

- NTNU
- Norges teknisk-naturvitenskapelige universitet
- Fakultet for naturvitenskap og teknologi
- Institutt for fysikk

• Fag ENERGI OG MILJØFYSIKK
(Energy and Environmental Physics)

OCEAN-WAVE ENERGY

Introductory lectures by
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1 & 3 October 2003

Shedden, 04/10/2003 10:00 AM

The wave energy resource

- Wave energy is a **non-polluting** and **renewable** source of energy, created by natural conversion of part of the wind energy above the oceans. Wind energy is created by natural conversion of part of the solar energy. With both of these energy conversions the flow of energy is concentrated.
- **Just below the ocean's water surface the wave energy flow, in time-average, is typically five times denser than the wind energy flow 20 m above the sea surface, and 10 to 30 times denser than the solar energy flow.**
- Hence, there are good prospects for development of commercial wave-power plants, which may in the future become significant components for providing energy to many coastal nations.

JP 2003-10


Ocean waves as energy resource

- Average energy intensity:
- Solar energy: 100 - 200 W/m²
- Wind energy: 400 - 600 W/m²
- Wave energy: 2 - 3 kW/m²

What is a wave?


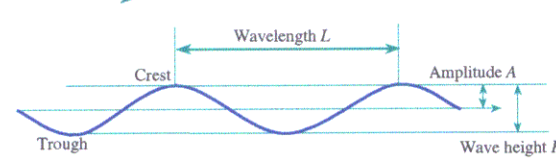
- Everyone has seen waves on lakes or oceans. Waves are actually a form of energy. Energy, not water, moves along the ocean's surface. The water particles only travel in small circles as a wave passes.

Snapshot of the water surface at a certain instant:



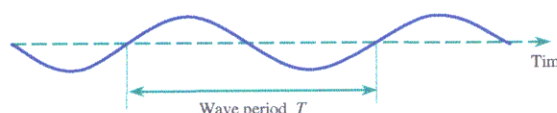
How to describe a wave

Snapshot of the water surface at a certain instant:

Surface elevation versus time

At a fixed position in space:



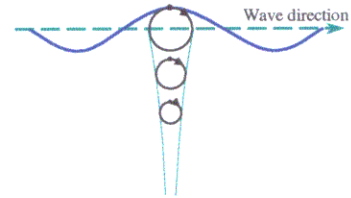
Frequency $f = 1/T$

Wind waves and swells

- Waves generated by wind are called *wind waves*. When the waves propagate outside their region of generation, they are called *swells* [in Norwegian: *dønningar*]. Where the water is deep, swells can travel very large distances, for instance across oceans, almost without loss of energy.

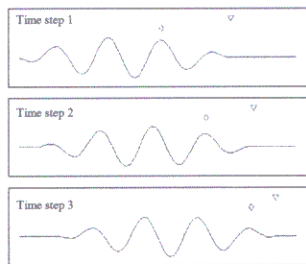
What happens underwater?

In deep water the water molecules travel in vertical circles (while in shallow water the motion is elliptical). This motion of water particles also happens underwater, but the particle velocity and thereby the circle radius decrease quickly as you go deeper in the water.



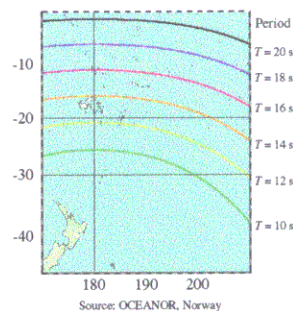
Wave velocities

- The energy in the waves travel with the *group velocity* c_g . The individual waves travel faster - they are born on the rear end of the group, and they die in the front end. On deep water this *phase velocity* is twice the group velocity:



$$c = 2c_g = \frac{g}{2\pi} T = (1.56 \text{ m/s}^2) \cdot T$$

Swells propagating across the Pacific



- Since the group velocity is proportional to the period, low-frequency waves move faster away from a storm centre than high-frequency waves. The figure shows the situation 4 days after a storm with centre located at 170° east and 50° south.

Energy content of waves

- For a sinusoidal wave of height H , the average energy E stored on a horizontal square metre of the water surface is:

$$E = k_E H^2$$

$$k_E = \rho g / 8 = 1.25 \text{ kW} \cdot \text{s/m}^4$$

$$\rho = \text{mass density of sea water} \approx 1020 \text{ kg/m}^3$$

$$g = \text{acceleration of gravity} \approx 9.8 \text{ m/s}^2$$

- Half of this is potential energy due to water lifted from wave troughs to wave crests. The remaining half is kinetic energy due to the motion of the water.

$$\text{Example: } H = 2\text{m} \Rightarrow E = 5 \text{ kW} \cdot \text{s/m}^2$$

Energy transport in waves

- The energy transport per metre width of the wave front is

$$J = c_g E$$

On deep water the group velocity is $c_g = gT/4\pi$, which gives

$$J = k_J T H^2$$

$$k_J = \rho g^2 / 32 \pi \approx 1 \text{ kW/m}^3\text{s}$$

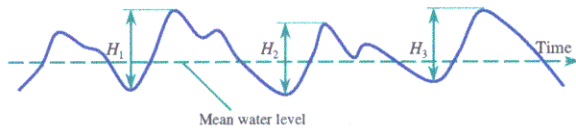
Example:

$$T = 10\text{s and } H = 2\text{m} \Rightarrow J = 40 \text{ kW/m}$$

Significant wave height

The real-sea wave height parameter is the *significant wave height*. It is traditionally defined as the average of the highest one third of the individual trough-to-crest heights H_i ($i=1,2,3,\dots$), and is denoted by $H_{1/3}$.

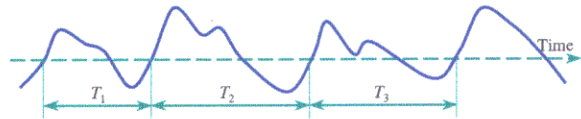
$$H_{1/3} = \frac{H_1 + H_2 + \dots + H_{N/3}}{N/3}$$



Average zero up-cross time T_z

- The individual *zero up-cross time* T_i is the time interval between two consecutive instants where the wave elevation crosses the zero level in the upward direction. An average of these over a certain time provides a useful measure of the real-sea wave period.

$$T_z = \frac{T_1 + T_2 + \dots + T_N}{N}$$



Wave spectrum

- A quantity derived from wave measurements is the so-called energy spectrum $S(f)$. It tells us how much energy is carried by the different frequency components in the real-sea "mixture" of waves. For a sinusoidal wave the average stored energy was given by

$$E = \rho g H^2 / 8$$

- For a real sea wave we have instead

$$E = \rho g \int_0^{\infty} S(f) df \approx \rho g H_s^2 / 16$$

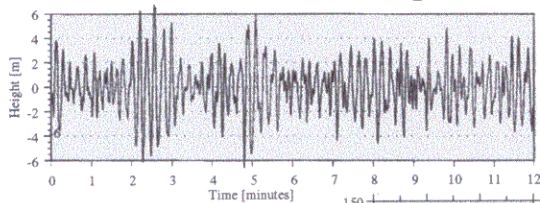
Wave energy transport in terms of significant wave height

$$\int_0^{\infty} S(f) df \approx H_s^2 / 16$$

- Here H_s is the modern definition of significant wave height, which in practice agrees quite well with our previous definition $H_{1/3}$. Another quantity, the so-called wave energy period T_j , may be derived from the wave spectrum $S(f)$. The energy transport by real sea waves is now calculated by

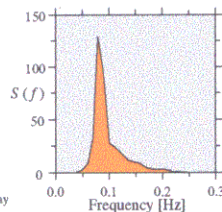
$$J = (k_j / 2) T_j H_s^2 \quad k_j / 2 = 0.5 \text{ kW/s m}^3$$

A measurement example



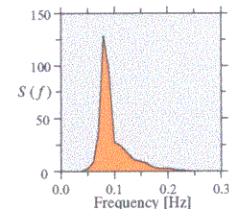
- This time series (above) from high sea shows that individual waves vary greatly in size and form. The corresponding energy spectrum is shown to the right. For this storm wave the significant wave height is $H_s = 8$ m.

Source: OCEANOR, Norway



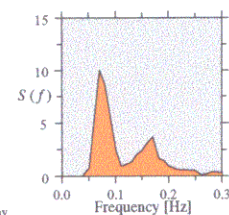
Real-sea spectra

- These are typical energy spectra from wind-sea conditions (top) and mixed wind-sea and swell conditions (bottom).



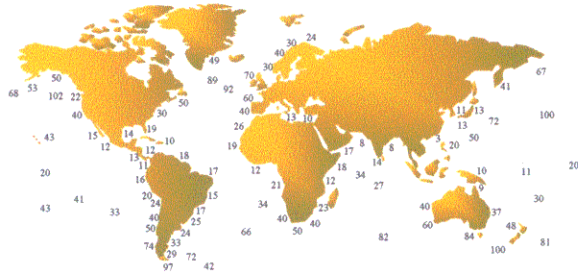
- The swell contains lower frequencies (high peak) than the wind waves (low peak).

- Significant wave heights: 8 m (top) and 3 m (bottom)



Source: OCEANOR, Norway

Distribution of wave energy transport



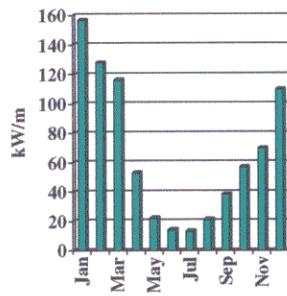
Average wave power levels are approximate and given in kW/m of the wave front.

Seasonal variation

- The average values of wave-energy transport vary somewhat from one year to next year. The values vary more between seasons. On the northern hemisphere, the average values for November and May may differ by a factor of two or more. There is significantly more wind energy and wave energy in winter than in summer, although it is opposite for solar energy. Because there may be waves (swells) even in the absence of wind, wave energy is more persistent than wind energy.

Seasonal variation at (57° N, 9° W)

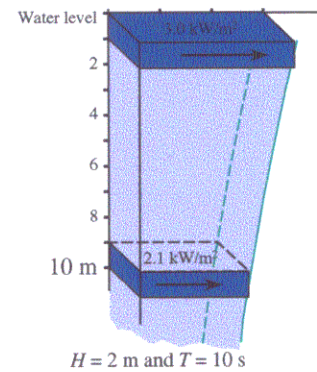
- The chart shows the seasonal variation of wave energy transport at a measurement site close to Barra in the Hebrides off the Scottish coast. The annual average for the shown year was 65 kW/m.



Based on WERATLAS, European Wave Energy Atlas, 1996

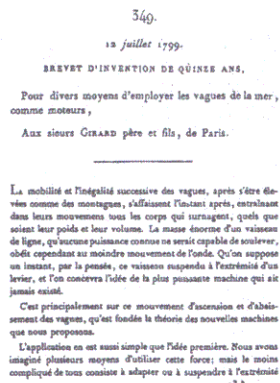
Vertical distribution of wave-energy transport

- As we have seen, the water particles move in circles with decreasing radius in the depth. Consequently, the energy flow density decreases as we go deeper in the water. In fact, on deep water, 95% of the energy transport takes place between the surface and the depth $L/4$. (L is the wavelength).

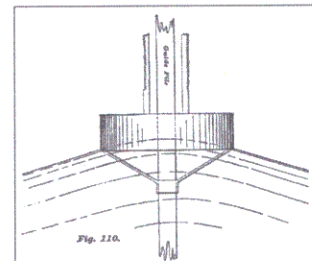


•The first patent we know of to utilise the energy of ocean waves dates from 1799 and was filed in Paris by the Girards, father and son, who had observed that waves could lift very large ships.

•However, many centuries earlier, Polynesians had discovered that they could utilise ocean waves for surfing (!).



- In 19th century proposals, the oscillating motion is transmitted to pumps or other suitable energy conversion machinery by mechanical means (such as racks and pinions, ratchet wheels, ropes and levers). The figure shows a float moving up and down. Cog wheels (not shown) are engaged by cog rods rigidly connected to the float.

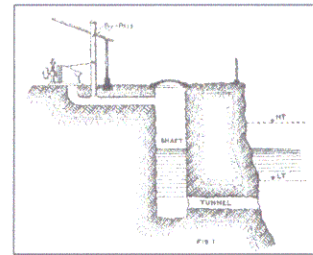


From a 57-page review paper in 1892 by A.W. Stahl, *The utilization of the power of ocean waves*.

- At present, wave energy is widely used for powering navigation buoys. This is an old idea, but it was first successfully realised in 1965, after a study by the Japan Research and Development Corporation, after which a Japanese company (Ryokuseisha) produced about 1200 buoys for world-wide use.



- An early practical application of wave power was a device constructed around 1910 at Royan, near Bordeaux in France. Here, Mr. Bochaux-Praceique supplied his house with 1 kW of light and power from a turbine, driven by air which was pumped by the oscillations of the sea water in a vertical bore hole in a cliff.

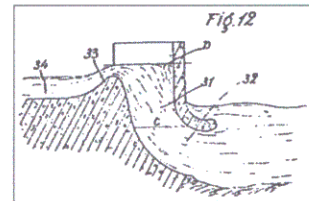


Drawing from 1920 showing Mr. Bochaux-Praceique's device. Reprinted with permission of Power Magazine, The McGraw Hill Companies

- At about the time of the first world war petroleum became the modern source of energy and conquered the world market. The interest for most other energy resources faded away. A new growing interest for instance at wave energy was initiated with the petroleum crisis in 1973.

Oscillating water column (OWC)

- Sea water enters a hollow structure with its lower opening submerged. Due to wave action the inside "water column" will oscillate. With the shown proposal some water at the upper part of the "column" is drained into an elevated water reservoir.



From British patent No. 741494 on oscillating water columns.

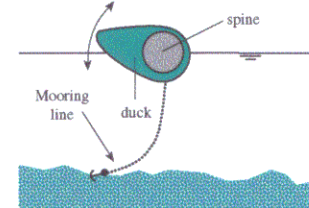
- 80 m long vessel Kaimei (= sea light) for testing various types of wave-activated air turbines.



Copyright: JAMSTEC, Japan

The Salter duck

- In 1974 Stephen Salter published a paper on a device which has become known as the "Salter duck", the "Edinburgh duck" or simply the "Duck", because the device, in its pitching oscillation, resembles a nodding duck. Several ducks share a common spine. The relative pitch motion between each duck and the spine is utilised for pumping hydraulic fluid through a motor.



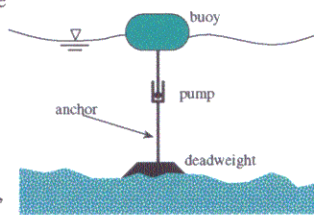
- During the late 1970s substantial wave-energy development programmes were launched by governments in several countries, in particular in the UK, Norway and Sweden. The financial support was dramatically reduced during the early 1980s when the petroleum price became lower and when there in the public opinion was a decreasing concern about energy and environment problems.

Conversion of wave energy

- The patent literature contains several hundreds of different proposals for the utilisation of ocean-wave energy. They may be classified in various ways into groups of, a dozen or less, different types.

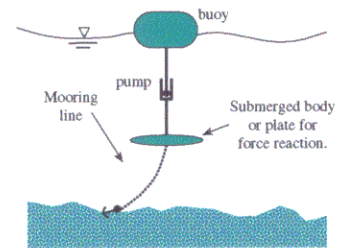
Force reaction

- To make use of the force the waves give, we need some kind of force reaction. The shown heaving buoy reacts against a fixed anchor on the sea bed. A pump, which is shown schematically, is activated by the heave motion of the buoy. The pumped fluid is used to run a motor (e.g. a turbine) not shown. The turbine, in turn, runs an electric generator.

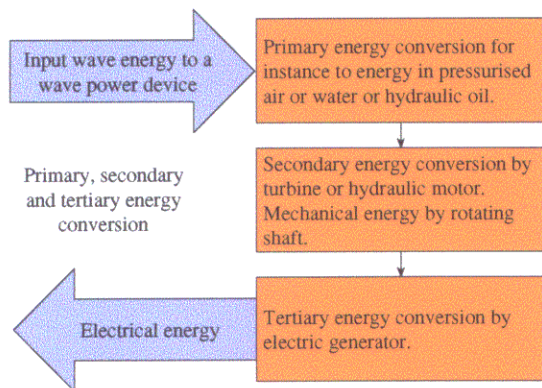


Force reaction by another body

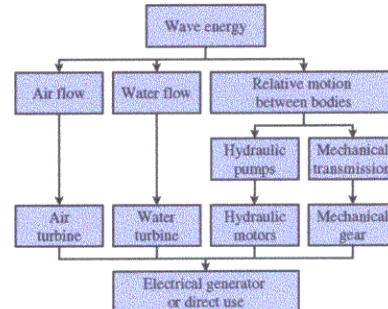
- An alternative is to let the wave force on the float react against another body, such as the shown submerged body. The power take-off pump is activated by the relative motion between the two bodies. A mooring line is required to prevent the system from drifting away from position.



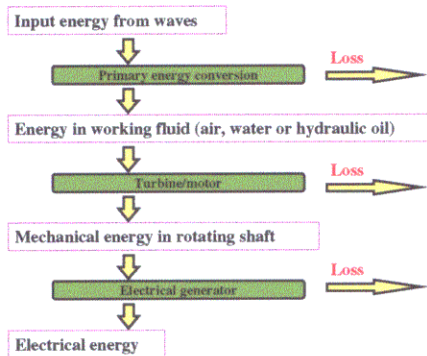
Steps of wave-energy conversion



Power take-off alternatives



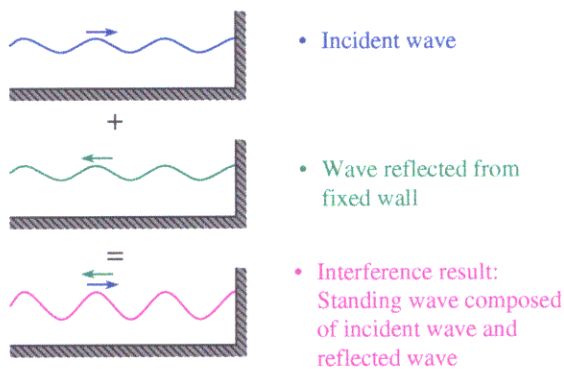
Schematic principle for extracting wave energy



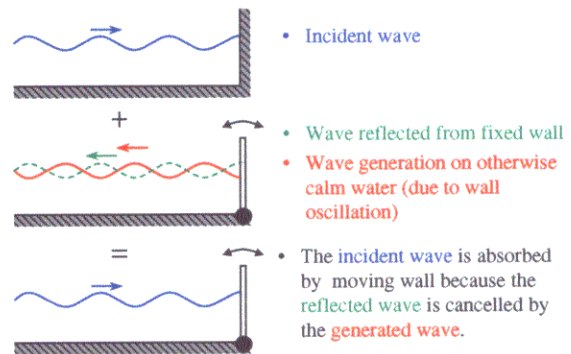
A paradox?

- Absorption of wave energy from the sea may be considered as a phenomenon of wave interference. Then wave energy absorption may be described by an apparently paradoxical statement:
 - *To absorb a wave means to generate a wave*
- or, in other words:
 - *To destroy a wave is to create a wave.*

Incident wave + reflected wave = standing wave



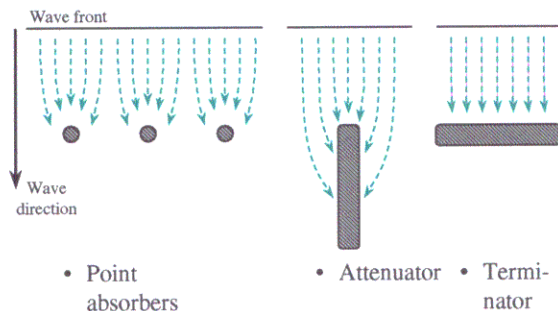
“To absorb a wave means to generate a wave”
- or “to destroy a wave means to create a wave”.



Classification of WECs

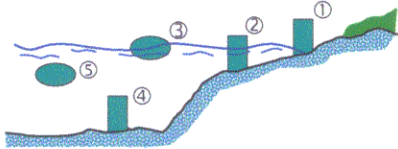
- All the different proposals and principles for wave energy conversion can be classified in several ways. We use these in order to see the differences and similarities between the wave energy converters (WECs).

- According to size and orientation



- According to location

- ① Shore-based
- ② Near-shore bottom-standing
- ③ Floating; near-shore or offshore
- ④ Bottom-standing or submerged on not too deep water.
- ⑤ Submerged not far from a water surface
- ⑥ Hybrid; units of types 2-5 combined with an energy storage (such as a pressure tank or water reservoir) and conversion machinery on land.



- According to end use of energy

- Electricity
- Desalination of sea water
- Refrigeration plants
- Pumping of clean sea water (fish farms, cleaning of contaminated lagoons and other sea areas with insufficient water circulation)
- Heating of sea water (e.g. for fish farms, and swimming pools)
- Propulsion of vessels
- Combination with desired reduction of wave activity

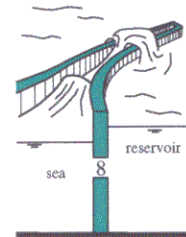
- According to form of primary energy conversion

- To hydraulic energy
- To pneumatic energy
- To mechanical energy (typical for the 19th century proposals)
- Directly to electricity (unfortunately no energy-storing buffer between wave input and electric output)

The tapered channel

- The tapered channel is a horizontal channel which is wide towards the sea where the waves enter and gradually narrows in a reservoir at the other side. As the waves pass through the channel, water is lifted over the channel wall and into the reservoir due to the shortage of space which occurs as the channel gets narrower.

Principle:



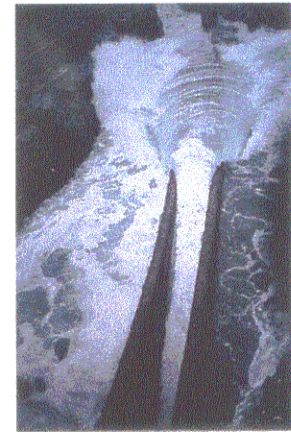
NORWAVE's TAPCHAN

• A tapered channel demonstration plant was built in 1985 at Toftestallen on the west coast of Norway. Due to the tapering of the horizontal channel, water is lifted to the reservoir 3 m above. The water in the reservoir flows back into the sea (behind the reservoir dam and turbine house) through a conventional low-pressure water turbine running a 350 kW generator connected to the local grid.



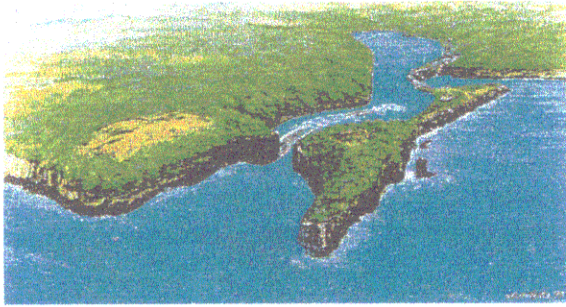
Copyright: NORWAVE AS, Norway, 1986

- Even on a rather calm day, the effect of squeezing the water in the narrowing space of the channel results in it gaining speed and fury, giving an impressive view as the water overtops the walls and bursts into the reservoir at Toftestallen.



Copyright: NORWAVE AS, Norway, 1986

INDONOR's planned TapChan power plant in Indonesia

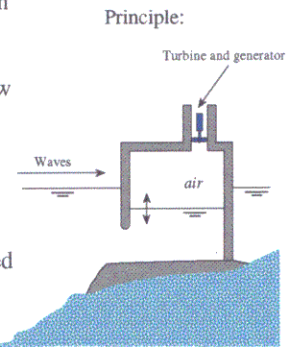


Installed power: 1,1 MW
Reservoir level: 4 m
Reservoir surface: 7000 m²

Collector: Length: 126 m. Max. width: 124 m
Tapered channel: Length: 60 m. Max. width: 7 m. Bottom: -8 m

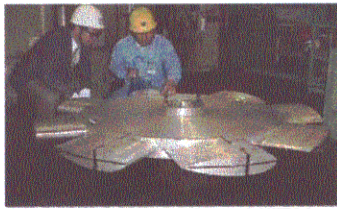
Oscillating water column (OWC)

- In an oscillating water column a part of the ocean surface is trapped inside a chamber which is open to the sea below the water line. When the internal water surface moves up and down in response to incident waves outside the chamber, the air in the chamber is pressed and sucked through a turbine due to the generated overpressure and underpressure.



The Wells turbine

- For a Wells turbine the direction of the torque is independent of the direction of the air flow. This is suitable for the air's oscillating motion induced by the sea waves.



Copyright: JAMSTEC, Japan

Sanze shoreline gully

- A lot of different designs of the OWC have been realised for research and demonstration purposes. The picture shows a Japanese OWC which was tested at Sanze on the west coast of Japan in 1984. It had two Wells turbines on each side of a 40 kW generator in order to cancel the thrust forces on the rotating shaft.



Copyright: JAMSTEC, Japan

Kværner Brug's OWC plant at Toftestallen, Norway

- The OWC structure is concrete below level +3,5 m and a steel structure between +3,5 m and +21 m. The machinery has a vertical shaft. The generator housing is at the top. Below is the (red) housing for the self-rectifying air turbine (500 kW).



Photo: J. Faabes, 1985.

Shoreline OWC, Isle of Islay, Scotland

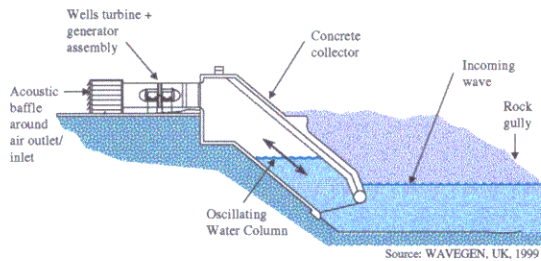
- This device was erected by Queens University, Belfast, in a project sponsored by the Department of Trade and Industry. The plant has a 75 kW Wells turbine and flywheels for energy storage. The system has been connected to the island's grid since 1991, but is now (1999) under decommissioning, as a new, improved design, LIMPET, is under construction just north of the previous site (next slide).



Photo: Håvard Eidsmoen, 1993

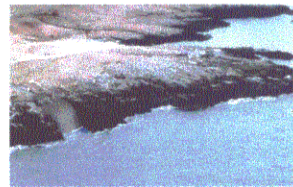
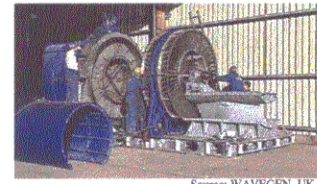
LIMPET

- The new OWC at Isle of Islay, LIMPET, with a 500 kW electric generator.



LIMPET

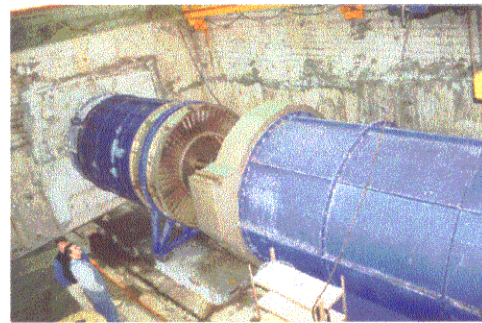
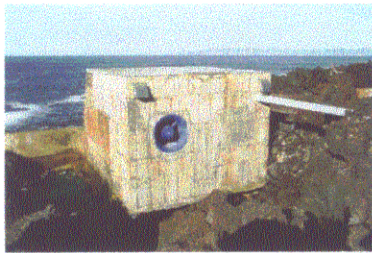
- Right: The 500 kW turbine to be installed with the new OWC.



- Left: The old Islay OWC is seen in the background (right). The new LIMPET device is indicated on the left.

The Pico Power Plant, Azores

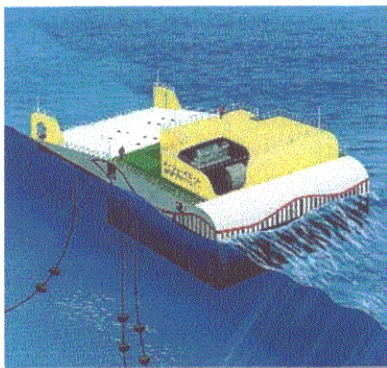
- An OWC pilot plant is now (1999) being tested on the island of Pico, Azores.
- The project is sponsored by the European Commission (JOULE programme) and coordinated by Instituto Superior Técnico in Portugal. It has a bottom-standing concrete structure and a water plane area of 144 m². The installed turbine has a rated power of 400 kW. Apart from being a test plant, the device is supposed to provide 8-9 % of the annual electrical energy demand of the 15 thousand islanders.



Air duct with turbine and air valve for the Pico wave power plant

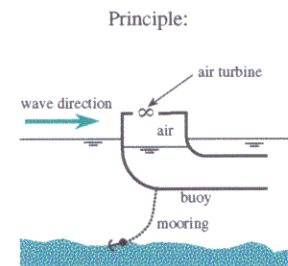
The MIGHTY WHALE

- A full-scale design of a device called the "Mighty Whale" has been constructed in Japan, and now (1999) sea trials are carried out in Gokasho bay.

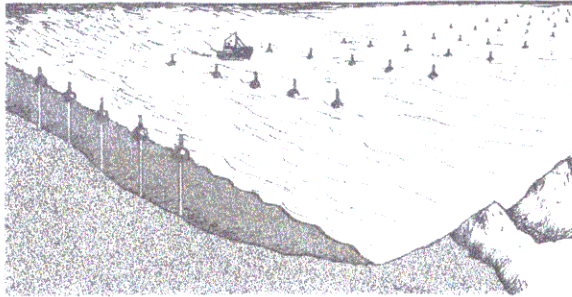


Backward bent duct buoy

- This buoy shape was proposed by the Japanese inventor and scientist Yoshio Masuda. The waves cause the hull to move, thereby giving rise to a change of the water level in the chamber. Results from wave tank tests have been very promising.

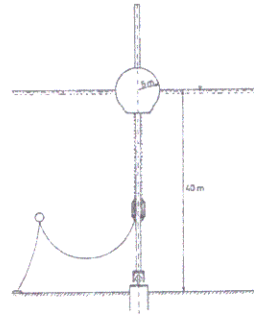


Array of point absorbers



Source: SINTEF, Norway, 1982.

The Trondheim point absorber



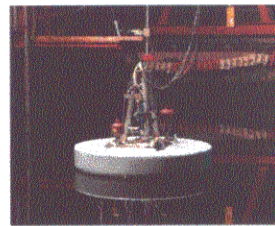
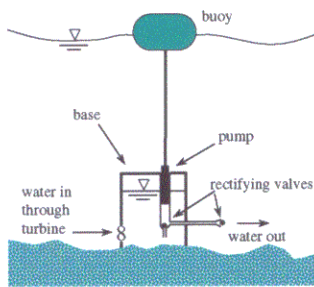
Source: K. Budal, 1981



Photo: J. Falnes, 1983

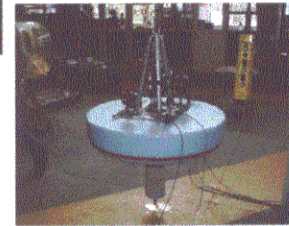
KN's device

- A proposal by Kim Nielsen in Denmark consists of a heaving buoy connected to a bottom-standing concrete base. The motion of the buoy results in a pumping that lowers the pressure in and removes water from the base housing. Then water from outside can drive the low-pressure turbine which generates electricity.



The RAMBØLL point absorber

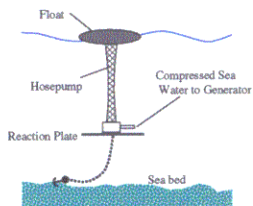
- The Rambøll point absorber represents a continuation of the work with the KN device in Denmark. A difference is that the power take-off is in the floating buoy in stead of a housing on the sea bed



Photos: RAMBØLL, Denmark, 1998

The Swedish hose pump

- This Swedish heaving buoy has uses a specially designed hose to pump sea water to high pressure.



Source: Tom Thorpe, UK



Photo: Technocean, Gothenburg, Sweden, 1984

Three hosepump units placed in the sea at Vinga, off the Swedish west coast.

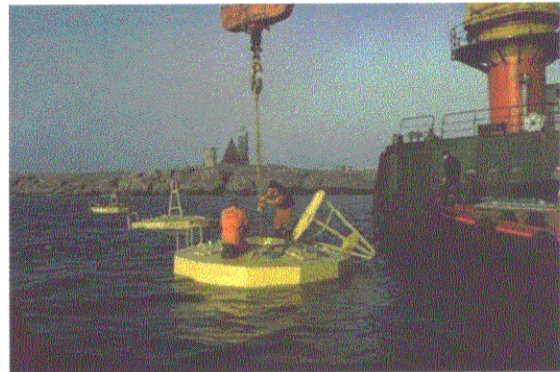


Photo: Technocean, Gothenburg, Sweden, 1984

The Swedish IPS buoy

The wave-power IPS buoy slides up and down along a vertical rod connected to inertial mass some distance down in the water. By mechanical or hydraulic means, activated through the relative motion between the buoy and the rod, wave energy is converted to useful energy.

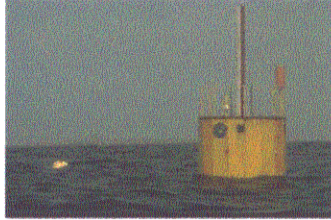


Photo: Technocean, Gothenburg, Sweden, 1981

Chinese navigation light buoy

- In China, research has been carried out at more than ten universities since 1980. The picture shows a 60W Chinese navigation light buoy, deployed in 1985 by Guangzhou Institute of Energy Conversion.



Wave-activated Generator for Navigational Buoy
Photo: Niandong Jiang, China, 1987

The ConWEC device

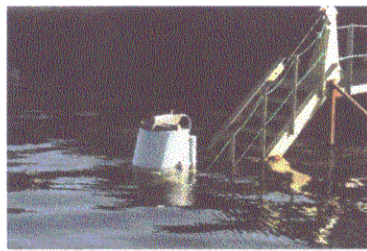
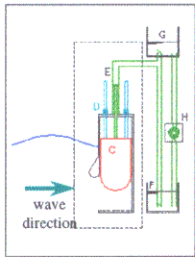
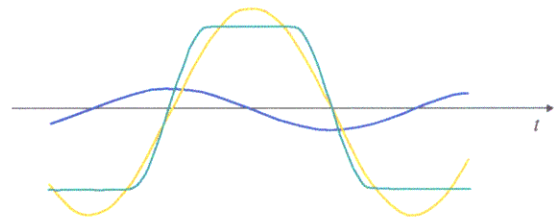


Photo and figure: ConWEC, Norway, 1998

- ConWEC is an OWC device where the more usual air turbine is replaced by a float with hydraulic power take-off.

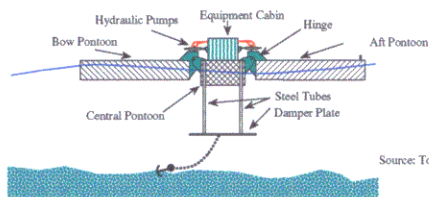


Optimal phase at resonance

Phase control by latching

Pitching raft

- A system called the McCabe Wave Pump has been designed to produce drinking water or electricity by use of wave energy. It has been developed by Dr. Peter McCabe and a team of engineers from Hydam Technologies Limited in Ireland. The device makes use of the slope change on the water surface due to waves. A 40 m long prototype was launched in the Shannon River near Kilbaha, County Clare in Ireland in 1996.



Source: Tom Thorpe, UK

Animation of "Pelamis"

pursued by the Scotch company
OCEAN POWER DELIVERY LTD.

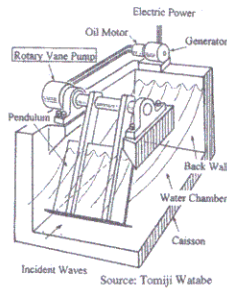
<http://www.oceanpd.com>

The Pendulor



Photo: Tomiji Watabe, 1999

- A new design of a device called Pendulor is being tested (picture) in the sea near Muroran, Hokkaido, Japan.

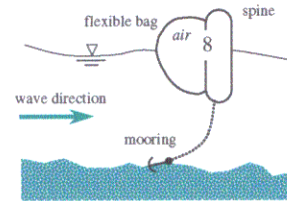


Source: Tomiji Watabe

The SEA Clam

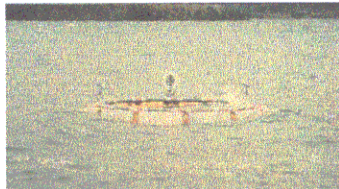
- As a part of the UK Wave Energy Programme, research and development have been carried out by Coventry Polytechnic in England. The result is a flexible bag device called the SEA Clam. A circular design was tested at 1/15th scale in the Scottish lake Loch Ness in 1986.

Principle:



Test of 1:15 scale CLAM model in Loch Ness

- Model with 12 air chambers, (black) rubber membranes and instrumentation cables prepared for test.
- Below: Model with white rubber membranes under test in Loch Ness.

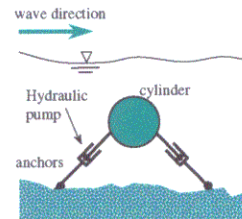


Photos reproduced by permission of L.Duckers/Sea Energy Associates, UK

The Bristol cylinder

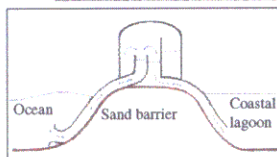
- This wave energy device was proposed by David Evans at the University of Bristol in England. In response to an incident wave the submerged horizontal cylinder oscillates vertically and horizontally. With a sinusoidal wave the combined oscillation results simply in a circular motion whereby all the incident wave energy may be absorbed provided the hydraulic power take-off is able to provide for optimum amplitude and optimum phase of the circular motion. The hydraulic power take-off is built into the anchors.

Principle:



Wave-driven sea-water pump

- In this OWC the air chamber is partly evacuated. Thus sea water is pumped across a sand barrier.



Source: S.P.R. Czitrom, Mexico, 1995

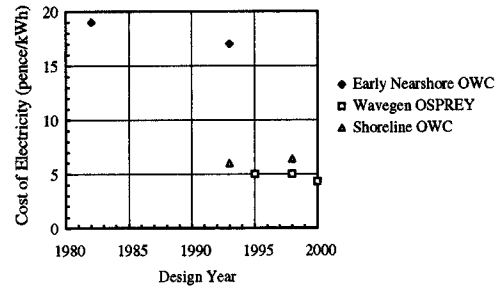
Is wave energy commercial?

- Wave energy utilisation is still in an early stage of technological development. It is commercially competitive in certain markets, such as to supply power for navigation buoys, for water desalination plants, and for isolated coastal communities with expensive electricity from diesel aggregates. With further research and development wave-energy devices will become economically competitive in an increasingly larger part of the energy market.

Cost reduction by experience and learning

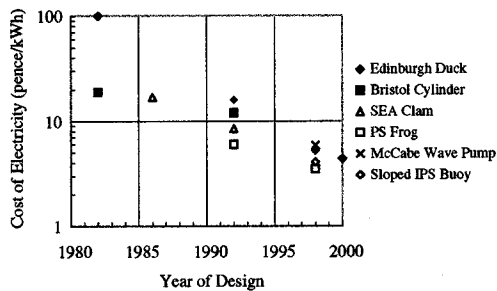
- It is a well-known fact that due to experience and improved methods of production the unit cost of a product usually diminishes as the production volume is increased. Thus, for electricity production in the US during 1926 to 1970 there was a main trend of 25 % decline in the inflation-corrected price for each doubling of the cumulative production. For retail gasoline processing the corresponding decline was 20 %. (J.C. Fischer, Energy Crisis in Perspective, John Wiley, New York, 1974.)

Estimated cost of electricity from various OWC devices versus year of design.



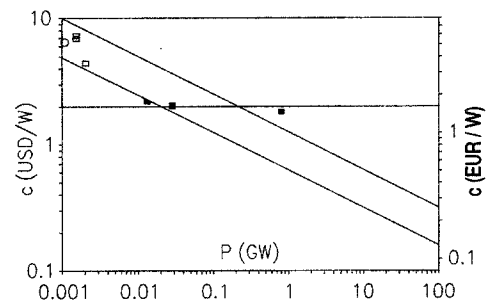
Source: Tom Thorpe, UK, 1998

Estimated cost of electricity from various offshore wave-energy devices versus year of design.



Source: Tom Thorpe, UK, 1998

Experience curve example: Estimated investment cost (c) relative to installed power capacity (P) versus cumulative volume of total installed capacity of wave power plants.



Source: J. Faloutsos, 1995

Promoting new energy technologies

- During the initial stages of the development of a new energy technology niche markets will be helpful. Otherwise, governmental subsidies to cover the difference between cost and market price may promote a new technology.

Initial handicap for new energy technologies

- Experience curves illustrate the handicap which new energy technologies have initially, in market competition with well-established conventional energy technologies. This fact must be borne in mind when comparisons are made of energy cost from new and conventional technologies. Such comparisons would be like comparing the performance of a child with the performance of an adult.