Marine Energy

Highlights

■ **PROCESS AND TECHNOLOGY STATUS –** Ocean energy encompasses a number of very different technologies that exploit a diverse range of marine energy sources including: ■ Wind-driven waves; ■ Tidal ranges (tidal barrage); ■ Tidal stream (marine currents); ■ Marine salinity gradients; and ■ Thermal gradients between warm surface water and deep (> 1000 m) cold water (also called ocean thermal energy conversion, OTEC)

■ **COSTS –** Most marine energy technologies are in an early stage of development, under demonstration, or have a limited number of applications and commercial installations. As a consequence, their performance and costs vary significantly, depending on technology options, sites and local resource conditions. The investment cost of tidal stream power is currently between \$6,000 and \$7,800/kW_e (US\$ 2008), and is projected to decline to \$5,000/kW_e by 2020, and to \$4,100/kW_e by 2030 as a result of technology learning and larger deployment. The investment cost of wave power is between \$6,800 and \$9,000/kW_e and it is expected to be reduced to \$5,700/kW_e by 2020 and to \$4,700/kW_e by 2030.

■ **POTENTIAL & BARRIERS –** In principle, the potential of marine energy is huge, but the economic potential is much more modest due to current high technology costs. Because of insufficient experience and demonstration, there is a lack of information and understanding regarding performance, lifetime, operation and maintenance of technologies and power plants. For example, the impact of the aggressive marine environment on materials and components, and the consequence on plant lifetime must be established. Significant research investment is still needed as well as government support for market deployment. Policy incentives such as feed-in tariffs may help initial deployment and cost reductions of these technologies by providing improved market certainty.

PROCESS AND TECHNOLOGY STATUS – Ocean (marine) energy includes a diverse range of energy resources and a number of technologies. The energy resources include: ■ Wind-driven waves; ■ Tidal ranges (tidal-range barrage); ■ Tidal stream (marine currents); ■ Ocean thermal energy (conversion), OTEC; and ■ Salinity gradients. Technologies to exploit OTEC and salinity gradients are not addressed in this overview as they presently have a lower level of R&D focus worldwide. Most ocean energy technologies consist of new concepts under demonstration. Power generation from tidal-range barrages is the most known and proven marine technology that has been working reliably in a small number of power plants with a combined capacity of about 500 MW_e (including the 254-MW_e Sihwa tidal barrage in South Korea). Marine wave and tidal stream technologies are in a stage of development similar to that of the wind industry in the 1980s, and commercial systems could become available between 2015 and 2025 (SEI, 2005).

■ **Wave power** - Wave power generation is based on the exploitation of the wind-driven wave energy. The best wave conditions for wave power are found at higher latitudes (away from the equator), with typical conditions of a deepwater power density of 60–70 kW/m of wave crest length declining to 20 kW/m near the shore (Figure 1). About 2% of the world's 800,000 km of coastline exceeds a power density of 30 kW/m, with a technical potential of about 500 GW_e based on a conversion efficiency of 40%. The United States alone holds a technical potential of approximately 100 GW_e (PG&E, 2009), the United Kingdom has an estimated

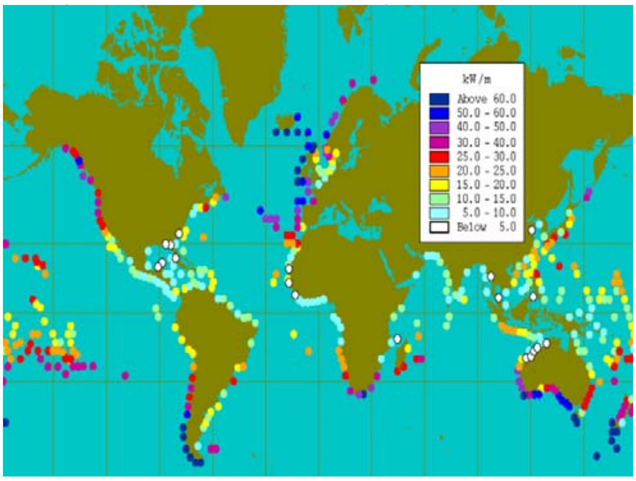

Fig 1 - Global Wave Energy Flux Distribution (Hagerman, 2005)

potential may be well below the technical potential (IPCC, 2007). There is a variety of wave energy technologies, resulting from the different ways in which energy can be absorbed from the waves, and depending on plant location (shoreline, near-shore, offshore) and water depth. A recent review (Falcão, 2008) identified about 100 projects with various working principles and different levels of development. On the basis of the working principle wave energy projects can be grouped as: **a) Oscillating Water Column** (OWC) systems, which use a pneumatic chamber and air turbines (Figure 2), and include onshore plants (e.g. Pico Plant in Azores, www.pico-owc.net and Limpet), near-shore plants (e.g. Mutriku,

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Basque Country) (Internet Source 1), and floating devices (OE Buoy, Oceanlinx, Australia, www.oceanlinx.co); **b) Oscillating Body** systems, which include multiple (rotation) bodies (e.g. Pelamis project, Portugal), point absorber devices (heave motion, e.g. AWS, Columbia Power Technologies, Ocean Power Technologies); surge devices such as Oyster (Henry et al, 2010; Internet Source 2), and AW-Energy's devices (Internet Source 3); **c) Overtopping Devices** that are based on the use of a water reservoir and water turbines (e.g. Wavedragon and Waveplan) (Internet Sources 4-5).

Some ongoing projects, along with companies involved, are briefly illustrated below. ● **Aquamarine Power** (UK) is testing the 315 kW$_e$ Oyster® power device at the European Marine Energy Centre (EMEC) in the Orkney islands (UK) and is developing the 800-kW Oyster II device (Internet source 2). ● **AWS Ocean Energy Ltd** (UK) has developed the Archimedes Waveswing™, a fully submerged wave converter with a linear generator, which has been demonstrated in 2004 in Northern Portugal (Internet Source 6). The company is now pursuing the development of the 2.5 MWe AWS-III device, a surface-floating wave power system. Along with Columbia Power Technologies (US) and Ocean Power Technologies Inc. the company has also developed a 250 kW$_e$ point absorber wave device with a permanent magnet linear generator buoy to be anchored to the sea floor (Figure 3, Internet Sources 7-9). ● **Ocean Energy Ltd** (Ireland) has developed a floating platform with a turbine for use in water depths of 30–50 m based on the oscillating water column concept (Internet Sources 10-11). ● **Ocean Power Technologies Inc.** (US) has developed the PowerBuoy® device, which testing phase started in December 2009 at Kaneohe Bay (Hawaii) and has also been carried out at EMEC (UK). Nine PowerBuoy device with a capacity of 150 kW$_e$ each and a total capacity of 1.39 MW$_e$ will also be installed 5 km off the Santoña coast, in Spain (Internet Sources 12-13). ● **Pelamis Wave Power Ltd** (PWP, UK) has developed a 750 kW$_e$ Pelamis module, for mooring in a 50–70 m deep water at 5–10 km from the shore. In August 2008, three Pelamis (2.25 MW$_e$) were installed and successfully tested for 3 months in Agucadoura, Northern Portugal (Figure 4). PWP is now working at a 2nd generation device that is currently (2010) being tested at EMEC (UK) and could be followed by four modules with a capacity of 3 MW$_e$ (Wise, 2008; Internet Sources 14-17). ● **Voith Hydro Wavegen Ltd** (UK) developed Limpet, an oscillating water column (owc) device for near-shore applications where the owc feeds a pair of counter-rotating turbines driving a 250 kW$_e$ generator, with a total capacity of 500 kW$_e$ (Heath, 2007; Internet Source 18). Major energy companies and utilities often provide financial support to the demonstration of various wave energy technologies. For example, Vattenfall supports the Pelamis project and the Wavebob project, the latter being an axi-symmetric, self-reacting point absorber (Wavebob Ltd, Internet Sources 19-20). According to Rodrigues (2005), if issues such as material corrosion, and implications for fishing are addressed, wave power could become commercial around 2020, with an estimated investment cost of €5,000-6,000/kW (€$_{2005}$), and a potential capacity of about 7000 MW$_e$.

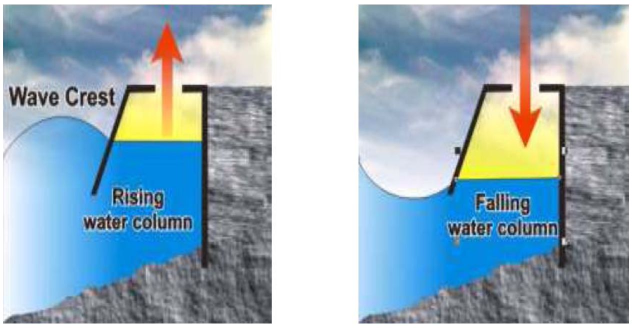

Fig 2 - Oscillating water column concept (Mueller et al, 2007)

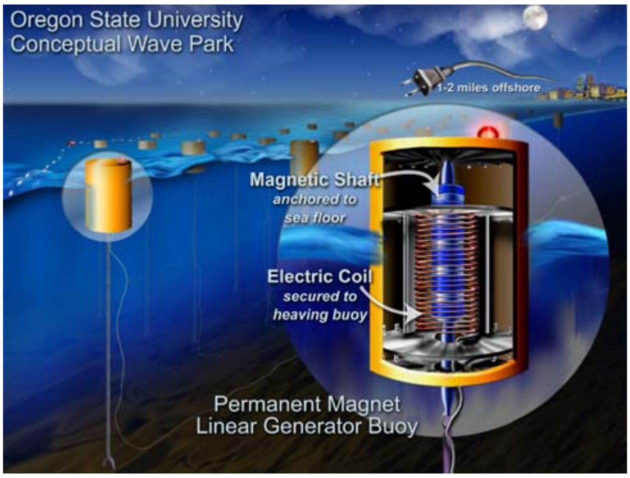

Fig 3 - AWS point absorber generator concept - Oregon State University (I-Source 9)

Fig 4 – A 750 kWe Pelamis unit, Aguçadura, Portugal (I-Source 15)

■ **Tidal power** - Tidal power is based on two technologies, namely tidal barrage power and tidal stream power (i.e. marine currents). **Tidal barrage power** is a relatively well known technology based upon capturing seawater with a barrage when the tide is high, then letting the water flow through hydro-turbines when tidal is low. There are also alternative operation modes. Unfortunately, the number of coastal sites where tidal barrages are economically and environmentally feasible is very limited. This is because a mean tidal range of at least 4.5 m is required for economical operation (Internet Source 21). For example, it has been estimated (SDC, 2007) that a tidal barrage at the Severn site in the UK could provide an electrical capacity ranging from 2.0 GW_e up to 8.6 GW_e under the most favourable assumptions. However, environmental concerns may pose an obstacle to the realisation of the Severn barrage (Internet Source 22). As a matter of fact, at present there is only a small number plants in operation worldwide, with a combined capacity of roughly 500 MW_e (including the 254-MW_e Sihwa tidal barrage in South Korea). An indicator of the cost effectiveness of a tidal barrage power plant is the Gibrat ratio, i.e. the length of the barrage (meter) to the annual energy production (kWh) ratio: the smaller the Gibrat the better the investment. For example, the Gibrat ratio for the current tidal power plant at la Rance (France) is 0.36, whereas the Gibrat ratio for the planned tidal power plant at the Severn (UK) would be 0.87 (Soriano, 2008). Based on the Gibrat ratio and other indicators and considerations, the global potential of tidal barrage power plants has been estimated at approximately 60 GW_e, with an electricity generation of about 150 TWh/year (Gorlov, 2001). **Tidal stream power** can be considered as a technology under demonstration (see Figure 5). ● In 2003, **Hammerfest Strøm** (Norway) installed the world's first 300 kW tidal turbine prototype in Kvalsundet, off Hammerfest. In 2007, the company signed an agreement with Scottish Power for further development of the technology (Internet Sources 23-24). Also, since 2003, the Italian company Ponte di Archimede has installed the 25-kW_e pilot Kobold plant (consisting of vertical axis turbines) in the strait of Messina, between Sicily and the Italian mainland (Internet Source 25). ● In 2006, **Verdant Power** (US) started the Roosevelt Island Tidal Energy project in New York City's East River. Phases 1 and 2 of the project involved testing and demonstrating a 35-kW_e *Kinetic Hydro Power System* (KHPS) prototype (Figure 6). The 3rd phase, includes scaling-up the prototype to the MW-size (Internet Source 26). ● In 2008, **OpenHydro** (Ireland) installed a 250-kW_e prototype at EMEC in the UK (Internet Source 27) and **Tocardo** (the Netherlands) demonstrated a 45-kW_e turbine, with a direct drive, 2-bladed rotor at Afsluitdijk (Internet Source 28). ● **Marine Current Turbines Ltd (**UK) installed a 1.2 MW_e SeaGen tidal stream unit at Strangford Lough (UK). The next phase of this project includes the installation of seven 1.5-MW_e SeaGen turbines with a total capacity of 10.5 MW_e near the island of Anglesey, also known as The Skerries (Figure 7; Internet Sources 29-30). ● In 2009, **Fri-El Green Power** has started testing a 500-kW_e tidal stream pilot plant (i.e. Fri-El Sea Power) in the Strait of Messina (Italy). The *Sea Power* device has been developed for either power generation from tides, oceanic circulations or for exploiting natural flow water streams (Figure 8; IEA, 2010; Internet Source 31). Also in 2009, **Lunar Energy Co** (UK) has started the tests of a 1 MW_e submersible turbine placed on the seabed (i.e. the Rotech Tidal Turbine, RTT – Figure 9). Lunar Energy is reported to supply 300 turbines, with a combined capacity of 300 MW_e to the Korean Midland Power Company (KOMIPO) for installation off the South Korean coast by 2015. Another unit is due for testing at EMEC (Internet Source 32). It has been estimated that on a global scale tidal stream power could provide some 800 TWh/year.

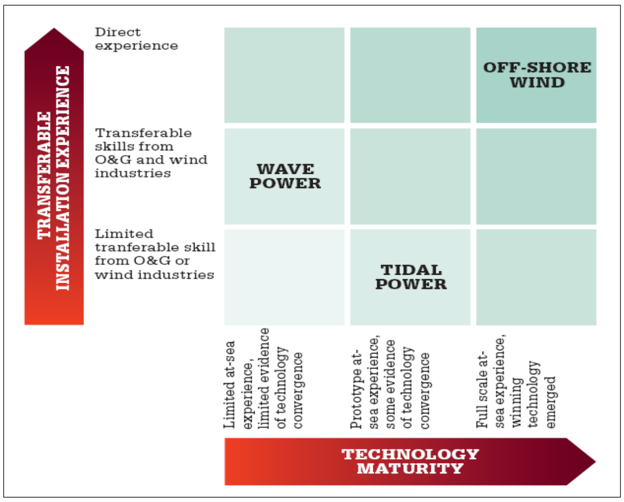

Fig. 5 – Offshore renewable technology maturity (IME, 2008)

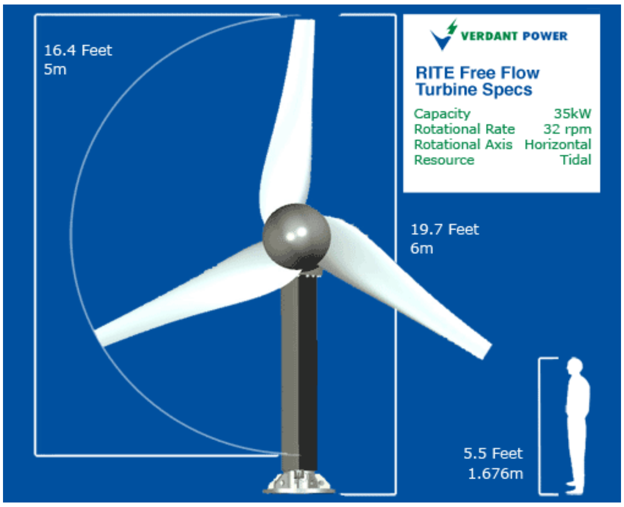

Fig 6 - Verdant Power power unit scheme (I-Source 26)

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COSTS[1] – Because of the harsh marine environment, and the early level of industrial development, the estimates of investment, operation and maintenance costs of the marine energy technologies are highly uncertain. For wave and tidal power, the capacity factor is typically between 30 and 40% of the rated power (Bedard, 2007). With regard to the investment cost of wave power the UK Carbon Trust reported in 2006, that some wave converters had been built at a cost of approximately $\$8,600/kW_e$ (Carbon Trust, 2006). The current (2008) investment costs of tidal stream power is estimated between $\$6,000/kW_e$. and $\$7,800/kW_e$. This cost is expected to decline to $\$5,000/kW_e$ in 2020, and to $\$4,100/kW_e$ in 2030. The investment costs of wave power is currently between $\$6,800/kW_e$ and $\$9,000/kW_e$, while it is projected to drop to about $\$5,700/kW_e$ in 2020 and to $\$4,700/kW_e$ in 2030. Taking into account a depreciation period of 15 years assumed for wave and tidal power plants, the generation cost of this type of power devices may come down from $340-400/MWh in 2010 to $200/MWh in 2030. A feed-in tariff incentive of ₤ 250/MWh ≈ $ 390/MWh (DECC, 2009) was suggested in the UK in 2009. for wave and tidal power. Governmental policies and financial incentives are therefore needed for these technologies to take off in the current market.

POTENTIAL & BARRIERS – Accelerated staged trials are needed to establish whether solutions under development are feasible and cost-effective. Because of insufficient experience from demonstration projects, there is a lack of understanding regarding the technology impacts on the environment. Also, the impact of the marine environment on components and equipment lifetime must be deeply investigated (AEA, 2006). In order for ocean energy technologies to enter the market, sustained governmental support is needed. Under favourable conditions, it has been estimated that a country with a favourable position such as the United Kingdom could realistically install between 1000 and 2000 MW_e based on wave and tidal stream power by 2020 (BWEA, 2009). In terms of order of magnitude, the potentials of the different marine energy technologies are provided in Table 1. While the technical potential is large, the economic potential is expected to be significantly lower.

Tab. 1 - Ocean Energy Potential (AEA, 2006; I- Source 2)

Energy Resource	Technology	Energy Potential, TWh/yr
Ocean Wave	Attenuators, Overtopping, OWC, Point absorbers, Submerged, Terminators, Rotors	8,000 (IPCC lower end estimate)
Tidal Stream	• Horizontal/Vertical- turbines, • Oscillating hydrofoils, • Venturi	800
Salinity Gradient	• Semi-permeable osmotic membranes	2000
OTEC	• Ranking cycle	10,000

[1]All costs quoted below are in 2008 US dollars

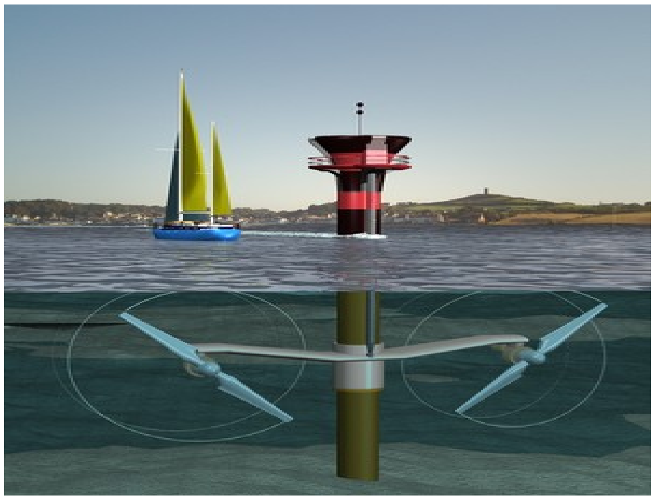

Fig 7 - OceanGen Marine Current Turbines (I-Source 30)

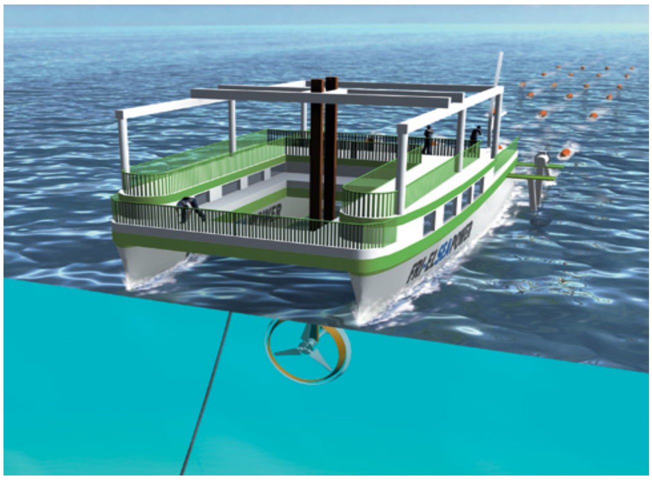

Fig 8 - Scheme of tidal stream converter - Fri-El Green Power (I-Source 31)

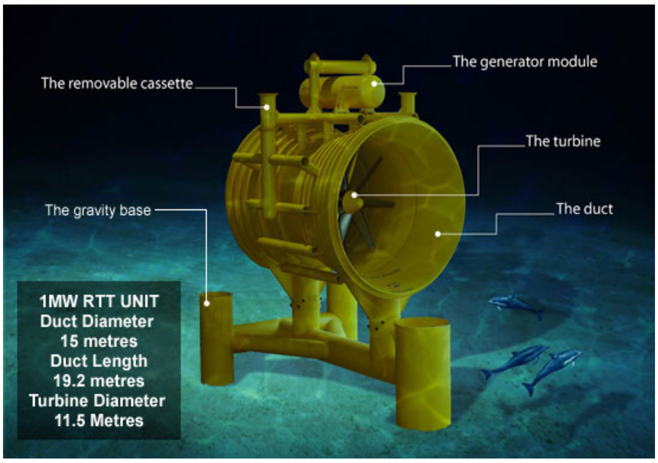

Fig 9 - Scheme of tidal stream power unit - Lunar Energy, UK (I-Source 32)

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Table 2 – Summary Table: Key Data and Figures for Marine Energy Technologies

Technical Performance	**Typical current international values and ranges**							
Energy input	Ocean energy							
Output	Electricity							
Technologies	Wave power (**Wave**)			Tidal-range Barrage (**TB**)			Tidal Stream (**TS**)	
Efficiency, %	Not applicable			Not applicable			Not applicable	
Construction time, months	Min.12; Typical 24; Max.36			Min. 36; Typical 48; Max.100			Min.12; Typical24; Max. 36	
Technical lifetime, yr	25			80			25	
Load (capacity) factor, %	33			22.5–28.5			33	
Max. (plant) availability, %	95			98			95	
Typical (capacity) size, MW_e	200+			200 (2000 Severn barrage)			20–200+	
Installed (existing) capacity, GW_e	Negligible			0.5			Negligible	
Average capacity aging								
CO_2 and other GHG emissions, kg/MWh	Negligible							
Costs (US$ 2008)								
Investment cost, including interest during construction, ($/kW)	6,800-9,000			5,000–5,500			6,000-7,800	
O&M cost (fixed and variable), $/kW/a	200			115			150	
Fuel cost, $/MWh	N/A			N/A			N/A	
Economic lifetime, yr	20			25			20	
Interest rate, %	10							
Total production cost, $/MWh (15 year depreciation)	400			300			340	
Market share	0			Negligible			0	
Data Projections	**2010**			**2020**			**2030**	
Technology	**Wave**	**TB**	**TS**	**Wave**	**TB**	**TS**	**Wave**	**TS**
Investment cost, including interest during construction, $/kW (BIN / CHP / HP)	7,900	5,250	6,900	5,700	4,200	5,000	4,700	4,100
Total production cost, $/MWh	400	260	340	290	240	250	240	200
Market share, % of global electricity output		<<1		<<1	<<1	<<1	1–2	1–2