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Wave power

Wave power is the capture of energy of wind waves to do useful work – for example, electricity generation, water desalination, or pumping water. A machine that exploits wave power is a **wave energy converter** (WEC).

Wave power is distinct from tidal power, which captures the energy of the current caused by the gravitational pull of the Sun and Moon. Waves and tides are also distinct from ocean currents which are caused by other forces including breaking waves, wind, the Coriolis effect, cabbeling, and differences in temperature and salinity.

Wave-power generation is not a widely employed commercial technology compared to other established renewable energy sources such as wind power, hydropower and solar power. However, there have been attempts to use this source of energy since at least 1890[1] mainly due to its high power density. As a comparison, the power density of the photovoltaic panels is 1 kW/m² at peak solar insolation, and the power density of the wind is 1 kW/m² at 12 m/s. Whereas, the average annual power density of the waves at e.g. San Francisco coast is 25 kW/m.[2]

In 2000 the world's first commercial Wave Power Device, the Islay LIMPET was installed on the coast of Islay in Scotland and connected to the National Grid.[3] In 2008, the first experimental multi-generator wave farm was opened in Portugal at the Aguçadoura Wave Park.[4]

Pelamis Wave Energy Converter on site at the European Marine Energy Centre (EMEC), in 2008

Azura at the US Navy’s Wave Energy Test Site (WETS) on Oahu

The mWave converter by Bombora Wave Power

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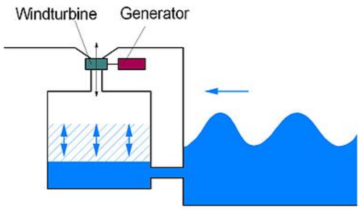
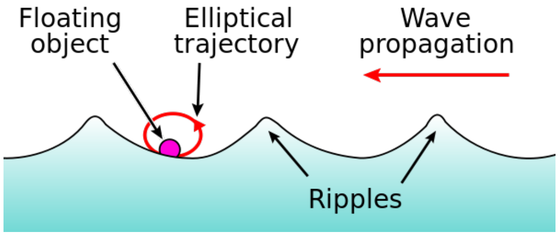


Wave Power Station using a pneumatic Chamber

Physical concepts

Waves are generated by wind passing over the surface of the sea. As long as the waves propagate slower than the wind speed just above the waves, there is an energy transfer from the wind to the waves. Both air pressure differences between the upwind and the lee side of a wave crest, as well as friction on the water surface by the wind, making the water to go into the shear stress causes the growth of the waves.[6]



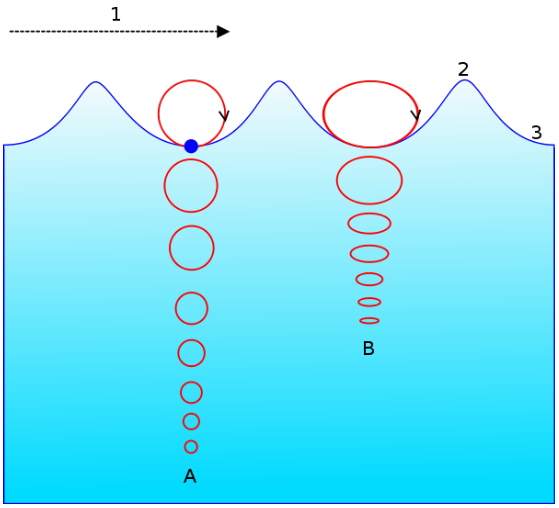
When an object bobs up and down on a ripple in a pond, it follows approximately an elliptical trajectory.

Wave height is determined by wind speed, the duration of time the wind has been blowing, fetch (the distance over which the wind excites the waves) and by the depth and topography of the seafloor (which can focus or disperse the energy of the waves). A given wind speed has a matching practical limit over which time or distance will not produce larger waves. When this limit has been reached the sea is said to be "fully developed".

In general, larger waves are more powerful but wave power is also determined by wave speed, wavelength, and water density.

Oscillatory motion is highest at the surface and diminishes exponentially with depth. However, for standing waves (clapotis) near a reflecting coast, wave energy is also present as pressure oscillations at great depth, producing microseisms.[6] These pressure fluctuations at greater depth are too small to be interesting from the point of view of wave power.

The waves propagate on the ocean surface, and the wave energy is also transported horizontally with the group velocity. The mean transport rate of the wave energy through a vertical plane of unit width, parallel to a wave crest, is called the wave energy flux (or wave power, which must not be confused with the actual power generated by a wave power device).



Motion of a particle in an ocean wave.
A = At deep water. The elliptical motion of fluid particles decreases rapidly with increasing depth below the surface.
B = At shallow water (ocean floor is now at B). The elliptical movement of a fluid particle flattens with decreasing depth.
1 = Propagation direction.
2 = Wave crest.
3 = Wave trough.

Wave power formula

In deep water where the water depth is larger than half the wavelength, the wave energy flux is[a]

$$P = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \approx \left(0.5 \frac{\mathrm{kW}}{\mathrm{m}^3 \cdot \mathrm{s}}\right) H_{m0}^2 \; T_e,$$

with P the wave energy flux per unit of wave-crest length, H_{mo} the significant wave height, T_e the wave energy period, ρ the water density and g the acceleration by gravity. The above formula states that wave power is proportional to the wave energy period and to the square of the wave height. When the significant wave height is given in metres, and the wave period in seconds, the result is the wave power in kilowatts (kW) per metre of wavefront length.[7][8][9][10]

Example: Consider moderate ocean swells, in deep water, a few km off a coastline, with a wave height of 3 m and a wave energy period of 8 s. Using the formula to solve for power, we get

$$P \approx 0.5 \frac{\mathrm{kW}}{\mathrm{m}^3 \cdot \mathrm{s}} (3 \cdot \mathrm{m})^2 (8 \cdot \mathrm{s}) \approx 36 \frac{\mathrm{kW}}{\mathrm{m}},$$

meaning there are 36 kilowatts of power potential per meter of wave crest.

In major storms, the largest waves offshore are about 15 meters high and have a period of about 15 seconds. According to the above formula, such waves carry about 1.7 MW of power across each metre of wavefront.

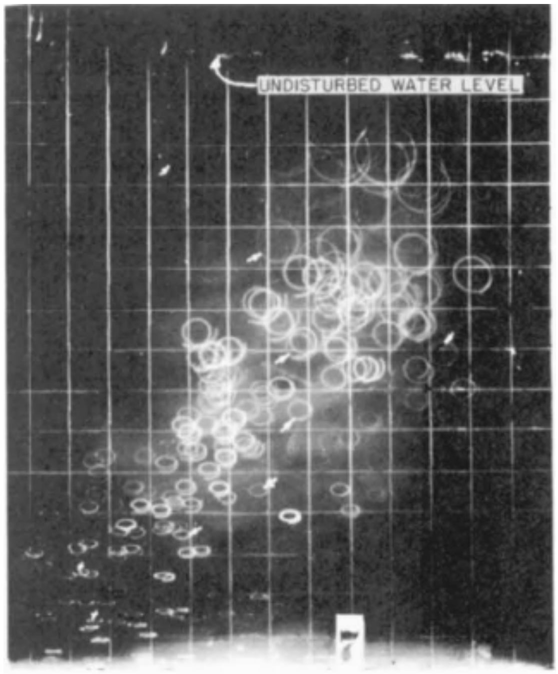
An effective wave power device captures as much as possible of the wave energy flux. As a result, the waves will be of lower height in the region behind the wave power device.

Wave energy and wave-energy flux

In a sea state, the average(mean) energy density per unit area of gravity waves on the water surface is proportional to the wave height squared, according to linear wave theory:[6][11]

$$E = \frac{1}{16} \rho g H_{m0}^2,$$ [b][12]

where E is the mean wave energy density per unit horizontal area (J/m²), the sum of kinetic and potential energy density per unit horizontal area. The potential energy density is equal to the kinetic energy,[6] both contributing half to the wave energy density E, as can be expected from the equipartition theorem. In ocean waves, surface tension effects are negligible for wavelengths above a few decimetres.



Photograph of the elliptical trajectories of water particles under a – progressive and periodic – surface gravity wave in a wave flume. The wave conditions are: mean water depth d = 2.50 ft (0.76 m), wave height H = 0.339 ft (0.103 m), wavelength λ = 6.42 ft (1.96 m), period T = 1.12 s.[5]

As the waves propagate, their energy is transported. The energy transport velocity is the group velocity. As a result, the wave energy flux, through a vertical plane of unit width perpendicular to the wave propagation direction, is equal to:[13][6]

$$P = E\, c_g,$$

with c_g the group velocity (m/s). Due to the dispersion relation for water waves under the action of gravity, the group velocity depends on the wavelength λ, or equivalently, on the wave period T. Further, the dispersion relation is a function of the water depth h. As a result, the group velocity behaves differently in the limits of deep and shallow water, and at intermediate depths:[6][11]

Properties of gravity waves on the surface of deep water, shallow water and at intermediate depth, according to linear wave theory

quantity	symbol	units	deep water (*h* > ½ *λ*)	shallow water (*h* < 0.05 *λ*)	intermediate depth (all *λ* and *h*)
phase velocity	$c_p = \frac{\lambda}{T} = \frac{\omega}{k}$	m / s	$\frac{g}{2\pi}T$	$\sqrt{gh}$ over/7.000000000/9	$\sqrt{\frac{g\lambda}{2\pi}\tanh\left(\frac{2\pi h}{\lambda}\right)}$
group velocity[c]	$c_g = c_p^2 \frac{\partial\left(\lambda/c_p\right)}{\partial\lambda} = \frac{\partial\omega}{\partial k}$	m / s	$\frac{g}{4\pi}T$	$\sqrt{gh}$	$\frac{1}{2}c_p\left(1+\frac{4\pi h}{\lambda}\frac{1}{\sinh\left(\frac{4\pi h}{\lambda}\right)}\right)$
ratio	$\frac{c_g}{c_p}$	–	$\frac{1}{2}$	1	$\frac{1}{2}\left(1+\frac{4\pi h}{\lambda}\frac{1}{\sinh\left(\frac{4\pi h}{\lambda}\right)}\right)$
wavelength	λ	m	$\frac{g}{2\pi}T^2$	$T\sqrt{gh}$	for given period *T*, the solution of: $\left(\frac{2\pi}{T}\right)^2 = \frac{2\pi g}{\lambda}\tanh\left(\frac{2\pi h}{\lambda}\right)$
general					
wave energy density	E	J / m²	$\frac{1}{16}\rho g H_{m0}^2$		
wave energy flux	P	W / m	$E\ c_g$		
angular frequency	ω	rad / s	$\frac{2\pi}{T}$		
wavenumber	k	rad / m	$\frac{2\pi}{\lambda}$		

Deep-water characteristics and opportunities

Deepwater corresponds with a water depth larger than half the wavelength, which is the common situation in the sea and ocean. In deep water, longer-period waves propagate faster and transport their energy faster. The deep-water group velocity is half the phase velocity. In shallow water, for wavelengths larger than about twenty times the water depth, as found quite often near the coast, the group velocity is equal to the phase velocity.[14]

History

The first known patent to use energy from ocean waves dates back to 1799, and was filed in Paris by Girard and his son.[15] An early application of wave power was a device constructed around 1910 by Bochaux-Praceique to light and power his house at Royan, near Bordeaux in France.[16] It appears that this was the first oscillating water-column type of wave-energy device.[17] From 1855 to 1973 there were already 340 patents filed in the UK alone.[15]

Modern scientific pursuit of wave energy was pioneered by Yoshio Masuda's experiments in the 1940s.[18] He tested various concepts of wave-energy devices at sea, with several hundred units used to power navigation lights. Among these was the concept of extracting power from the angular motion at the joints of an articulated raft, which was proposed in the 1950s by Masuda.[19]

A renewed interest in wave energy was motivated by the oil crisis in 1973. A number of university researchers re-examined the potential to generate energy from ocean waves, among whom notably were Stephen Salter from the University of Edinburgh, Kjell Budal and Johannes Falnes from Norwegian Institute of Technology (later merged into Norwegian University of Science and Technology), Michael E. McCormick from U.S. Naval Academy, David Evans from Bristol University, Michael French from University of Lancaster, Nick Newman and C. C. Mei from MIT.

Stephen Salter's 1974 invention became known as Salter's duck or *nodding duck*, although it was officially referred to as the Edinburgh Duck. In small scale controlled tests, the Duck's curved cam-like body can stop 90% of wave motion and can convert 90% of that to electricity giving 81% efficiency.[20]

In the 1980s, as the oil price went down, wave-energy funding was drastically reduced. Nevertheless, a few first-generation prototypes were tested at sea. More recently, following the issue of climate change, there is again a growing interest worldwide for renewable energy, including wave energy.[21]

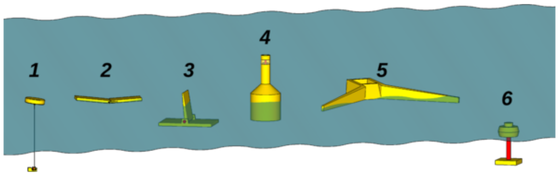
The world's first marine energy test facility was established in 2003 to kick-start the development of a wave and tidal energy industry in the UK. Based in Orkney, Scotland, the European Marine Energy Centre (EMEC) (http://www.emec.org.uk/) has supported the deployment of more wave and tidal energy devices than at any other single site in the world. EMEC provides a variety of test sites in real sea conditions. Its grid-connected wave test site is situated at Billia Croo, on the western edge of the Orkney mainland, and is subject to the full force of the Atlantic Ocean with seas as high as 19 metres recorded at the site. Wave energy developers currently testing at the centre include Aquamarine Power (http://www.aquamarinepower.com/), Pelamis Wave Power (http://www.pelamiswave.com/), ScottishPower Renewables (http://www.emec.org.uk/about-us/wave-clients/scottishpower-renewables/) and Wello (http://www.wello.eu/).[22]

Modern technology

Wave power devices are generally categorized by the **method** used to capture or harness the energy of the waves, by **location** and by the **power take-off system**. Locations are shoreline, nearshore and offshore. Types of power take-off include: hydraulic ram, elastomeric hose pump, pump-to-shore, hydroelectric turbine, air turbine,[23] and linear electrical generator. When evaluating wave energy as a technology type, it is important to distinguish between the four most common approaches: point absorber buoys, surface attenuators, oscillating water columns, and overtopping devices.

Point absorber buoy

This device floats on the surface of the water, held in place by cables connected to the seabed. The point-absorber is defined as having a device width much smaller than the incoming wavelength λ. A good point absorber has the same characteristics as a good wave-maker. The wave energy is absorbed by radiating a wave with destructive interference to the incoming waves. Buoys use the rise and fall of swells to generate electricity in various ways including directly via linear generators,[24] or via generators driven by mechanical linear-to-rotary converters[25] or hydraulic pumps.[26] Electromagnetic fields generated by electrical transmission cables and acoustics of these devices may be a concern for marine organisms. The presence of the buoys may affect fish, marine mammals, and birds as potential minor collision risk and roosting sites. Potential also exists for entanglement in mooring lines. Energy removed from the waves may also affect the shoreline, resulting in a recommendation that sites remain a considerable distance from the shore.[27]



Generic wave energy concepts: 1. Point absorber, 2. Attenuator, 3. Oscillating wave surge converter, 4. Oscillating water column, 5. Overtopping device, 6. Submerged pressure differential

Surface attenuator

These devices act similarly to point absorber buoys, with multiple floating segments connected to one another and are oriented perpendicular to incoming waves. A flexing motion is created by swells that drive hydraulic pumps to generate electricity. Environmental effects are similar to those of point absorber buoys, with an additional concern that organisms could be pinched in the joints.[27]

Oscillating wave surge converter

These devices typically have one end fixed to a structure or the seabed while the other end is free to move. Energy is collected from the relative motion of the body compared to the fixed point. Oscillating wave surge converters often come in the form of floats, flaps, or membranes. Environmental concerns include minor risk of collision, artificial reefing near the fixed point, electromotive force effects from subsea cables, and energy removal effecting sediment transport.[27] Some of these designs incorporate parabolic reflectors as a means of increasing the wave energy at the point of capture. These capture systems use the rise and fall motion of waves to capture energy.[28] Once the wave energy is captured at a wave source, power must be carried to the point of use or to a connection to the electrical grid by transmission power cables.[29]

Oscillating water column

Oscillating Water Column devices can be located onshore or in deeper waters offshore. With an air chamber integrated into the device, swells compress air in the chambers forcing air through an air turbine to create electricity.[30] Significant noise is produced as air is pushed through the turbines, potentially affecting birds and other marine organisms within the vicinity of the device. There is also concern about marine organisms getting trapped or entangled within the air chambers.[27]

Overtopping device

Overtopping devices are long structures that use wave velocity to fill a reservoir to a greater water level than the surrounding ocean. The potential energy in the reservoir height is then captured with low-head turbines. Devices can be either onshore or floating offshore. Floating devices will have environmental concerns about the mooring system affecting benthic organisms, organisms becoming entangled, or electromotive force effects produced from subsea cables. There is also some concern regarding low levels of turbine noise and wave energy removal affecting the nearfield habitat.[27]

Submerged pressure differential

Submerged pressure differential based converters are a comparatively newer technology [31] utilizing flexible (usually reinforced rubber) membranes to extract wave energy. These converters use the difference in pressure at different locations below a wave to produce a pressure difference within a closed power take-off fluid system. This pressure difference is usually used to produce flow, which drives a turbine and electrical generator. Submerged pressure differential converters frequently use flexible membranes as the working surface between the ocean and the power take-off system. Membranes offer the advantage over rigid structures of being compliant and low mass, which can produce more direct coupling with the wave's energy. Their compliant nature also allows for large changes in the geometry of the working surface, which can be used to tune the response of the converter for specific wave conditions and to protect it from excessive loads in extreme conditions.

A submerged converter may be positioned either on the seafloor or in midwater. In both cases, the converter is protected from water impact loads which can occur at the free surface. Wave loads also diminish in non-linear proportion to the distance below the free surface. This means that by optimizing the depth of submergence for such a converter, a compromise between protection from extreme loads and access to wave energy can be found. Submerged WECs also have the potential to reduce the impact on marine amenity and navigation, as they are not at the surface. Examples of submerged pressure differential converters include M3 Wave (http://www.m3wave.com/m3tech), Bombora Wave Power (http://www.bomborawave.com)'s mWave, and CalWave (http://calwave.energy).

Environmental effects

Common environmental concerns associated with marine energy developments include:

- The risk of marine mammals and fish being struck by tidal turbine blades;
- The effects of electromagnetic fields and underwater noise emitted from operating marine energy devices;
- The physical presence of marine energy projects and their potential to alter the behavior of marine mammals, fish, and seabirds with attraction or avoidance;

- The potential effect on nearfield and far-field marine environment and processes such as sediment transport and water quality.

The Tethys database provides access to scientific literature and general information on the potential environmental effects of wave energy.[32]

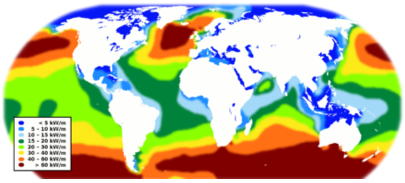
Potential

The worldwide resource of coastal wave energy has been estimated to be greater than 2 TW.[33] Locations with the most potential for wave power include the western seaboard of Europe, the northern coast of the UK, and the Pacific coastlines of North and South America, Southern Africa, Australia, and New Zealand. The north and south temperate zones have the best sites for capturing wave power. The prevailing westerlies in these zones blow strongest in winter.

Estimates have been made by the National Renewable Energy Laboratory (NREL) for various nations around the world in regards to the amount of energy that could be generated from wave energy converters (WECs) on their coastlines. For the United States in particular, it is estimated that the total energy amount that could be generated along its coastlines is equivalent to 1170 TWh per year, which would account to approximately 10 kWh per United States citizen per day. That's almost 5% of the overall energy consumption per average citizen, including transport and industry. [34] While this sounds promising, the coastline along Alaska accounted for approx. 50% of the total energy created within this estimate. Considering this, there would need to be the proper infrastructure in place to transfer this energy from Alaskan shorelines to the mainland United States in order to properly capitalize on meeting United States energy demands. However, these numbers show the great potential these technologies have if they are implemented on a global scale to satisfy the search for sources of renewable energy.

WECs have gone under heavy examination through research, especially relating to their efficiencies and the transport of the energy they generate. NREL has shown that these WECs can have efficiencies near 50%.[34] This is a phenomenal efficiency rating among renewable energy production. For comparison, efficiencies above 10% in solar panels are considered viable for sustainable energy production.[35] Thus, a value of 50% efficiency for a renewable energy source is extremely viable for the future development of renewable energy sources to be implemented across the world. Additionally, research has been conducted examining smaller WECs and their viability, especially relating to power output. One piece of research showed great potential with small devices, reminiscent of buoys, capable of generating upwards of 6 W of power in various wave conditions and oscillations and device size (up to a roughly cylindrical 21 kg buoy).[36] Even further research has led to development of smaller, compact versions of current WECs that could produce the same amount of energy while using roughly one-half of the area necessary as current devices.[37]

Challenges



World wave energy resource map

There is a potential impact on the marine environment. Noise pollution, for example, could have a negative impact if not monitored, although the noise and visible impact of each design varies greatly.[9] Other biophysical impacts (flora and fauna, sediment regimes and water column structure and flows) of scaling up the technology are being studied.[38] In terms of socio-economic challenges, wave farms can result in the displacement of commercial and recreational fishermen from productive fishing grounds, can change the pattern of beach sand nourishment, and may represent hazards to safe navigation.[39] Waves generate about 2,700 gigawatts of power. Of those 2,700 gigawatts, only about 500 gigawatts can be captured with current technology.[28] Since 2008, the Swedish company Seabased AB has deployed several units of wave energy converters (WECs) manufactured with different designs. Offshore deployments of WECs and underwater substation are being complicated procedures. Seabased discussed these deployments in terms of economy and time efficiency, as well as safety. Certain solutions are suggested for the various problems encountered during the deployments. It is found that the offshore deployment process can be optimized in terms of cost, time efficiency and safety.[40] In 2019 the Swedish production subsidiary Seabased Industries AB was liquidated due to "extensive challenges in recent years, both practical and financial".[41]

Wave farms

A group of wave energy devices deployed in the same location is called wave farm, wave power farm or wave energy park. Wave farms represent a solution to achieve larger electricity production. The devices of a park are going to interact with each other hydrodynamically and electrically, according to the number of machines, the distance among them, the geometric layout, the wave climate, the local geometry, the control strategies. The design process of a wave energy farm is a multi-optimization problem with the aim to get a high power production and low costs and power fluctuations.[42]

Wave farm projects

United Kingdom

- The Islay LIMPET was installed and connected to the National Grid in 2000 and is the world's first commercial wave power installation
- Funding for a 3 MW wave farm in Scotland was announced on February 20, 2007, by the Scottish Executive, at a cost of over 4 million pounds, as part of a £13 million funding package for marine power in Scotland. The first machine was launched in May 2010.[43]
- A facility known as Wave hub has been constructed off the north coast of Cornwall, England, to facilitate wave energy development. The Wave hub will act as giant extension cable, allowing arrays of wave energy generating devices to be connected to the electricity grid. The Wave hub will initially allow 20 MW of capacity to be connected, with potential expansion to 40 MW. Four device manufacturers have as of 2008 expressed interest in connecting to the Wave hub.[44][45] The scientists have calculated that wave energy gathered at Wave Hub will be enough to power up to 7,500 households. The site has the potential to save greenhouse gas emissions of about 300,000 tons of carbon dioxide in the next 25 years.[46]
- A 2017 study by Strathclyde University and Imperial College focused on the failure to develop "market ready" wave energy devices – despite a UK government push of over £200 million in the preceding 15 years – and how to improve the effectiveness of future government support.[47]

Portugal

- The Aguçadoura Wave Farm was the world's first wave farm. It was located 5 km (3 mi) offshore near Póvoa de Varzim, north of Porto, Portugal. The farm was designed to use three Pelamis wave energy converters to convert the motion of the ocean surface waves into electricity, totalling to 2.25 MW in total installed capacity. The farm first generated electricity in July 2008[48] and was officially opened on September 23, 2008, by the Portuguese Minister of Economy.[49][50] The wave farm was shut down two months after the official opening in November 2008 as a result of the financial collapse of Babcock & Brown due to the global economic crisis. The machines were off-site at this time due to technical problems, and although resolved have not returned to site and were subsequently scrapped in 2011 as the technology had moved on to the P2 variant as supplied to E.ON and Scottish Renewables.[51] A second phase of the project planned to increase the installed capacity to 21 MW using a further 25 Pelamis machines[52] is in doubt following Babcock's financial collapse.

Australia

- Bombora Wave Power[53] is based in Perth, Western Australia and is currently developing the mWave[54] flexible membrane converter. Bombora is currently preparing for a commercial pilot project in Peniche, Portugal.
- A CETO wave farm off the coast of Western Australia has been operating to prove commercial viability and, after preliminary environmental approval, underwent further development.[55][56] In early 2015 a $100 million, multi megawatt system was connected to the grid, with all the electricity being bought to power HMAS Stirling naval base. Two fully submerged buoys which are anchored to the seabed, transmit the energy from the ocean swell through hydraulic pressure onshore; to drive a generator for electricity, and also to produce fresh water. As of 2015 a third buoy is planned for installation.[57][58]
- Ocean Power Technologies (OPT Australasia Pty Ltd) is developing a wave farm connected to the grid near Portland, Victoria through a 19 MW wave power station. The project has received an AU $66.46 million grant from the Federal Government of Australia.[59]
- Oceanlinx will deploy a commercial scale demonstrator off the coast of South Australia at Port MacDonnell before the end of 2013. This device, the *greenWAVE*, has a rated electrical capacity of 1MW. This project has been supported by ARENA through the Emerging Renewables Program. The *greenWAVE* device is a bottom standing gravity structure, that does not require anchoring or seabed preparation and with no moving parts below the surface of the water.[60]

United States

- Reedsport, Oregon – a commercial wave park on the west coast of the United States located 2.5 miles offshore near Reedsport, Oregon. The first phase of this project is for ten PB150 PowerBuoys, or 1.5 megawatts.[61][62] The Reedsport wave farm was scheduled for installation spring 2013.[63] In 2013, the project had ground to a halt because of legal and technical problems.[64]
- Kaneohe Bay Oahu, Hawaii – Navy's Wave Energy Test Site (WETS) currently testing the Azura wave power device[65] The Azura wave power device is 45-ton wave energy converter located at a depth of 30 metres (98 ft) in Kaneohe Bay.[66]

Patents

- WIPO patent application WO2016032360 (https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2016032360&redirectedID=true) — 2016 *Pumped-storage system* – "Pressure buffering hydro power" patent application
- U.S. Patent 8,806,865 (https://www.google.com/patents/US8806865) — 2011 *Ocean wave energy harnessing device* – Pelamis/Salter's Duck Hybrid patent
- U.S. Patent 3,928,967 (https://www.google.com/patents/US3928967) — 1974 *Apparatus and method of extracting wave energy* – The original "Salter's Duck" patent
- U.S. Patent 4,134,023 (https://www.google.com/patents/US4134023) — 1977 *Apparatus for use*

in the extraction of energy from waves on water – Salter's method for improving "duck" efficiency
- U.S. Patent 6,194,815 (https://www.google.com/patents/US6194815) — 1999 *Piezoelectric rotary electrical energy generator*
- Wave energy converters utilizing pressure differences US 20040217597 A1 (http://www.google.com/patents/US20040217597) — 2004 *Wave energy converters utilizing pressure differences*[67]

See also

- Wave power in New Zealand
- Wave power in Scotland
- Ocean thermal energy conversion
- Office of Energy Efficiency and Renewable Energy (OEERE)
- World energy consumption
- List of wave power stations
- List of wave power projects

Notes

a. The energy flux is $P = \frac{1}{16}\rho g H_{m0}^2 c_g$, with c_g the group velocity, see Herbich, John B. (2000). *Handbook of coastal engineering*. McGraw-Hill Professional. A.117, Eq. (12). ISBN 978-0-07-134402-9. The group velocity is $c_g = \frac{g}{4\pi}T$, see the collapsed table "*Properties of gravity waves on the surface of deep water, shallow water and at intermediate depth, according to linear wave theory*" in the section "*Wave energy and wave energy flux*" below.

b. Here, the factor for random waves is $\frac{1}{16}$, as opposed to $\frac{1}{8}$ for periodic waves – as explained hereafter. For a small-amplitude sinusoidal wave $\eta = a \cos 2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)$ with wave amplitude a, the wave energy density per unit horizontal area is $E = \frac{1}{2}\rho g a^2$, or $E = \frac{1}{8}\rho g H^2$ using the wave height $H = 2\,a$ for sinusoidal waves. In terms of the variance of the surface elevation $m_0 = \sigma_\eta^2 = \overline{(\eta - \bar{\eta})^2} = \frac{1}{2}a^2$, the energy density is $E = \rho g m_0$. Turning to random waves, the last formulation of the wave energy equation in terms of m_0 is also valid (Holthuijsen, 2007, p. 40), due to Parseval's theorem. Further, the significant wave height is *defined* as $H_{m0} = 4\sqrt{m_0}$, leading to the factor $\frac{1}{16}$ in the wave energy density per unit horizontal area.

c. For determining the group velocity the angular frequency ω is considered as a function of the wavenumber k, or equivalently, the period T as a function of the wavelength λ.

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