and priorities for action in the near, medium and long term. An effective roadmap also includes metrics and milestones to allow regular tracking of progress towards the roadmap's ultimate goals.

A roadmap also evolves in the sense that the process does not stop when the document is published. Rather, the roadmap evolves as progress is made, external factors change and more information becomes available. Technology-specific roadmaps are sometimes updated more frequently than national-level roadmaps (e.g., every two to five years) to reflect progress, changes in available resources or scheduling considerations.

A successful roadmap contains a clear statement of the desired outcome followed by a specific pathway for reaching it. This pathway should include goals, milestones, gaps, barriers, priorities and timelines.

But simply writing a roadmap is not enough – the true measure of success is whether or not the roadmap is implemented and achieves the organization's desired outcome.

The roadmap's development process includes two types of activities (Expert Judgment and Consensus; Data and Analysis) and four phases (Planning and Preparation, Visioning, Roadmap Development and Roadmap Implementation and Revision). After a roadmap is completed, implementation and updating ensure the complete realization of the vision and goals.

Expert workshops and consensus-building activities form the core of an effective technology roadmapping process. Workshops gather a cross section of experts in technology, policy, economics, finance, social sciences and other disciplines to formulate roadmap goals and milestones, identify gaps, determine priorities and assign tasks.

In the planning and preparation phase, the organization undertaking the roadmapping initiative needs to answer several questions:

- Which technology areas or classes will the roadmap consider?
- What is the time frame for the roadmapping effort? Is the roadmap a five-year plan, 20-year plan or a 50-year plan?
- What is the current state of the technology under consideration (current installed base, potential energy savings, cost, efficiency, etc.)?
- Will the roadmap be used primarily to guide national government decision making?
- Will the roadmap need to engage the private sector to achieve the stated goals?
- What existing tools or analysis, such as other roadmaps, can be used to influence scoping decisions?

The purpose of OTEO's roadmap is to accelerate the adoption of marine renewable technologies, focusing on the value chain. The scope and objectives states what kinds of project the roadmap is expected to guide and over what time frame. The process sets how the roadmap will be developed and includes the schedule for completion. The types of organizations and individuals expected to participate in the roadmap process should be carefully chosen.

The aim of the situation analysis for technologies is to develop accurate information on the current status of costs, performance, technology readiness, manufacturers, vendors, market penetration and limitations. The aim of the situation analysis for markets is to develop accurate information on the current status of the supply chain (suppliers, distributors and customers). The aim of the situation analysis for public policies is to develop accurate information on the current status and requirements of existing laws, regulations, policy directives and other rules which affect the technologies and markets in the roadmap; but this analysis should also include information on trends that are likely to lead to new policies or to prevent policies from being enacted.

The phase following the roadmap planning and preparation is setting a vision: the process of defining the desired pathway for a technology's deployment. Once a vision is established, the roadmap development phase begins, drawing on analysis and expert judgment to define the activities, priorities and time lines required to reach the desired vision.

Launching the roadmap and putting in place tracking systems are the final steps in the roadmap implementation and adjustment process. The final roadmap outlines a set of priorities – research projects, technology demonstrations, policy advances, regulatory changes and financial commitments – that are needed over a defined time frame to achieve the roadmap's goals. The first stage of implementation is to begin those activities.

The mechanics of funding research projects or pursuing regulatory changes is highly dependent on an organization's unique characteristics and is not the focus of the IEA's guide. Whatever the mechanism of project initiation and management, engaging stakeholders to address near-term priorities is a key first step in implementing the roadmap.

There are six vital aspects to consider when designing a roadmap process: stakeholder participation, resource constraints, critical inputs, roadmap design, buy-in and dissemination and monitoring and tracking.

A technology roadmap requires certain critical inputs to establish a sound baseline of the current state of the art and provide a basis for defining future technology. The process requires reliable national energy data, modeling and analysis tools and capabilities, and detailed engineering and cost performance information for competing energy technologies.

A few critical inputs are mandatory to write a useful roadmap report:

- Which regulators and policy leaders can provide insight on factors affecting technology adoption?
- What data is needed to establish baseline conditions, set goals and targets, and prepare forecasts?
- Which private entities will be critical for technology success?

8.3. EUROPEAN AND PORTUGUESE DIRECTIVES, PLANS AND COMMUNICATIONS

The supply chain related to the development of these type of marine renewable projects involves a broad number of products and services, starting at the development and production of devices all the way up to the support infrastructures. The international deployment and investment level projections referred to below, as well as the national targets and strategies, will engage private Portuguese companies with knowledge and skills to move into the project's value chain to gain international visibility into a sector with strong worldwide expansion.

In the last six years the EC's outlook on the energy, the sea and the industrialization in Europe has evolved significantly. The speech has changed from the need to acquire knowledge about ocean resources and to create jobs towards focus on innovation on commercial products and to launch funding mechanisms specifically to support emerging technologies. A few of the EC Directives and Communications, presented below year by year, show the evolution towards a firm support to the development of the maritime renewable energy sector at European level.

2007	- A European Strategic Energy Technology Plan (SET Plan): Towards a low carbon future [4]
2008	- A European Strategy for Marine and Maritime Research: a coherent European Research Area framework in support of a sustainable use of oceans and seas [5] - Offshore Wind Energy: action needed to deliver on the Energy Policy Objectives for 2020 and beyond [6]
2009	- The promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC [7]
2010	- Europe 2020 – a strategy for smart, sustainable and inclusive growth [8] - Maritime Spatial Planning in the EU – achievements and future development [9]
2011	- Horizon 2020 - The Framework Program for Research and Innovation [10], [11] - Developing a Maritime Strategy for the Atlantic Ocean Area [12] - Energy Roadmap 2050 [13]
2012	- Renewable Energy: a major player in the European energy market [14] - Blue Growth: opportunities for marine and maritime sustainable growth [15] - NER300 – A Commission Decision laying down criteria and measures for the financing of commercial demonstration projects which aim at the environmentally safe capture and geological storage of CO2, as well as demonstration projects of innovative renewable energy technologies [16]
2013	- Energy Technologies and Innovation [17] - Action Plan for a Maritime Strategy in the Atlantic area [18]

Several international reports were considered in the preparation of the OTEO roadmap. They complement the messages and measures proposed by these EU Directives and Communications. The two have been written by the European Ocean Energy Association (EU-OEA) and others by the Ocean Energy Systems, the Renewable UK, the European Wind Energy Association (EWEA), the Global Wind Energy Council and the International Energy Association (IEA). A few topics were selected from these reports:

These reports estimate a huge growth for ocean and offshore wind energies and point out the most crucial needs:

- To produce electricity in a reliable and cheap way in order to be able to have a competitive position in the market by 2025;
- To highlight the value chain potential for exploitation of this sector from synergies with more advanced sectors such as offshore wind, oil and gas, and shipbuilding.
- To support SMEs;
- To simplify the processes of licensing and leasing of the seabed;
- To launch market mechanisms and funding which encourages investor confidence and promotes public-private co-investment and risk sharing;
- To support R & D for demonstration, design of device systems, new materials and technologies and installation of Test Centres;
- To invest in operational support and infrastructures (ports and shipyards), implying the planning of manufacturing vessels;
- Portugal, even with increased risk aversion in this period of austerity, has one of the greatest wave power resources in Europe, which becomes attractive and inevitable for mass development on the Iberian coast after 2020;

European Ocean Energy Association (EU-OEA)	- Towards European Industrial Leadership in Ocean Energy in 2020 [19] - Industry Vision Paper [20]
Ocean Energy Systems (OES) of the International Energy Agency (IEA)	- International Vision Report [21]
European Environment Agency (ECN)	- Renewable Energy Projections as Published in the National Renewable Action Plans of the European Member States [22]
Renewable UK	- Marine Energy in the UK – State of the Art Industry Report [23]
European Wind Energy Association (EWEA)	- The European offshore wind industry – key trends and statistics 2012 [24]
Global Wind Energy Council	- Global Wind Report [25]

• Uncertainties about feed-in-tariffs, high electricity bills and level of financial support for ocean energy, which has an impact on access the financing of projects and the investor's confidence in manufacturing throughout the supply chain;

• Crescent well organized opposition of wind energy in the UK. However, opinions show that more than two thirds of the British support offshore wind.

These ideas are aligned with the EC Directives and Communications presented above. Now it's time to look at the Portuguese public policies and experts' reports. In Portugal, there are three main legislative acts to consider:

• Decision to launch the Pilot Zone in São Pedro de Moel (2008)

• National Strategy for Energy 2020 (2010)

• The more recent National Renewable Energy Action Plan (NREAP) [26]

The first one is Decree-Law n.º 5/2008 [27], which creates a Pilot Zone in São Pedro de Moel (Central Portugal) with 320 square meters aiming to test wave and offshore wind prototypes (connected, or not, to the national grid) and allowing their evolution of pre-commercial or commercial farms. The Government assigned the Pilot Zone management to REN, the Portuguese transmission system operator [28].

The second one is the National Strategy for Energy (ENE 2020) [29], launched in 2010, which assures Portuguese compliance with European policies to mitigate climate change conditions. This strategy allows Portugal to achieve, by 2020, the target of 60% of produced electricity and 31% of total electricity consumption coming from renewable sources, according to the 20-20-20 strategy. ENE 2020 stresses support in the development of innovative technologies like smart grids, wave energy and the roadmap for energy technologies and envisages further installation of 3000 MW of onshore wind subject to an increasing demand on the electricity consumption, the storage capacity, the costs of offshore wind technologies and the environment impacts of these new technologies.

Although being at a demonstration stage, wave energy is relevant to the Government due to the high potential of the Portuguese coast and the commitment to boost an industrial cluster related to marine activities. The Government has promoted a Pilot Zone to foster the development of this technology with the ambition to achieve 250 MW power by 2020.

The third one is the most recent NREAP and sets the targets and objectives to achieve in order to fulfill Portuguese international commitments related with the use of energies produced from renewable sources. Projections and incentives in NREAP 2013 for the marine renewable energy sector are less ambitious then in 2010.

This plan forecasts 6 MW of power capacity installed in wave energy by 2020 (as opposed to 250MW planned in 2010), it still presents an incentive to develop the Pilot Zone created in 2008. For the offshore wind energy, the planned power decreases from 75 MW to 27 MW (this takes into consideration the plan presented for the next stages of the WindFloat project, with a 30 M€ funding already granted by the NER300program).

The Portuguese NREAP states that although a 18% reduction in the installed capacity of renewable energy by 2020 is being planned, the share of electricity produced by renewable sources will be higher in the new NREAP (60% vs. 55%), as the global share to be achieved will be likely 35% (instead of the 31% target set in 2010).

Other Portuguese strategic decisions are also important. One is the National Strategy for the Sea 2013-2020, already approved by the Government but not yet published, which refers to the opportunity of developing energy production systems in the maritime space due to the saturation of the onshore wind capacity. The growth of this sector, in the medium and long term, will contribute to the creation of new products and services related to the industrial enhancement which will have a significant economic impact. The physical conditions of the Portuguese coastal zone will help technology improvement of floating offshore wind in the short term, as well as of wave and tidal technologies with several prototypes being tested in Portugal.

New funding schemes for the period of 2014-2020, will be set in Portugal, complementing the European ones such as the Common Strategic Framework for the Structural Funds which emphasize the support to areas like energy and environment, Horizon 2020 and the Atlantic Ocean.

Another relevant tool is the legislation related to feed-in-tariffs [30], [31]. In 2007 feed-in-tariffs for wave energy were restored after being withdrawn in 2005. Currently, the electricity remuneration value decreases with the evolution of the technologies maturity at both national and international levels. For offshore wind, there is only a tariff for the WindFloat prototype. Additionally, the Basic Law for the Planning and Management of the Maritime Space is under final discussion in Parliament.

Besides Government decisions on maritime renewable energy, a few reports shortly described below, show an increasing attention on the offshore renewable energy potential in Portugal: The Blue Growth for Portugal from COTEC,Challenges from the Sea 2020 – Collective Efficiency Strategies, coordinated by Oceano XXI (the Portuguese Cluster for the Sea Knowledge and Economy), LEME 2012, PwC Barometer for the Sea Economy and the Renewable Energy Policy Action Plan paving the way towards 2010 from APREN (Portuguese Association of Renewable Energies).

COTEC: "The Blue Growth for Portugal" [32]

Although Portugal has the largest exclusive offshore area in the EU, it doesn't have a true economic sector focused on the exploitation of offshore energy. However it is expected that in the medium term, the situation changes as there are a group of companies working in the wave energy sector, as well as offshore wind, (WindFloat) and an equally promising project of seaweed for biofuels.

In Portugal, only wave and wind have sufficient natural resources with the potential to contribute significantly to the generation of electricity and to enhance commercially viable industries.

Portugal offers important competitive advantages in the offshore wind and wave energy sectors when compared to European countries and even with worldwide, countries. Portugal can transform the wind into energy through the deployment of floating offshore wind farms, which are appropriate for the deep waters, a characteristic of the Portuguese continental shelf, as data gathered by the WindFloat project show. Moreover, at the European level, Portugal is currently one of the countries with larger onshore wind penetration, which shows a limitation on the use of the inland territory and that, in the case of abuse of that usage, will make people react against the installation of wind turbines. The opposition to this source of energy is a real concern in some European countries.

Portugal also has a long coastline, where most of the cities and the population are concentrated and therefore most of the energy consumption. This means very good grid infrastructures, ports and even shipyards, if these are used to the development process of offshore renewable energies. Moreover, the wave energy resource in Portugal is average-high at a global scale. Another advantage of the Portuguese coast is the mild climate which allows an easy access to the devices deployed for most of the year, as well as moderate maritime tides and currents which facilitate mooring and a steady permanence of floating devices on the sea.

Portugal still has a specific legislation supporting wave energy which should be extended to all offshore alternative energy sources, including offshore wind and seaweed cultivation to produce biofuels. Finally, Portugal has significant technical-scientific competences in wave and offshore wind energy, with research and development centres connected to universities, state and private laboratories, as well as to companies which have been involved in the technology development of this sector.

Oceano XXI: “Challenges from the Sea 2020” [33]

In this report, Oceano XXI presents similar ideas to COTEC. Additionally it points out other favorable conditions within this sector, like the feed-in-tariffs and the distinctive characteristics of the Pilot Zone – geographic location, dimension, geophysical aspects and access rules. It highlights several R&D institutions – WavEC Offshore Renewables, Instituto Superior Técnico (IST), Laboratório Nacional de Energia e Geologia (LNEG), Instituto Hidrográfico (IH), Instituto de Soldadura e Qualidade (ISQ), Instituto de Engenharia Mecânica e Gestão Industrial (INEGI), amongst others. It also highlights several demonstration projects carried out in Portugal – wave energy with the oscillating water column technology in the Pico plant since 2007, the AWS technology (Aguçadoura) and the 3 Pelamis devices, the floating offshore wind energy WindFloat (Aguçadoura) and Waveroller and Wavebob devices for wave energy production.

But Oceano XXI also stresses a few constraints to the development of the maritime renewable energy sector: lack of a naval industry, constant changes/fusions/extinctions of public authorities, lack of experience of some of the public licensing institutions, lack of specific national funding tools (specially within the current financial crises), unclear public perception about the weight of the renewable energy component in the electricity bill, insufficient interdisciplinary cooperation, limited Portuguese experience in innovation processes and insufficient laboratorial infrastructure for the development of marine energy technologies.

Other reports, like “LEME 2012, Price Waterhouse and Coopers (PwC) Barometer for the Sea Economy”[34], refers to offshore renewable energies as a potential contributor to the Portuguese economy in the future. The Association for Renewable Energies (APREN) presents its Renewable Energy Policy Action Plan (REPAP)[35] similar to NREAP 2010.

8.4. ACTION PLAN FOR THE OTEO PROJECT

This chapter describes what has been done so far and future actions are proposed to achieve the goals set in previews roadmaps.

The OTEO roadmap is available on the OTEO website [36] and is now summarized in this book. Although being a technology roadmap focused on the supply chain, several other areas have a strong influence here. Hence, it shall not be committed exclusively to industrial issues. Themes like public policies, funding, training and outreach actions shall be considered. Short reasons are explained below:

- Public Policies - administrative (licensing and consenting processes), regulatory and public funding mechanisms (including a reassessment of feed-in-tariffs in place in Portugal) will have a critical impact on technology action plans by private companies.

• European funding programs presented in Chapter 8.3 seem to showcase that one issue has been overcome at the EC level. So the industrialization plan may commit to innovation in new materials (new components like merging steel with concrete, for instance), in developing mass production processes and the cooperation between industry and universities. There is an obvious link to Horizon 2020 (1st calls were opened on 11 December 2013). Loans with low interest rates or grants for industrial activities (and maybe also to services rendering) must be a part of the whole value chain.

• A training and education program must begin now, starting with gathering information on human resource needs – PhDs, Masters and technicians for operational activities – with an effective cooperation between industry, universities and high schools.

• Outreach sessions for local stakeholders and population will strengthen and accelerate the implementation of marine renewable energy equipments.

A few questions posed on Chapter 8.2 with the objective of preparing a useful roadmap report have already been answered – see below - or may need further discussion:

• Which regulators and policy leaders can provide insight on factors affecting technology adoption? The policy makers are identified and will be informed about the results of the OTEO project.

• What data is needed to establish baseline conditions, set goals and targets, and prepare forecasts? One of the recommendations of this project is that data gathered and processed for the FCT project must be submitted to a larger expert audience (public and private entities) for a more comprehensive acceptance.

• Which private entities will be critical for technology success? A significant number of entities related in the supply chain were identified and several of them answered the questionnaire used in the interviews and participated in the final workshop.

The preparation of the OTEO roadmap used the findings obtained in the roadmaps referred to in Chapter 8.1:

• "Principles for a Roadmap Preparation", whose conclusions could be found in Portuguese in [1].

• "A Roadmap for Offshore Renewable Energies in Portugal - Conception, Monitoring and Roadmap's updating: Application to the Development of Marine Energies in Portugal"; the deliverables are available in [2].

Eleven themes were selected from the first roadmap and the targets associated to the vision were gathered from the second one. These topics were: Project Developers; Promoters; Manufacturing of Electric and Electronic equipment; Manufacturing of Electric Cables; Manufacturing of Mooring Cables, Anchors and Chains; Shipbuilding and Ship Repair Industry; Ports; Inland Transport and Logistics; Maritime Transports and Vessel Owners; Manufacturing of Metalworking, Machines and other equipments; Research, Development & Innovation.

The selected themes were grouped in four major areas for detailed discussion in the workshop: Research, Development & Innovation; Manufacturers, Ports and Shipbuilding; Transportation; and Project Developers and Promoters of prototypes or farms.

The conclusions were focused on opportunities and challenges and are presented below:

Research and Development

Opportunities:

The best opportunities seem to be related to marine energies and not to the development of the energy production systems. These technology and support services must be developed paying attention to other maritime activities with potential synergies and with a focus on an international perspective. Relevant opportunities were found in:

• Monitoring (operational and environmental).

- Energy resource characterization, site selection and the deployment specification of marine energy farms.

- O&M support of marine energy farms, including maritime security, inspection systems and methodologies, corrosion and cathodic protection, electric interconnection and integrated O&M support systems.

- Numerical and experimental simulation.

- Devices and farms control to improve grid efficiency and stability, including storage systems.

Challenges:

- To strengthen the cooperation between R&D centers with the objective of developing enough dimension to be a relevant player both near the EC and the major European multinationals within the sector.

- To strengthen the innovation mechanisms within the R&D centers, for instance employing qualified people in innovation management.

- To strengthen the marketing and sales mechanisms in R&D activities.

- To strengthen the consulting mechanisms between R&D institutions and private companies to improve the inter-communication and mutual understanding.

- To assure enough funding for sea activities and for the correlated support infrastructures.

Manufacturers, Ports and Shipbuilding

Opportunities:

- To leverage the existing know-how in the different sectors of the national value chain, offering project developers a package solution, aiming to create a national cluster in the marine renewable energy sector. This cluster shall promote the international visibility of Portuguese companies.

- This sector, being quite new, may allow Portuguese companies to be active players on the standards and technical specifications' updates for projects in the sector.

- To use the available funding tools to develop innovation/reengineering projects for products and services needed in the sector.

Challenges:

- The offshore renewable energy sector has steadily evolved in North European countries, while in Portugal it has, in some ways, stalled its contribution to the national added value in this sector.

- Major companies in Portugal, like EDP (WindFloat's promoter) and REN (in charge of the Pilot Zone) must play an important role in the promotion of this national cluster, using national know-how and skills during the implementation of their projects.

- Entities like EnergyIN shall lobby with public authorities to allocate part of the new funding tools (like those related to Horizon 2020), to provide conditions for Portuguese companies to be more competitive in this sector (for instance, through the development of innovative products).

Transports

Opportunities:

- Regarding transports and ports logistic, there is the need for a well-considered analysis for investment purposes. The offshore renewable energy market doesn't have enough maturity to allow companies rendering services, suppliers and ports, to consider making high risk investments due to the lack of information regarding their return.

- Although marine renewable energies show a relevant economic potential, the risk level associated to the sector is a strong inhibitor to the investment needed from companies to play a role in the supply chain.

- However, the significant development of the on-shore wind sector incorporates a vast and deep know-how which may be transferred to the off-shore wind sector.

- The investment in the development of vessels like the Bourbon's (used in the WindFloat deployment) would hardly make sense because it is too specialized.

- There is a relevant job creation potential.

Challenges:

- The main challenge for the development of the whole supply chain is the consistency and credibility of the marine renewable energy projects.

- To establish reliable and achievable sets and milestones is a major contribution factor to leverage the marine renewable energies.

- There are no appropriate vessels in Portugal for the deployment and transport of platforms like WindFloat. However, a growth of the sector would result in additional requirements for support vessels' innovation in the long-term and Portuguese companies will commit themselves to make investments in this sector.

- In case of an emergency, the current maintenance response processes may demand a deep reflection over the applied methods of the marine renewable energies sector and the maritime sector in general.

- There is a strong need for the qualification and training of technicians.

Project Developers and & Promoters

Opportunities:

- Development of new vessels for O&M

- Definition of new public policies which foster the next European frame program for offshore renewable energy.

- To launch driving projects.

- Pilot Zone – The access conditions have not been published yet, so the regulatory regime still contains gaps and subsequent normative acts which have not been determined, therefore, harming the need for a clear and unequivocal definition of the activity expected within the offshore renewable energy sector.

- Barriers for sector development with Environmental Impact regulations.

- To set priorities, in case of conflicts of use in the maritime space.

Challenges:

To set conditions that foster investment, offering incentives that protect national economy through:

- Resource Mapping.

- Simplicity in the licensing processes, namely in the demonstration projects.

- Public policy stability.

- To enhance the Portuguese natural conditions (resources, ports and grid close to the coast).

- To assure the confidentiality of data gathered by private companies.

- To set incentive programs for R&D, to make prototype tests in laboratories, etc.

- To create highly qualified technology infrastructures.

- To review the feed-in-tariffs and their time frame.

8.5. CONCLUSIONS

WindFloat, a very promising 2 MW floating offshore wind technology, has been tested in Portugal. Over the course of two years the device has produced 8 GWh. The total cost of this demonstration project, installed in Aguçadoura (North of Portugal), was 23M€. 60 companies were involved in the manufacturing, installation and deployment steps. 40 of them were Portuguese, to whom 50% of the project costs were awarded. The next phase of the project will have 5 devices with a total of 27 MW installed capacity; funding is already assured by the NER300 program.

In 2011, as detailed in Chapter 8.3, the EC, through Horizon 2020, focused its attention on innovation and, with the Roadmap 2050 for Energy, showed the strong need for public and private support in renewable energies, namely the offshore wind and ocean energy, in order to avoid being subsidized and aiming at becoming competitive in the market. In 2012, priority was given to the research of offshore wind and wave energy and to boost investors' confidence; the NER300 program was presented as a good example of success. It was stated that, in Europe, offshore wind power will overcome onshore wind power by 2030. Finally, work must be done on the cost reduction of new technologies – amongst which floating offshore wind and ocean energy are very promising, although only a few will be mature after 2020. Measures shall be taken to foster the investment in the renewable energy value chain and to call the attention of the public, authorities and private leaders. The EC announced the launch of an Integrated Roadmap by the end of 2013 and also that Member States will develop an action plan until mid-2014 to fit this roadmap. The Atlantic Strategy action plan will exploit and promote offshore wind and ocean energy, reinforce synergies between offshore and onshore energies, develop multiuse platforms and contribute to maximizing renewable energy production in the outmost regions.

International reports produced in 2010 and onwards, highlight Europe's need to support the supply chain in areas such as manufacturing, innovation and synergies. Another focus will be the research in R&D and in test infrastructures like EMEC in Scotland. They point out that Portugal, even though currently facing an austere and risk aversion period, has a very good wave resource, making mass-market deployment inevitable and refer to UK, where offshore wind power will raise up to 18 GW against 13 GW for onshore wind by 2020. These reports draw attention for abrupt changes in the tariff policies in several European countries which lead to uncertainty and undermine the investors' confidence in these technologies as well as inside the value chain.

Still in Chapter 8.3, and looking at the Portuguese public policies for the marine renewable sector, three decisions were highlighted: the launch of the Pilot Zone in January 2008 - although without published regulation yet, the national commitment to achieve Europe 20-20-20 targets and the NREAP 2013 (with 6 MW for wave energy and 27 MW for offshore wind by 2020). The National Strategy for the Sea, already approved and to be published shortly, also emphasizes the positive physical conditions of the Portuguese coast for the exploitation of marine renewable energies and calls for the creation of funding tools complementary to the European ones, in order to support the sector development. The existence of feed-in-tariffs for wave energy and for WindFloat prototype is also worthwhile refering too.

National reports highlight the competitive conditions Portugal offers, like good wind and wave resources and the jurisdiction over a huge maritime space which may be used as a complement to its inland territory, almost saturated with wind turbines. But they also emphasize the very wide, interconnected grid by the coast, where 75% of the population lives and good ports and shipyards are available. Portugal also has adequate legislation and several scientific institutions specialized in this sector. Nonetheless, Portugal doesn't have a true economic sector focused on the exploitation of marine renewable energies. It lacks a culture of innovation in the industry, as well as knowledge within the licensing entities and the public in general and specific funding sources.

As stressed above, in the last six years, the EC outlook on the energy, the sea and the industrialization in Europe has evolved significantly. The speech has changed from the need to acquire knowledge about ocean resources and to create jobs up to focusing on innovative commercial products and to launching funding mechanisms especially in supporting emerging technologies.

Moreover, the EC strongly fosters innovation in this area, focusing on the investment of the development of products with commercial potential but still funding research on immature technologies (as in wave energy prototypes, due to the associated high risk for technology developers). The EC also stresses its attention on the development of offshore wind platforms, advanced materials, manufacturing industry and electricity storage.

One of the OTEO project goals was the preparation of a roadmap that presented priority lines and concrete measures to influence the Portuguese development of the sector, in particular the supply chain. To achieve this, a significant number of stakeholders related to the supply chain were identified and several of them answered the questionnaire used in the interviews and participated in the final workshop, following the IEA's roadmap methodology (described in Chapter 8.4). Previous Portuguese roadmap projects which focused on the vision for the sector and that promoted further discussions in different workshops with public and private participants, have now had continuity.

The fourth step of the IEA roadmap concept is the implementation phase. However, the outcome and conclusions of these interviews and workshops need the approval of the Portuguese Government and their strong commitment to launch the roadmap and to implement measures which give answers to those conclusions and to draw full benefit of the results obtained.

Considering the technological state of the art (installed power, potential saving costs on energy imports and on the production cost, efficiency, etc.), who is going to be the OTEO roadmap leader in the implementation stage?

If these problems were solved, the roadmap monitoring and revision must be put in place to guarantee the success of the established targets. The "Roadmap for Offshore Renewable Energies in Portugal - Conception, Monitoring and Roadmap's updating: Application to the Development of Marine Energies in Portugal" has created tools which allow for the fulfillment of this purpose, helping to adjust to national public policies if the targets were not reached.

For countries with enough funding resources which may attract the market and foster technology development and implementation, the involvement of external sectors is not critical. But in the Portuguese's case, to achieve the roadmap targets, it is crucial that both the public and private sector share responsibilities. Neither one nor the other have technical competences or funding resources needed to research, develop, implement and monitor the technological progress alone. The participation of a large number of experts, with a broad expertise, in the interviews and workshops of the OTEO project, seems to be vital to assure a strong support for its implementation.

The report"Desafios do Mar 2020 – Estratégias de eficiência coletiva" (Sea Challenges 2020 – Strategies for collective efficiency), published by Oceano XXI[33], the cluster for the knowledge and economy of the sea, proposes that several projects and structural measures should be put in place in order to develop the sector, namely: a competence center for the training, conception and implementation of marine renewable energies, a multi-use demonstration site in the Pilot Zone, the offer of incentives for the installation of different wave and wind energy demonstration farms, building an experimental Portuguese offshore platform, developing competences related to the conception of an offshore grid, ports and shipyards, adaptation to the new mass production processes of renewable energy devices and components (in a close cooperation with the shipbuilding industry), the assessment of the marine renewable resources and the mapping and characterization of the licensed areas.

The European SET Plan, in 2007, didn't make any reference to marine renewable energies. Only in 2011, through the Atlantic Strategy and the Roadmap 2050 for Energy, was it recognized by the EC, that floating offshore and wave energy needed to start to get strong support from public and private entities, allowing these two technologies to become competitive.

The OTEO project sets as a strategic goal to achieve a deep national and international knowledge of the offshore energy technologies and the co-related support technologies, to foster the Portuguese competitiveness and the entrepreneurship of this sector. The aim of the OTEO project analysis was to develop accurate information on the current status of the supply chain (suppliers, distributors and customers), number of companies, size of the market and number of participants. It should also include information on the factors which are likely to affect the structure of the market and its participants, as well as a summary of forecasts, projections and expectations for the market sectors or segments.

One of the conclusions was that the OTEO roadmap would not be committed to industry issues only. The success of technology development and implementation depends on the actions taken by a variety of key stakeholders like scientists, project developers, entrepreneurs, funding organizations and community leaders. It became obvious along the OTEO project that public policies should be analyzed to develop accurate information on the current status and requirements of existing laws, regulations, policy directives, public funding mechanisms (including a reassessment of the current feed-in-tariffs scheme in Portugal) and other rules which affect the technologies and markets in the roadmap. The situation analysis for public policies should also include information on trends that are likely to lead to new policies or to prevent policies from being enacted. A training and education program must begin now, starting with the gathering of information on human resource needs – PhDs, Masters and technicians for operational activities – with an effective cooperation between industry and universities and high schools.

Therefore, one relevant objective of this proposed roadmap is to help politic authorities make decisions and foster the private sector to commit to the targets set in the vision. Considering the goals defined by the SET Plan and the Roadmap for Energy 2050, at the European Community level and the NREAP, at a national level, the references for the roadmap will be 2020, 2030 and 2050.

To achieve the roadmap objectives it is vital to put into place a set of actions which answer to the priorities that were the main outcome of the project - in the areas of technology demonstration, improvement of public policies, regulatory changes and financing commitments.

A few themes, positive and negative, were emphasized in the OTEO final workshop:

- Positive: good Portuguese knowledge and skills in almost all components of the supply chain; the potential for the development of new sectors beyond the industry sectors already involved in the WindFloat's installation and deployment phases; the new clusters in the sector; the ports and shipbuilding industry which may achieve new opportunities in joint efforts and capacities; CAPEX and OPEX assessment for floating offshore wind; new industry materials for the device components and the foundations; and the Pico Plant in the Azores Islands as one of the Portuguese test centers.

- Negative: difficulties on gaining access to test facilities for different TRLs; funding concentrated mainly on mature technologies; the implementation delay of the Pilot Zone in São Pedro de Moel; the complexity of licensing and permitting procedures; the location of the industry facilities; the lack of specialized human resources; the roads dimension; and the investment needed in R&D and Innovation.

So, simply writing a roadmap is not enough – the true measure of success is whether the roadmap is or not implemented and if it achieves the organization's desired outcome. The OTEO roadmap is now formally launched. The critical outcome is willingness amongst those responsible to acting upon its recommendations. The roadmap intends to be used primarily to guide the national government's decision making but also to engage the private sector in achieving the stated goals.

As been said, Portugal is already competitive in the marine renewable energy sector. The most recent EC Directives and Communications have driven enough conditions to allow Portugal to overcome all constraints and mitigate the barriers highlighted by national reports and the OTEO project. On top of this, the possible combination in the same project of Horizon 2020 with other structural funding programs, provide additional support to the sector.

A strong dissemination plan will keep going after the end of the OTEO project, using this book, the website and newsletters from several stakeholders. Moreover, the OTEO project leaders are willing to present it to the Portuguese Government, namely the Ministers with authority in Energy, Sea, Economy and Science.

A common vision with the Government will allow the enacting of the appropriate legislation, to place Portugal as an important player in the global marine renewable energy market, attracting foreign investments and contributing to Portuguese exports. But the private sector must also play a significant role, namely EDP and REN which can leverage a maritime renewable energy cluster, offering opportunities to the Portuguese SME companies abroad.

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CONCLUSIONS

9

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To understand the future relevance of Offshore Renewable Energy (ORE) we need to look wider. Wider into the world's energy system, wider into ocean development and wider into the world's socio-economic development. In an increasingly economic, environmental and social integrated world it is essential for Portugal to look wider in order to figure out what are the alternatives and challenges to be addressed, when and how.

The world population in the early fifties was in the range of 2.5 billion inhabitants and the average power consumption per capita was close to 1 kW. Today the world population is around 6.7 billion and the average power consumption is about 2.5 kW. In 2050, the lifespan of some people, the world population will be around 9.2 billion and the consumption per capita could be around 3 kW. The dramatic increase in world population and the access of a larger share of this population to energy commodities, results in an increase of world annual energy (and average power) consumption by a factor of 10 in this time interval, as shown by the green curve on Figure 9.1 obtained from the EIA World Energy Outlook 2011[1] .

This plot also shows another very relevant point: the energy sources available to mankind and their possible contribution to the energy supply requirements according to the BP - Statistical Review 2013 [2] (for oil, gas and coal) and the Energy Watch Group "Uranium Resources and Nuclear Energy" [3] (for uranium). The areas of the geometric figures (a rectangle with a triangular end) represent the energy which is possible to produce using the "known" energy sources that can be exploited using the present (2013) technology and costs. The height of the geometric figures is defined by the present share of each energy source.

It is obvious from Figure 9.1 that there is a very significant energy supply problem, even if the "known" energy sources potential are wrong by a factor of 2 (even if the shale gas is expected to impact at the world level, the size of this impact is limited since it is in the order of magnitude of the conventional gas impact). It is also clear that this energy supply problem is something that we may need to face relatively soon, indeed within the lifetime of the younger part of the world (and Portuguese) population. We may conclude that we need to develop every energy source which may be possible to use, even if some may turn out to be a bit more expensive than others (as in-

1 This plot is an update from a similar plot taken from the "The World Energy Problem", a presentation by Miguel Golden de Sousa Prado (see e.g. www.wavec.org) [5].

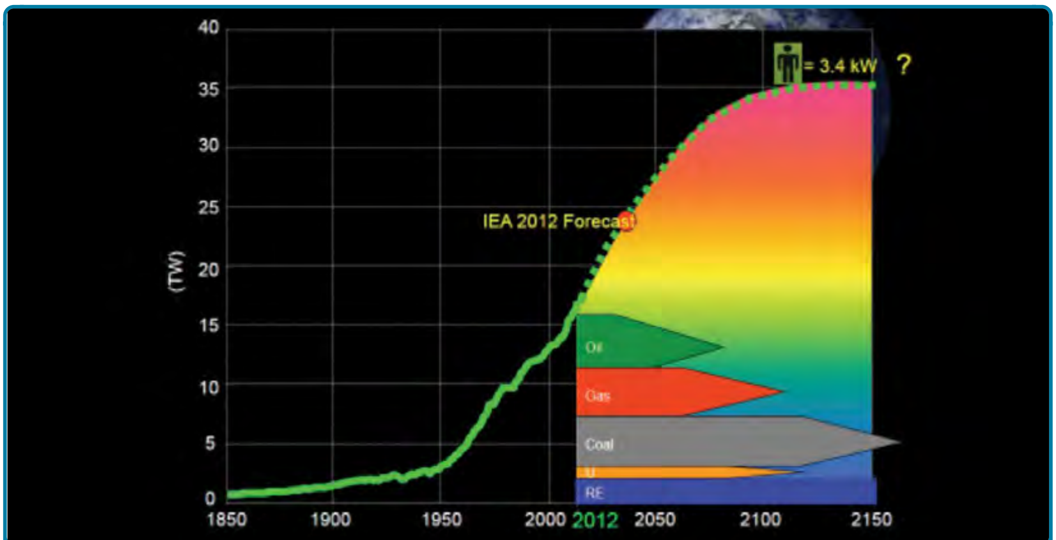

Figure 9.1 – World power consumption and energy supply [1].

deed it already happens today with some energy sources being more expensive or intrusive or less environmental friendly than others). The impact of an energy supply shortage will be a slow increase of the average cost of energy with more or less relevant short-time price fluctuations, due to shortage of energy exploitation, transportation or processing infrastructures. Europe and in particular Portugal, is within the geographies which are most exposed to these price fluctuations, due to its dependence on external energy supply.

Another well-known impact of fossil fuels and nuclear electrical energy, are their environmental impacts, even if of different nature. Even if the discussion of the fossil fuel impact on climate change is still open, it seems irresponsible not to take measures, that at reasonable costs contribute to reducing the risk of climate change.

Renewable energy integration in the energy system is aligned with the two previous concerns: security of energy supply and climate change mitigation. Furthermore they contribute to local job creation and economic growth and to the stabilization of the energy cost, as its costs are less dependent on external factors. This is why a significant increase of renewable energy is taking place in the world as shown in Figure 9.2, with the developing countries being responsible for about 46% of the total investment, of which China is responsible for about 25% of the total investment.

As mentioned in Chapters 1, 2 and 3, there are many forms of Offshore Renewable Energy (ORE) as shown in Figure 9.3, where the theoretical potential of the different sources and the total world energy consumption are shown. Even if only a small percentage (typically in the order of 10%) of the theoretical resource can be converted into electricity, it still is a very relevant contribution, in the order of the total world electricity consumption.

Hopefully it is now clearer why ORE should be developed, even in a time of financial crisis when money is less available and the willingness to take risk is smaller. They have the potential to contribute to the security of energy supply, to mitigate the climate change and to create local jobs and economic growth. Moreover, ORE has other potential impacts which are relevant everywhere and in particular to Portugal: they contribute to develop ocean economy, by: i) developing innovative enabling technologies (the topic of Chapter 4) with potential to be used in other ocean based applications (fish farming, ocean mining, ocean monitoring, etc.); ii) bringing to the ocean economy sector companies from the energy sector, that otherwise would not be part of it and iii) contributing to developing infrastructures (support vessels, etc.) also relevant for other ocean economy uses.

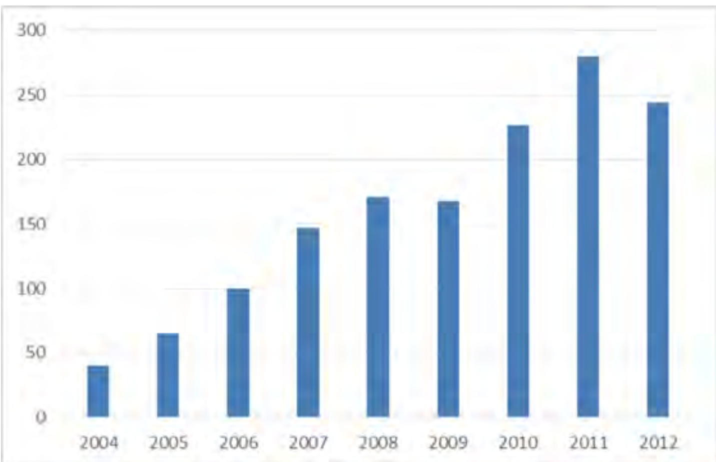

Figure 9.2 – Global new investment in renewable energy [4].

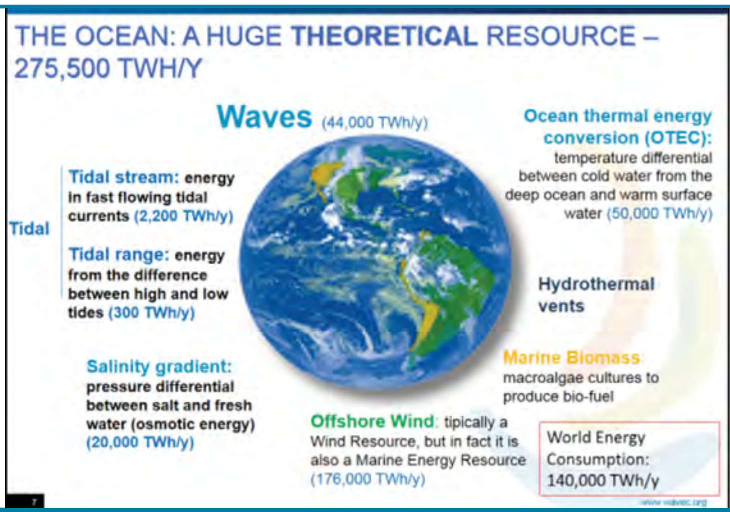

Figure 9.3 – Offshore Renewable Energy sources and its theoretical resources.

As mentioned in Chapters 1, 2 and 3, Portugal's interest in ocean energy started in the middle seventies of last century with R&D activities at IST and a few years later at LNEG. This research activity led to the construction of the wave energy plant on Pico Island, Azores, in a joint effort of the two previous organizations, EDP and EDA. The fifteen year old Pico plant is at present owned and operated as a demonstration plant by WavEC Offshore Renewables, a centre dedicated to the development of ORE created in 2003 by the association of several companies and R&D bodies. With the turn of the century, the demonstration activities in Portugal at sea increased: the AWS in 2001-4, the Pelamis in 2007-8, the Waveroller from 2008 onwards and the WindFloat from 2012 onwards. Relevant public policies also took place in Portugal, namely the setting-up of the first feed-in tariff for wave energy in 2001 and the creation of the wave energy pilot zone announced in 2007 and published in 2008. These two policy measures were responsible for bringing to Portugal four demonstration projects approved under the FP7 program in the second half of the first decade of the 21st century, even if only the Surge project (Waveroller) was developed in Portugal (a second one was moved to Spain and the other two were cancelled by the corresponding consortia). The relevance of the appropriate public policies, partly the subject of Chapter 8 of this book, is well illustrated with the above examples.

The recognition that ORE offers a very important development opportunity to Portugal moved INEGI, WavEC and EnergyIN to propose and develop the OTEO project. The project aims at fostering the national know how on ORE technologies and enabling technologies, in an international environment, in order to promote entrepreneurship and competitiveness in the Portuguese industry, by addressing a large number of important factors, which are covered in the present book:

1. The state-of-the-art of ORE technology (Chapter 3) and market (Chapter 4), including a review of past projects, their success and failures, the market and technology challenges and possible routes for success. The analysis show that offshore wind energy is progressing well, both in terms of market and technology, in particular for fixed foundations, the solution for shallow waters. Recent development of floating foundations, of which the WindFloat technology is a good and successful example, is progressing well, but still at a demonstration phase and a way to go mainly in cost reduction. Tidal energy is in a similar phase as floating offshore wind, as the technology seems to have stabilized in horizontal axis two or three blade turbines but still several open technology solutions, namely fixed or floating foundations, upstream or downstream turbines, etc. Tidal turbine demonstration plants have shown the ability to work continuously for extended

periods under real ocean conditions and as a result there is a significant involvement of large industrial companies and utilities with the first demonstration farms in the pipeline. The main challenge and uncertainty for tidal energy is on the deployment and O&M methods. This is also an open area for wave energy. However wave energy technology has not yet stabilized with several alternative concepts still under development and no single demonstration prototype showing to be sufficiently reliable to operate continuously in the real ocean environment. As a result, wave energy technology and market are clearly less mature. OTEC and salinity gradient technology and market are slightly less developed than wave energy. A small number of small OTEC and Salinity Gradient demonstration projects have been developed with limited results, even if larger OTEC projects have been announced. An alternative approach for OTEC is its application for thermal energy (district heat and cooling). Offshore Macro-Algae cultivation for biofuels is also an area which has grown interest. Whilst macro-algae cultivation is a common practice in some countries, its competitive large scale development requires the development of techniques and technology that is now taking place in the laboratory and at sea. Macro-algae for bio-combustible which is therefore in a phase that is not very different to wave, OTEC or salinity gradient technologies (and market).

2. Enabling technologies for ORE is also a very relevant issue addressed in Chapter 4. Enabling technologies are those support technologies needed for moorings and electrical connections, deployment, operation and maintenance. Most of the enabling technologies being used in ORE are based on the power industry (gears, hydraulic equipment, air and water turbines, gears, etc.) fixed foundation offshore wind (in particular for electrical connections) and oil and gas industries (moorings, anchors, standards and certification, support vessels, analysis tools and model testing, etc.). However significant differences exist, namely in respect to the oil and gas industry: they need to be cheap and reliable, in many cases accept significant motions, be prepared for a very intense fatigue cases due to the inversion of the loads at a rate of 3 million cycles per year, etc. The enabling technologies sector is particularly interesting for Portugal: as they are, to some extent, less dependent on the specific ORE to be used the uncertainty in the technology development route is smaller (in particular if we take wave energy) when compared to the development route of the specific ORE technology; however, as there is no oil and gas industry neither fixed foundation offshore wind in Portugal, there is little experience to support the specialization of the Portuguese industry in this area.

3. The last four chapters of this book deal with relevant aspects related to the industrialization of ORE, namely in Portugal: market development (Chapter 5), supply chain issues in general (Chapter 6) and in Portugal (Chapter 7) and roadmap definition and implementation (Chapter 8). For companies to invest in ORE they need to see a market opportunity. Thus it is particularly relevant for companies to understand the stage of development of the ORE market and how this is expected to develop in the forthcoming years, as well as how they are or can be positioned in this market. Market development depends on the present and future costs of ORE and on the existing and future public policies. But to setup the appropriate support public policies. a good understanding of the socio-economic benefits of ORE for the EU and the different member countries is required. One such benefit is energy production but another very important one is job and wealth creation and this is determined by the quality and involvement of the local supply chain. Therefore, there are two relevant questions related to the supply chain: i) how can we maximise the revenue from the supply chain; ii) how can we guaranty that there is no shortage or excess of supply chain capacity. Identifying a vision for ORE development and the actions which need to be developed to attain this vision, is the role of the roadmap. The conclusion drawn from Chapter 8 is that, the roadmap is a process with well-known rules which needs to be inclusive in order to be widely accepted and recognized. Two other important aspects for the Portuguese roadmap are the need to attract foreign investment and the need to put in place the actions which are identified in the roadmap. The delay in the development of the ORE pilot zone is a matter of great concern and

an alert for the success of ORE implementation in Portugal.

Summarizing, Portugal has a very long coast, with an enormous ORE potential, both in terms of energy production and job and wealth creation. This was recognized many years ago and a number of important actions from R&D organizations, companies and public authorities have been taken. The financial crisis and some oscillation on the willingness to move ahead (feed-in tariff for wave energy and implementation of the ORE pilot zone, retraction in private investment) somehow induced by the limited success of some early projects (namely the Pico, AWS and Pelamis projects) need to be balanced by a clear vision on how to address the ORE opportunity for Portugal. The OTEO project proposes the following routes:

1. Setting up clear support public policies able to attract national and foreign investment (this requires a good understanding of what others are offering and of our strong and weak points), namely:

Clear and attractive feed-in tariff;

a. Simplified and clear licensing and permitting processes;

b. Identification and characterization of areas suitable for ORE deployment;

c. Easy access to relevant data on the areas for deployment.

2. Support the development of knowledge, know-how and specialization based competitive supply chain capable of capturing the high added-value components and services of this new industry;

3. Active participation in the EU and international initiatives on ORE.

The development and implementation of such a strategy requires the will and intelligence of many stakeholders. INEGI, WavEC and EnergyIN are aligned in their willingness to cooperate with each other and with all other stakeholders in such an effort.

9.1. REFERENCES

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OFFSHORE RENEWABLE ENERGY

CURRENT STATUS-FUTURE PERSPECTIVES FOR PORTUGAL

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