- NTNU
- Noregs teknisk-naturvitskaplege universitet
- Fakultet for naturvitskap og teknologi
- Institutt for fysikk

- Fag ENERGI OG MILJØFYSIKK - TFY4300
- (Energy and Environmental Physics)

OCEAN-WAVE ENERGY

Introductory lectures by
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9 & 11 October 2013

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Ocean waves as energy resource

- Ocean waves represent a clean and renewable energy source, come into being by conversion of wind energy when winds blow along the sea surface.
- Wind energy, in turn, originates from solar energy, because sun heating produces low pressures and high pressures in the atmosphere.
- In either of these two energy conversions, energy flow becomes intensified.

Ocean waves as energy resource

- Ocean waves represent a clean and renewable energy source, come into being by conversion of wind energy when winds blow along the sea surface. Wind energy, in turn, originates from solar energy, because sun heating produces low pressures and high pressures in the atmosphere. In either of these two energy conversions, energy flow becomes intensified.
- Just below sea surface the average wave-power level (energy transport) is typically five times denser than the wind energy transport 20 m above the water, and 10 to 30 times denser than average solar energy intensity.
- This fact gives good prospects for development of feasible commercial methods for utilisation of wave energy. Thus waves may, in future, provide substantial contributions to the energy supply of many coastal nations.

- Average energy intensity:

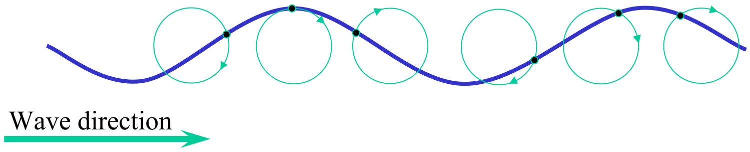
- Solar energy: 100 - 200 W/m^2
- Wind energy: 400 - 600 W/m^2
- Wave energy: 2 - 3 kW/m^2

Ocean waves represent an impressive energy resource.

What is a wave?

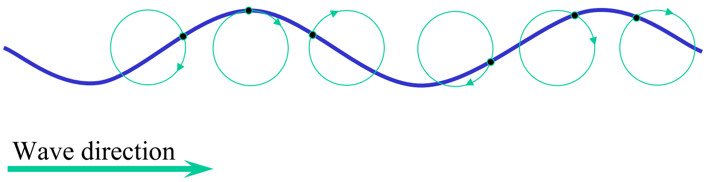
- Everyone has seen waves on lakes or oceans. Waves are actually a form of energy. Energy, not water, moves along the ocean's surface. The water particles only travel in small circles as a wave passes.

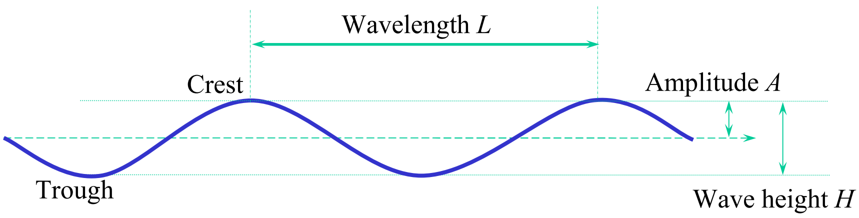
Snapshot of the water surface at a certain instant:



How to describe a wave

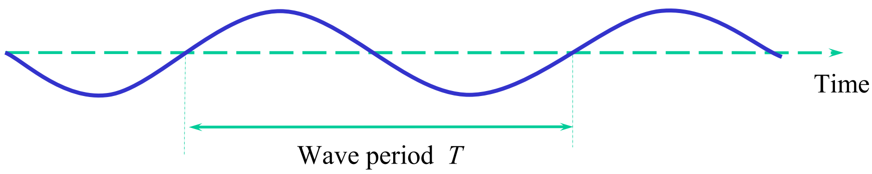
Snapshot of the water surface at a certain instant:





Surface elevation versus time

At a fixed position in space:



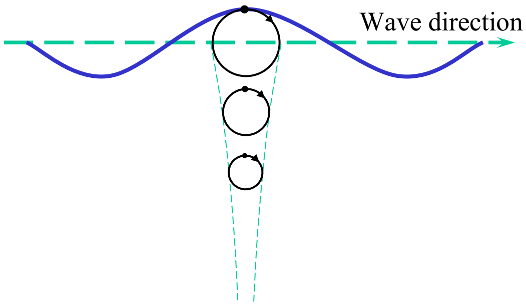
Frequency f = 1 / T

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.

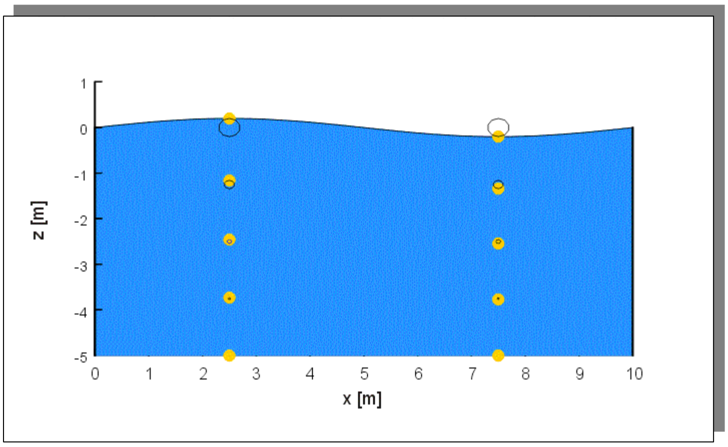


Animation of wave motion

made at
Chalmers Technical University,
Gothenburg, Sweden

CHALMERS Water Environment Transport

Particle orbits in deep water*

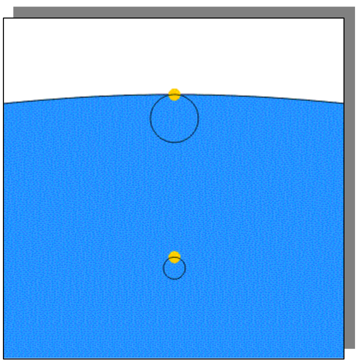


* Waterdepth larger than half the wave-length

CHALMERS Water Environment Transport

Particle orbits in deep water*

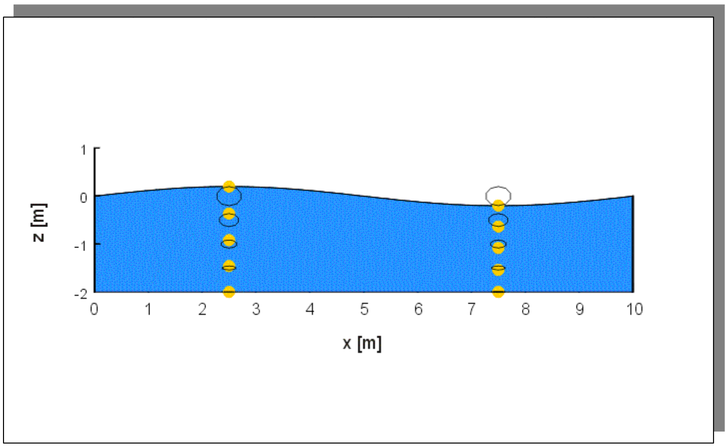
Close-up near surface



* Waterdepth larger than half the wave-length

CHALMERS Water Environment Transport

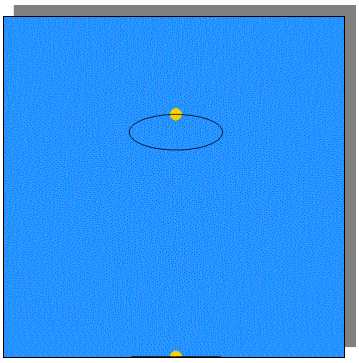
Particle orbits, shallower water



CHALMERS Water Environment Transport

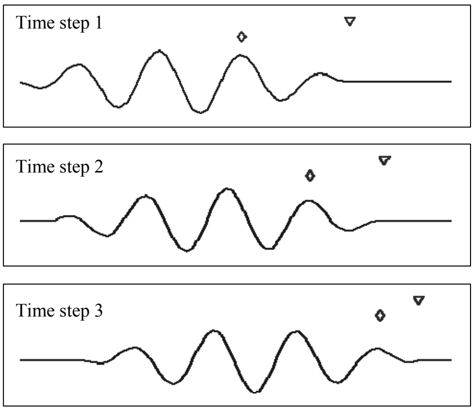
Particle orbits, shallower water

Close-up near bottom



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:

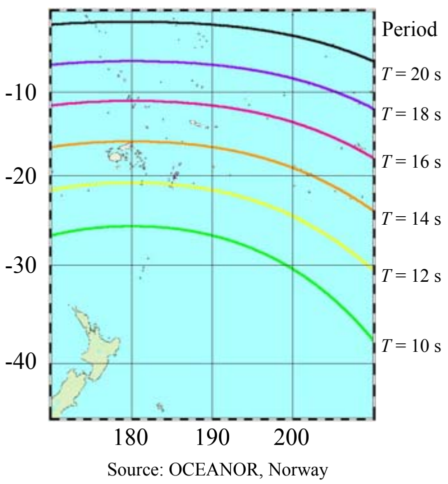


$$c = 2c_g = \frac{g}{2\pi}T = (1.56\ \mathrm{m/s^2}) \cdot T$$

Ring-shaped waves from a stone dropped into a calm lake

Photo: Magne Falnes, 1999

Swells propagating across the Pacific



Source: OCEANOR, Norway

- 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 170º east and 50º 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:

$$E = k_E H^2$$

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

ρ = mass density of sea water ≈ 1020 kg/m^3

g = acceleration of gravity ≈ 9.8 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.

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

The wave-power level

- The “wave-power level” (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

$$J = k_J T H^2$$

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

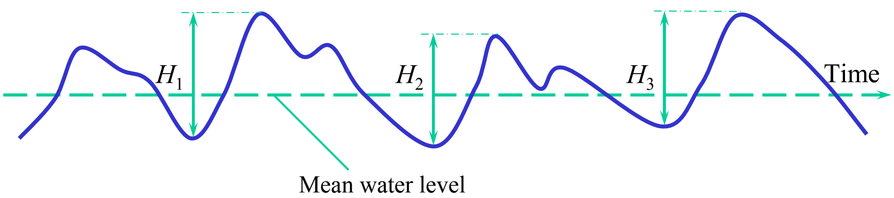
Example:

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

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,…), and is denoted by $H_{1/3}$.

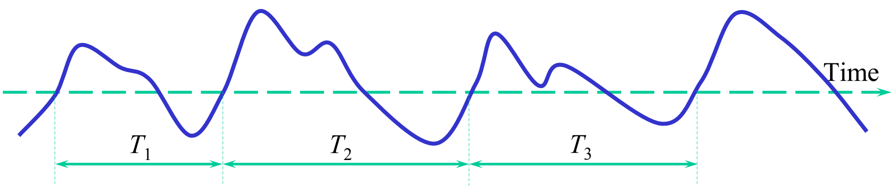
$$H_{1/3} = \frac{H_1 + H_2 + \cdots + H_{N/3}}{N/3}$$



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.

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



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

$$E = \rho g \int_0^\infty S(f)\,\mathrm{d}f \equiv \rho g H_s^{\,2} / 16$$

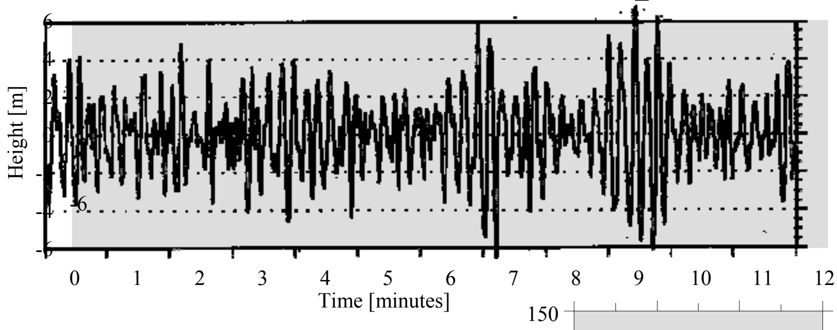
Wave-power level in terms of significant wave height

$$\int_0^\infty S(f)\,\mathrm{d}f \equiv H_s^{\,2}/16$$

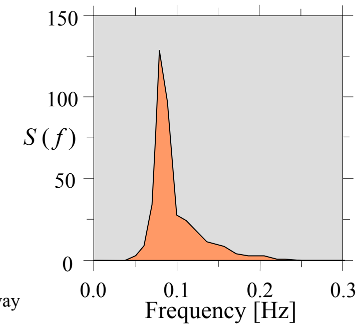
•Here H_s is the modern definition of significant wave height, which in practice agrees quite well with our previous definition $H_{1/3}$. Another quantity, the so-called wave energy period T_J, may be derived from the wave spectrum $S(f)$. The wave-power level by real sea waves is now calculated by

$$J = (k_J/2)T_J H_s^{\,2} \qquad k_J/2 \approx 0.5\ \mathrm{kW/s\,m^3}$$

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.



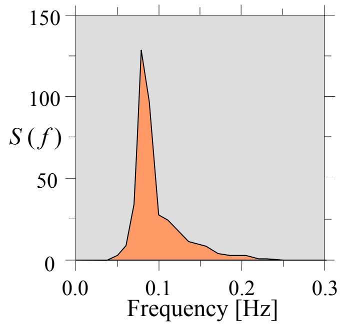
Source: OCEANOR, Norway

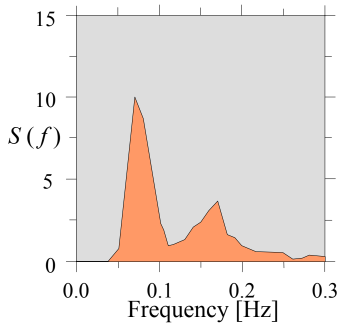
Real-sea spectra

•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 the wind waves (low peak).

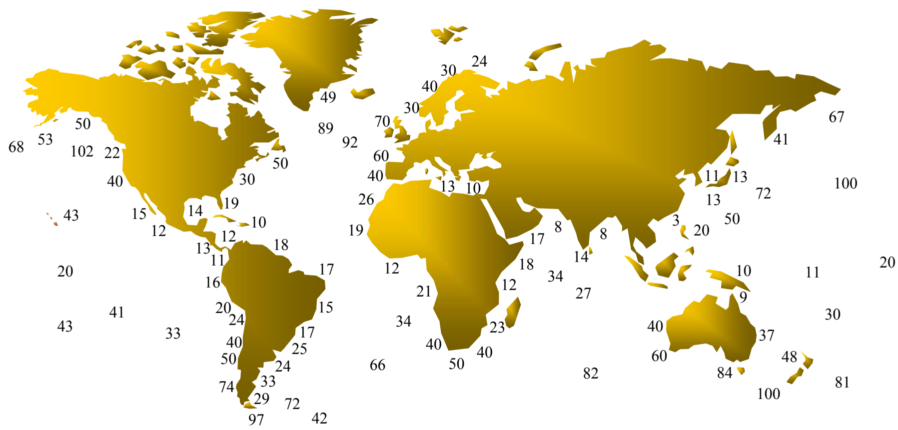
•Significant wave heights: 8 m (top) and 3 m (bottom)





Source: OCEANOR, Norway

Distribution of wave energy transport



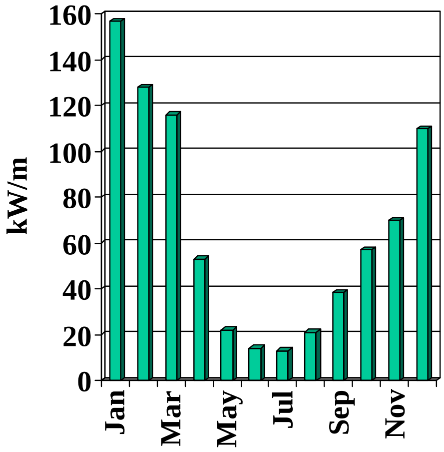
Average wave power levels are approximate and given in kW/m of the wave front.

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

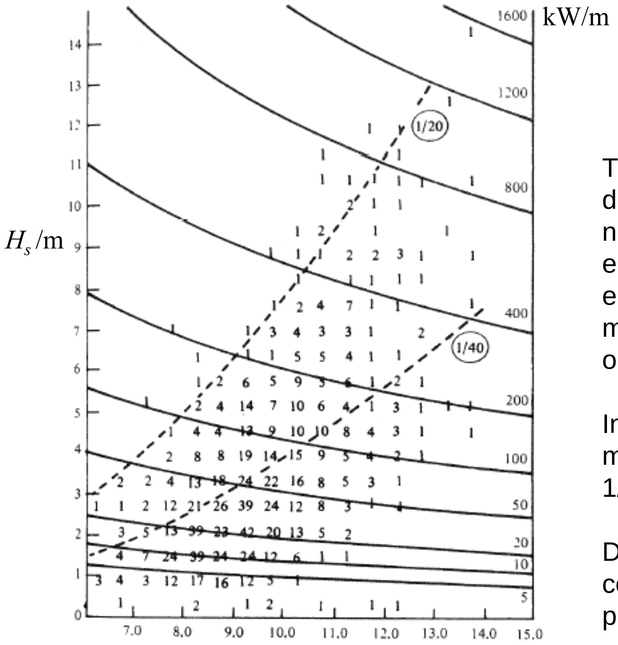


Figure after Ian Glendenning 1978 (cf. book # D6 in the list: http://folk.ntnu.no/falnes/w_e/books_wave_energy.htm).

T_z/s

“Scatter”-diagram

The numbers on the graph denote the average numbers of occurrences of each H_s -T_z combination for each 1000 wave measurements made over one year.

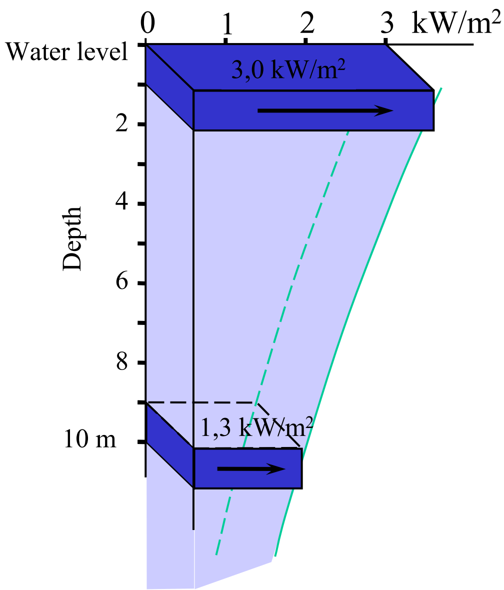
Increasing curves indicate maximum wave steepness 1/40 and 1/20.

Declining curves indicate constant values of wave-power level in kW/m.

Source : Ian Glendenning, 1977

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).

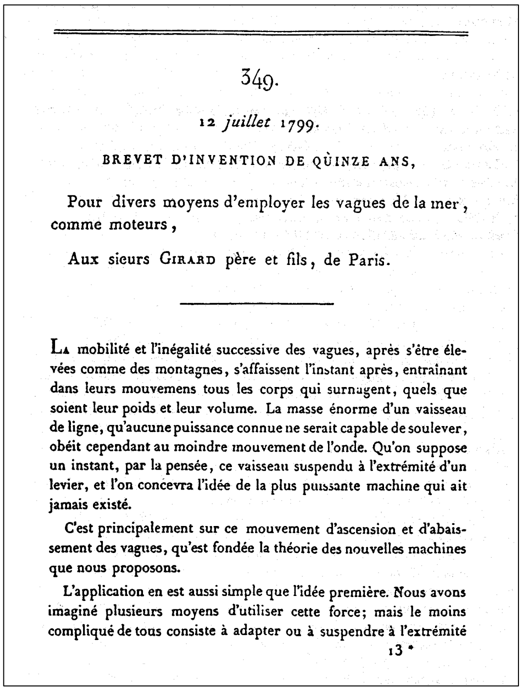


$J = 40$ kW/m

$H = 2$ m and $T = 10$ s

•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 (!).



349.

12 *juillet* 1799.

BREVET D'INVENTION DE QÙINZE ANS,

Pour divers moyens d'employer les vagues de la mer, comme moteurs,

Aux sieurs GIRARD père et fils, de Paris.

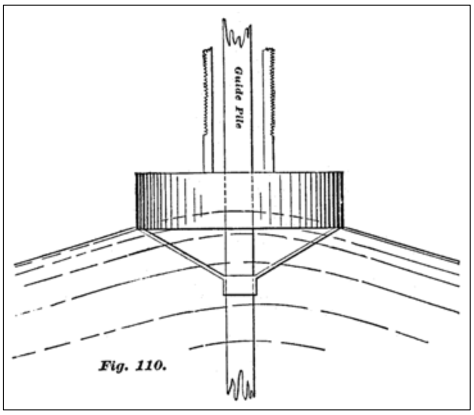
LA mobilité et l'inégalité successive des vagues, après s'être élevées comme des montagnes, s'affaissent l'instant après, entraînant dans leurs mouvemens tous les corps qui surnagent, quels que soient leur poids et leur volume. La masse énorme d'un vaisseau de ligne, qu'aucune puissance connue ne serait capable de soulever, obéit cependant au moindre mouvement de l'onde. Qu'on suppose un instant, par la pensée, ce vaisseau suspendu à l'extrémité d'un levier, et l'on concevra l'idée de la plus puissante machine qui ait jamais existé.

C'est principalement sur ce mouvement d'ascension et d'abaissement des vagues, qu'est fondée la théorie des nouvelles machines que nous proposons.

L'application en est aussi simple que l'idée première. Nous avons imaginé plusieurs moyens d'utiliser cette force; mais le moins compliqué de tous consiste à adapter ou à suspendre à l'extrémité

13 *

- 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.

MAGNE

BARNEAFHOLDSBLAD

No. 12. | 16de juni 1901. | II. aarg.

Elektriske fyrbøier.

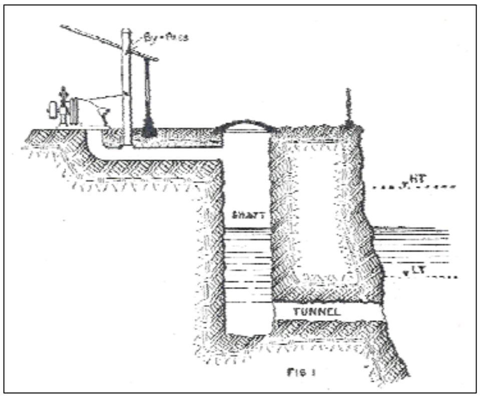
Du ved, der er en mægtig kraft i bølgeslagene. Selv om det er stille veir, saa er dog altid havbølgerne i bevægelse og kan hæve og sænke de største skibe. Nu har menneskene, som jo af Gud er sat til at herske over naturen og bruge dens kræfter i sin tjeneste, ogsaa fundet paa at bruge de kræfter, som ligger i bølgeslagene, til at fabrikere elektricitet, denne

en pumpe i bevægelse, og pumpen slynger en vandstrøm imod en turbin, og turbinen sætter en maskine igang, maskinen (dynamo kaldes den) frembringer elektricitet, og elektriciteten igjen et kraftigt lys.

Paa søen kan det være mørkt, og farlige banker, holmer og skjær truer skibene. Det er derfor godt at faa kraftige og kjendte

Front page of a 1901 issue of the Norwegian children’s magazine Magne. It talks about “Electrical light buoys” for navigation.

•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.

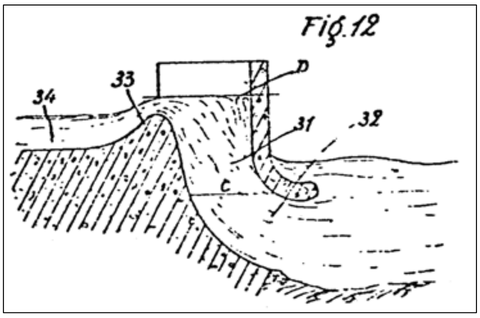


Drawing from 1920 showing Mr. Bochaux-Praceique’s device. Reprinted with permission of Power Magazine, The McGraw Hill Companies

- 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)

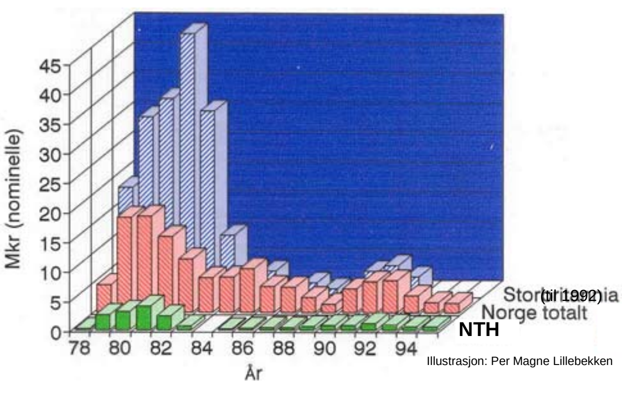
- Sea water enters a hollow structure with its lower opening submerged. Due to wave action the inside "water column" will oscillate. With the shown proposal some water at the upper part of the "column" is drained into an elevated water reservoir.



From British patent No. 741494 on oscillating water columns.

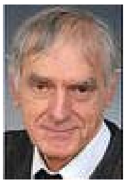
- During the late 1970s substantial wave-energy development programmes were launched by governments in several countries, in particular in the UK, Norway and Sweden. The financial support was dramatically reduced during the early 1980s when the petroleum price became lower and when there in the public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

Governmental funding of wave-energy research after 1977, for UK (to 1992) and Norway (to 1995).



Three pioneer inventors in wave-energy research

Yoshio Masuda
started 1947, in Japan, experiments on technical devices to utilise energy of waves.



Stephen Salter
started wave-energy research in 1973 at the University of Edinburgh, Scotland.

Kjell Budal
initiated wave-energy research in 1973 at the technical university NTH in Trondheim, Norway.

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

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.

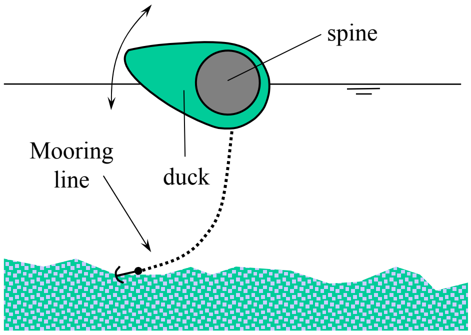


Illustration: Jørgen Hals 1999

Salter’s nodding Duck

Scotland (Stephen Salter, University of Edinburgh)

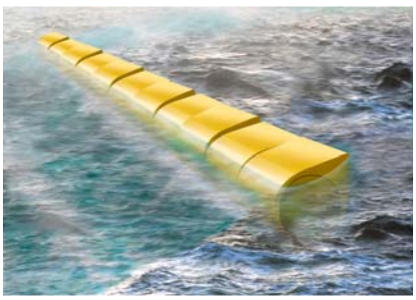


Illustration: Bjarne Stenberg, 2007

Energy conversiond through pumps, pressure tank, hydraulic motor an electric generator

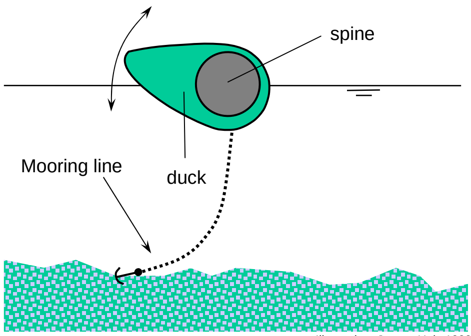


Illustration: Jørgen Hals 1999

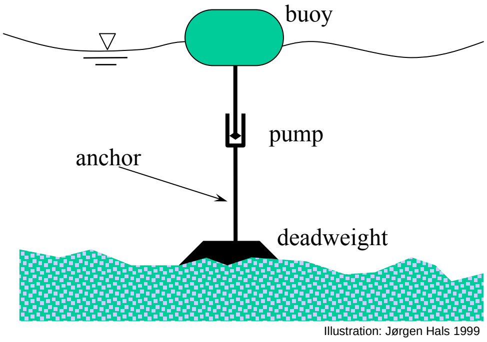
Research work in Edinburgh with the spine, a long tube, at least 100 m long, has evolved into the Pelamis project:

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.

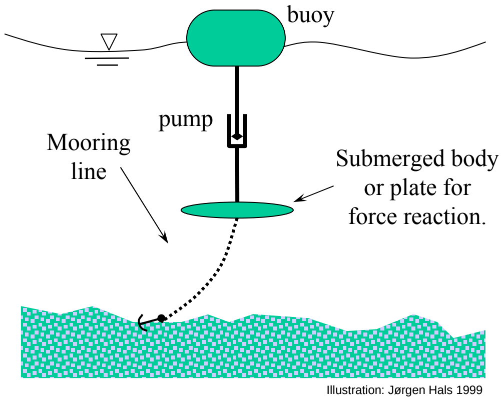
Force reaction

- 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.

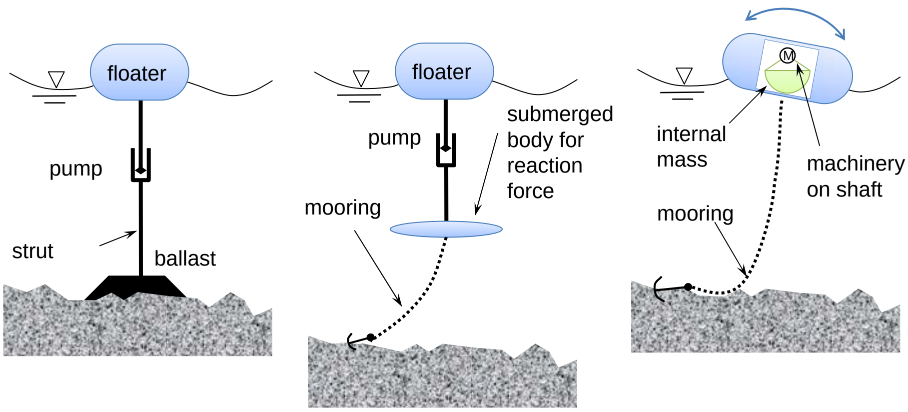


Force reaction

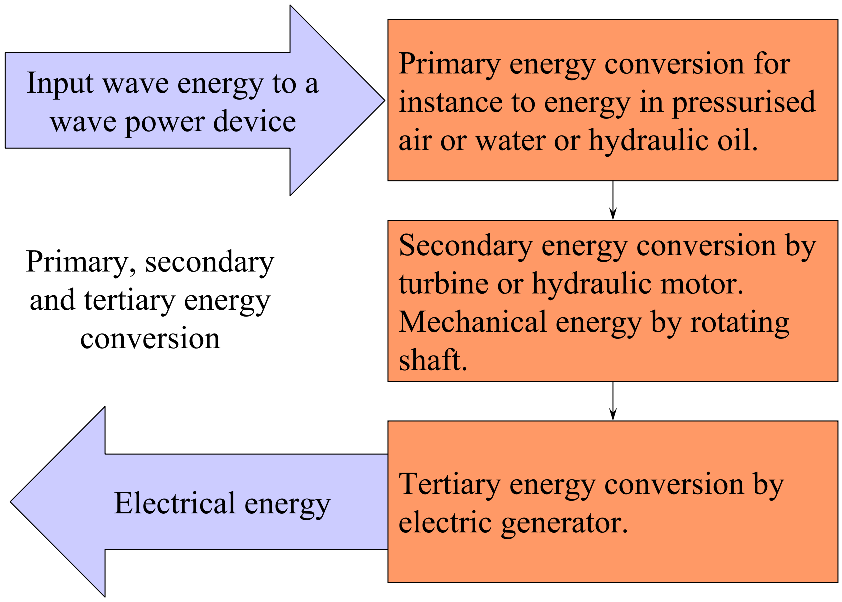
- against sea bed

- against another immersed body

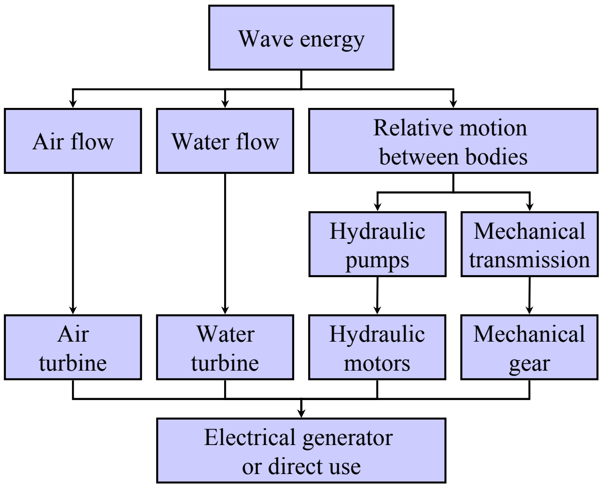
- against another internal body

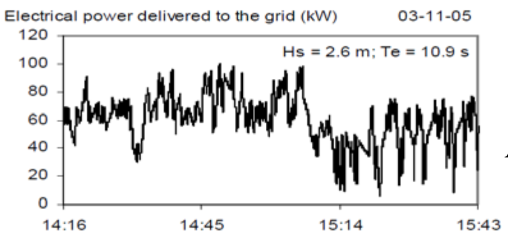


Steps of wave-energy conversion



Power take-off alternatives

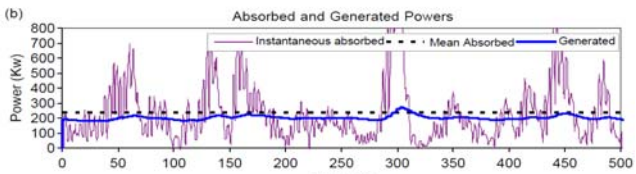




Air turbine,
Pico plant

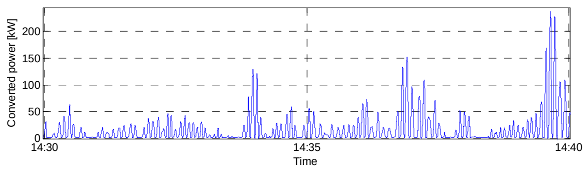
Instantaneous power:
- acceptable
for the grid?

Source: Neumann et al., 2006



Source: Henderson, 2006

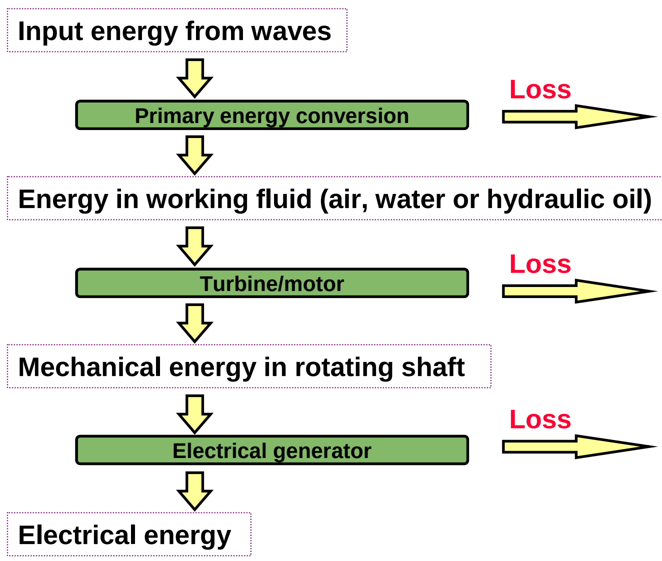
Hydraulic machinery, Pelamis



Direct driven generator, AWS

Graph, drawn by J. Hals, based on prototype testing data received 2007 from Teamwork Technology.

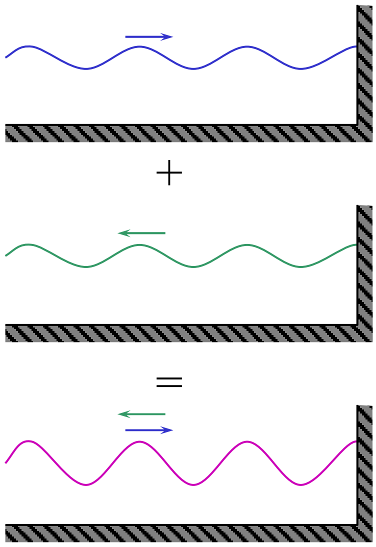
Schematic principle for extracting wave energy



A paradox?

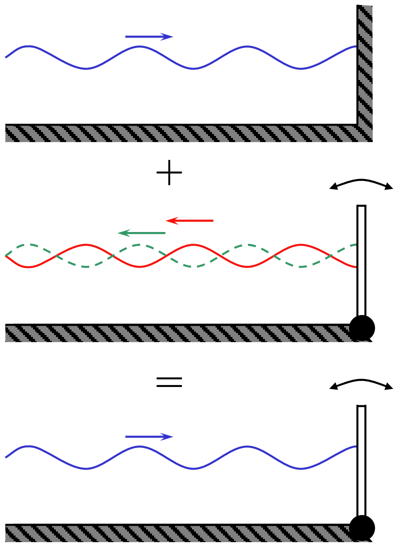
- Absorption of wave energy from the sea may be considered as a phenomenon of wave interference. Then wave energy absorption may be described by an apparently paradoxical statement:
    - ***To absorb a wave means to generate a wave***
- or, in other words:
    - ***To destroy a wave is to create a wave.***

Incident wave + reflected wave = standing wave



- Incident wave
- Wave reflected from fixed wall
- Interference result: Standing wave composed of incident wave and reflected wave

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



- Incident wave
- Wave reflected from fixed wall
- Wave generation on otherwise calm water (due to wall oscillation)
- The incident wave is absorbed by moving wall because the reflected wave is cancelled by the generated wave.

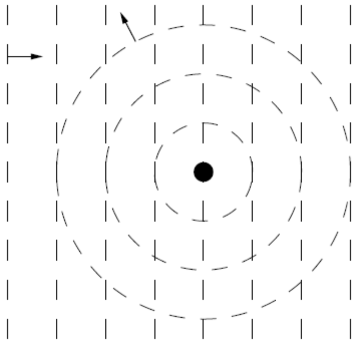
In this simple example, at optimum radiated-wave generation, the maximum absorbed energy equals 100 percent of the incident wave energy. Not also that the required, optimum, radiated wave has the same amplitude as the incident wave. Thus,

$$P_{r,OPT} = P_{a,MAX}$$

Observe that, in order to absorb, from the sea, the theoretically maximum wave power, **it is necessary that the wave-absorbing oscillating system, at optimum, has an *ability* to radiate as much power as the theoretically maximum absorbed power.**

This statement is valid also for systems of different geometrical configurations, where the maximum absorbed power is less than 100 percent of the incident wave power, provided **the required optimum oscillation can be realised**, that is, when no physical amplitude limitation, or other constraint, prevents the desired radiated wave from being realised.

Plane incident wave interfering with an outgoing isotropic wave:



For any vertically oscillating axisymmetric body, the maximum absorbed power equals the wave-power level *J* multiplied by the wavelength *λ* divided by 2*π*:

$$P_{a,MAX} = J/k = J\lambda/2\pi$$

$$P_{r,OPT} = P_{a,MAX}$$

[These theoretical results were derived about 1976, independently, by research teams at NTH (Norway), at University of Bristol (UK) and at MIT (USA).]

For a single wave-energy converter (WEC) unit, how large should the installed power take-off (PTO) machinery be?

And how large should the hull volume be?

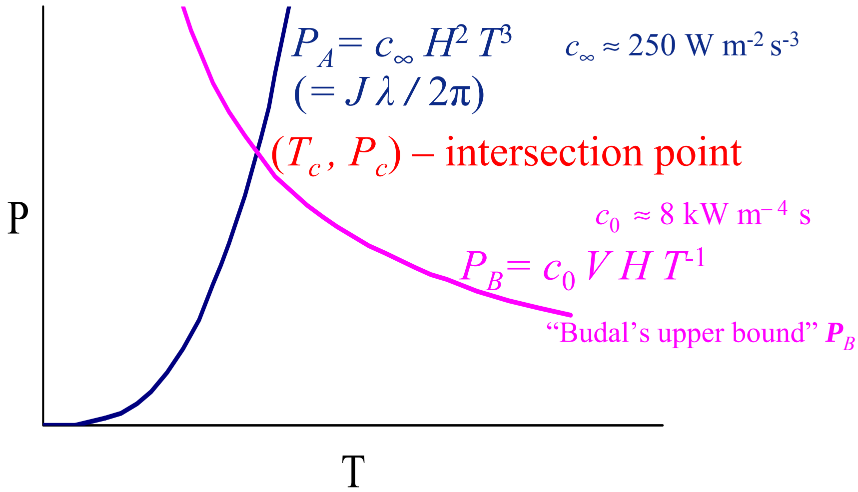
Should the hull volume be large enough for generation of our optimum radiated wave?

YES, for rather small incident waves.
NO, for larger waves or for extreme waves! Then the absorbed power will be larger than the radiated power.

The physical size of the WEC unit, and the power capacity of the PTO machinery, should match the wave climate. Require that the machine capacity is fully utilised for, e.g., one third of an average year!

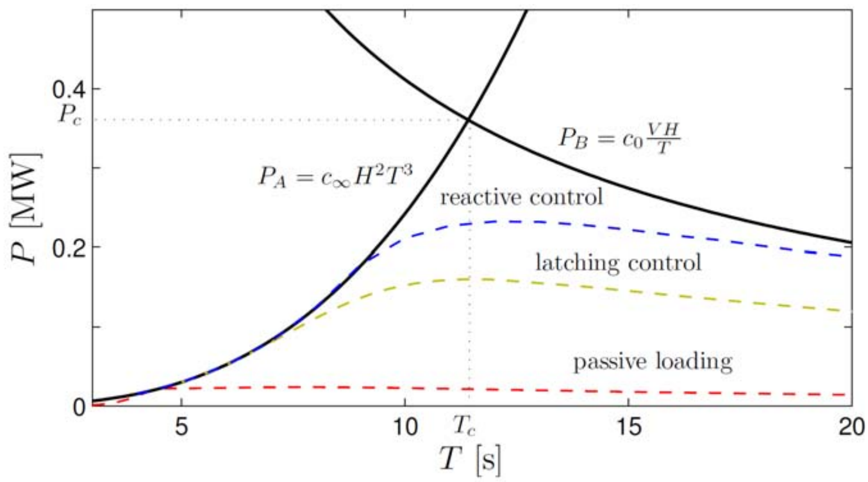
[Falnes, J. and Hals, J. Heaving buoys, point absorbers and arrays. *Philosophical Transactions of the Royal Society A*, Vol 370, No 1959, pp 246-277, 28 January 2012. (doi: 10.1098/rsta.2011.0249).]

Two upper bounds for absorbed wave power P



V – swept volume. $H = 2A$ – wave height. T – wave period.

$H = 2A = 1$ m. $V = 500$ m^3 (heaving semisubmerged sphere, 10 m diameter).



$P_{a,\text{react}}/P_c \sim 0.6$ $P_{a,\text{latch}}/P_c \sim 0.5$

$P_{a,\text{passiv}}/P_c$ typically within 0.05 – 0.2, depending on V and H.

Some important concluding remarks

- - - of the paper (doi: 10.1098/rsta.2011.0249). "**Heaving buoys, point absorbers and arrays**".(by Falnes & Hals, 2012) in *Philosophical Transactions of the Royal Society A*, Vol 370, pp 246-277.]

To absorb a wave means to radiate a wave.

Match WEC's swept volume and PTO capacity to the wave climate.

WEC volume not larger than 300 cubic metre (for wave climate as off the western coast of Scotland).

Power capacity in the range of 0.1 to 0.4 MW, depending on type of phase control.

Develop one viable WEC unit before investing too much in developing a sizable wave-power plant (array, consisting of hundreds or thousands of single WEC units).

Focusing of waves

For a rough wave climate as off the western coast of Scotland, the volume of a WEC unit should not be larger than 300 cubic metre.

And the power capacity should be in the range of 0.1 to 0.4 MW, depending on type of phase control.

The volume, as well as the power capacity, may preferably be larger if waves are focused and if the WEC unit is located in the focal area.

Artificial focusing of water waves by means of submerged lens structures has been proposed and tested.

Mehlum, E.: "Recent developments in the focusing of wave energy". Proc. 2nd Internat. Symp. Wave Energy Utilization (H. Berge, ed), pp 419-420, Tapir, Trondheim,1982.
Stamnes, J.J., Løvhaugen, O., Spjelkavik, B., Mei, C.C.,Lo, E. and Yue, D.K.P. "Nonlinear focusing of surface waves by lens theory and experiments". Journal of Fluid Mechanics, Vol 135, pp 71-94, 1983.

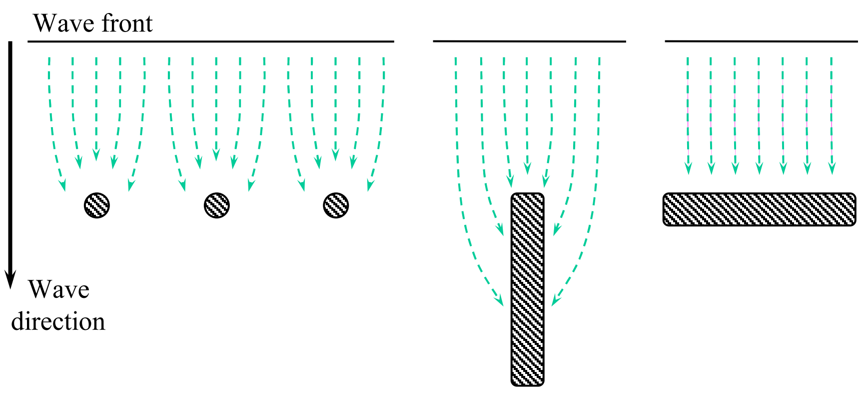
Kjell Budal proposed artificial focusing of water waves by means of parabolically arranged dynamic reflectors.

See Section 6.2 (pp 64-73) in Kyllingstad, Å. "Approximate analysis concerning wave-power absorption by hydrodynamically interacting buoys". Thesis for the "dr.ing." degree, NTH, University of Trondheim, 1982.

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).

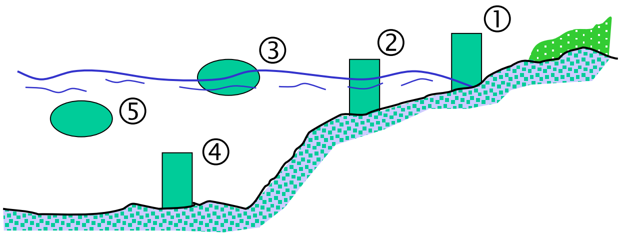
- According to size and orientation



- Point absorbers
- Attenuator
- Termi-nator

- 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

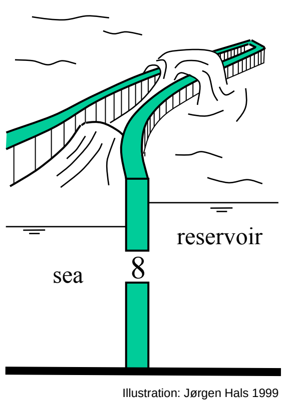
- According to form of primary energy conversion

- 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

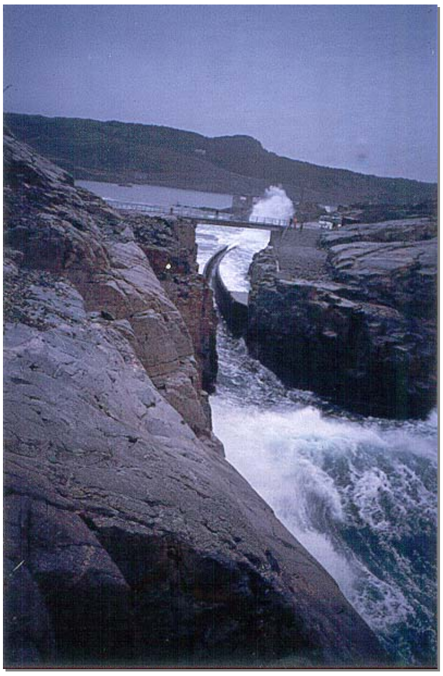
- The tapered channel is a horizontal channel which is wide towards the sea where the waves enter and gradually narrows in a reservoir at the other side. As the waves pass through the channel, water is lifted over the channel wall and into the reservoir due to the shortage of space which occurs as the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

Principle:

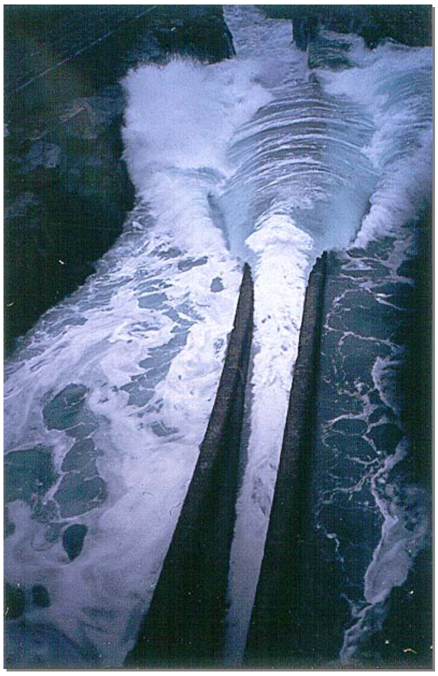


NORWAVE's TAPCHAN

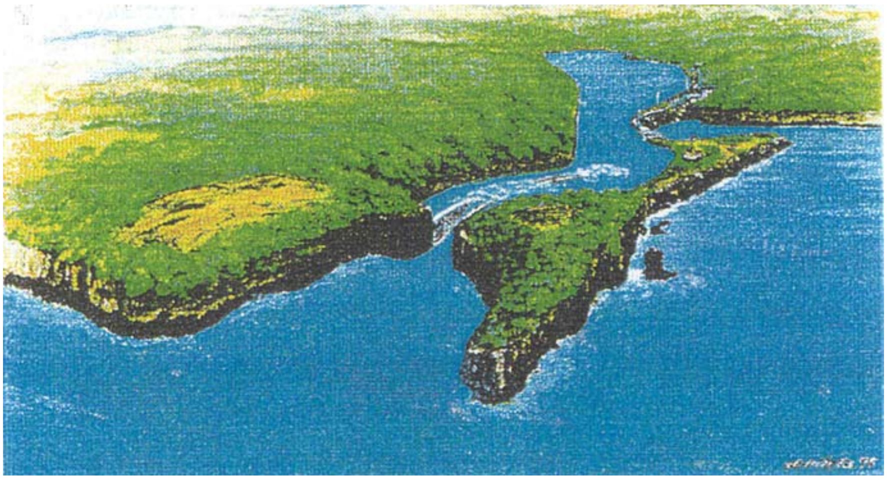
•A tapered channel demonstration plant was built in 1985 at Toftestallen on the west coast of Norway. Due to the tapering of the horizontal channel, water is lifted to the reservoir 3 m above. The water in the reservoir flows back into the sea (behind the reservoir dam and turbine house) through a conventional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



- 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 impressing view as the water overtops the walls and bursts into the reservoir at Toftestallen.



INDONOR's planned TapChan power plant in Indonesia



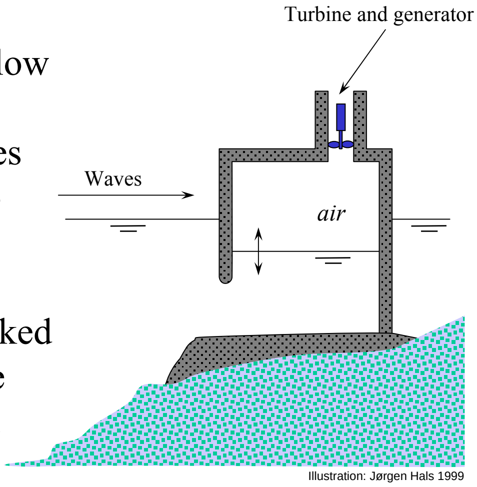
Installed power: 1,1 MW
Reservoir level: 4 m
Reservoir surface: 7000 m^2

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.

Principle:



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

- 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.

Sanze shoreline gully

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. Falnes, 1985.

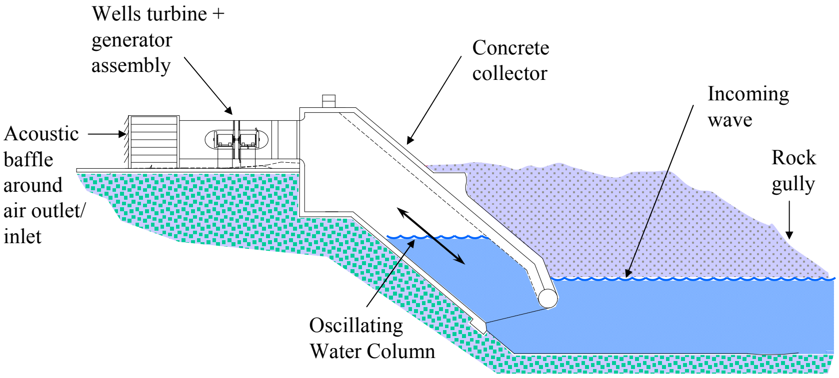
Shoreline OWC, Isle of Islay, Scotland

Photo: Håvard Eidsmoen, 1993

- 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 decommisioning, as a new, improved design, LIMPET, is under construction just north of the previous site (next slide).

LIMPET

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



Source: WAVEGEN, UK, 1999

LIMPET

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

Source: WAVEGEN, UK

Source: WAVEGEN, UK

- 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


Photo: A. Sarmento, IST, Portugal, 1999

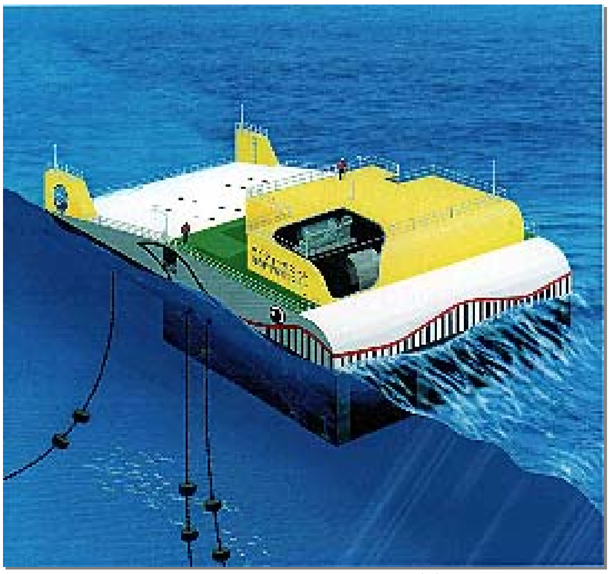
- An OWC pilot plant
- is now (1999) being
- tested on the island
- of Pico, Azores.
- The project is
- sponsored by the European Commission (JOULE programme) and coordinated by Instituto Superior Técnico in Portugal. It has a bottom-standing concrete structure and a water plane area of 144 m^2. The 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.


Photo: A. Sarmento, IST, Portugal, 1999

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

Yoshio Masuda

- This buoy shape was proposed by the Japanese inventor 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.

Principle:

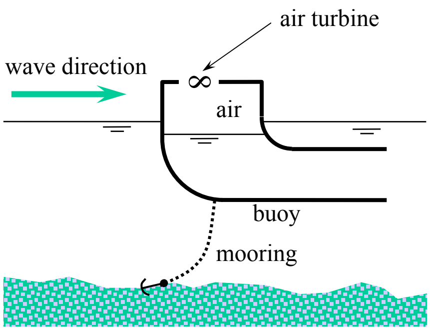
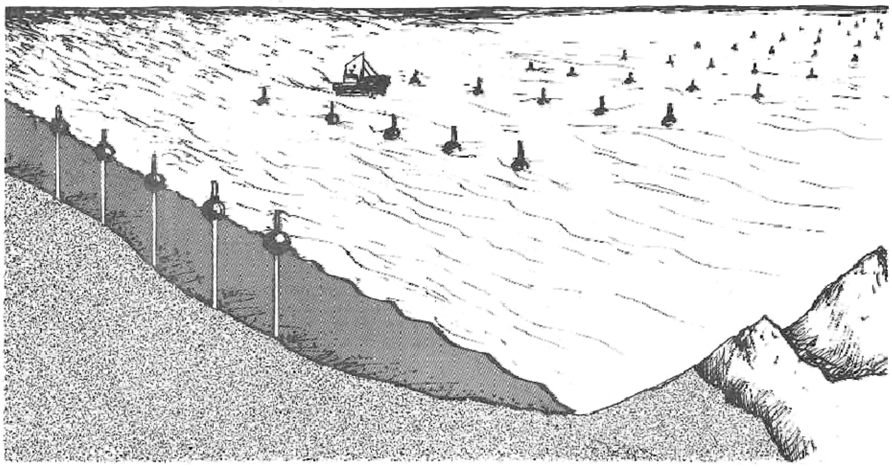


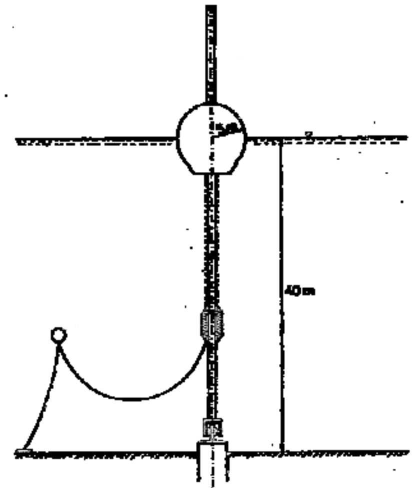
Illustration: Jørgen Hals 1999

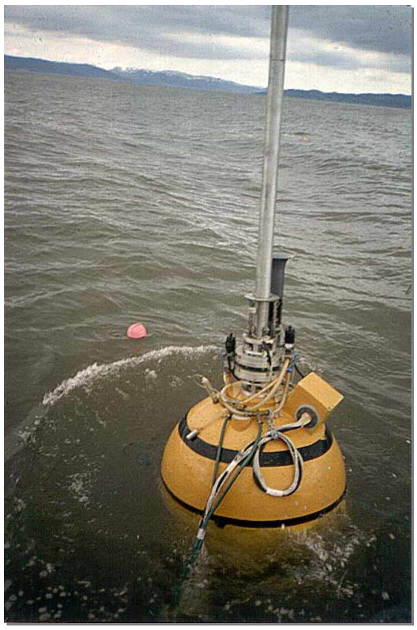
Array of point absorbers



Source: SINTEF, Norway, 1982.

The Trondheim point absorber





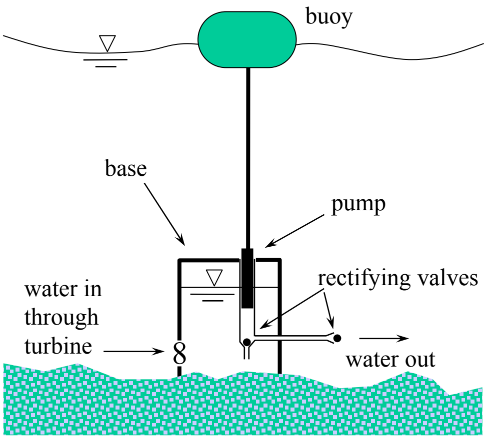
Source: K. Budal, 1981

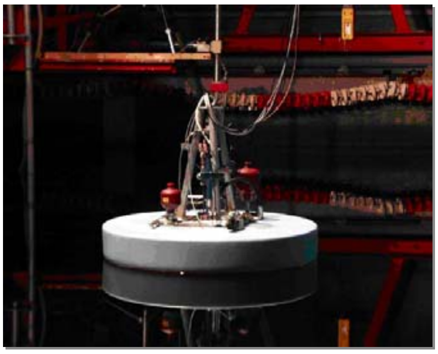
Photo: J. Falnes, 1983

Phase-controlled power-buoy model (type E) under test in the Trondheim Fjord, 1983. Video clip [also on http://folk.ntnu.no/falnes/w_e/.]

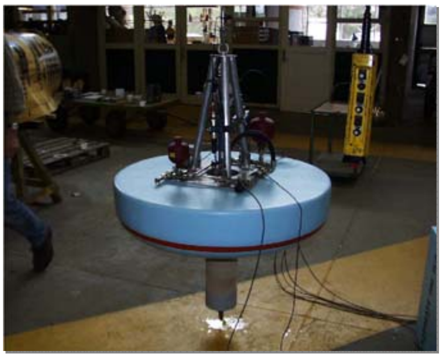
KN's device

- 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

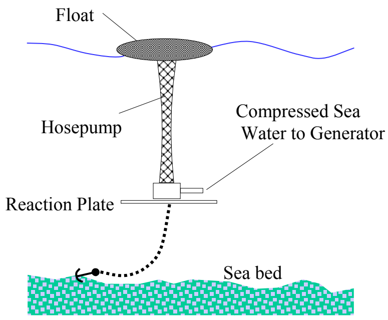


- The Rambøll point absorber represents a continuation of the work with the KN device in Denmark. A difference is that the power take-off is in the floating buoy in stead of a housing on the sea bed

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

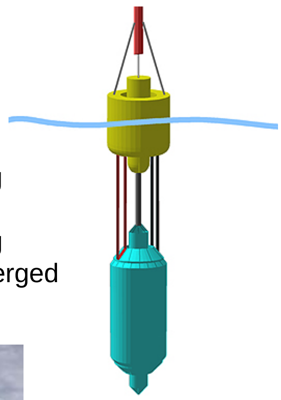
Chinese navigation light buoy

- 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.

Photo: Niandong Jiang, China, 1987

Oscillating buoys

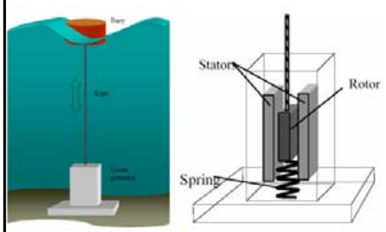
Wavebob (I)



Irish WEC utilising relative motion between a floating body and a submerged body.

Seabased AB (S)

Svedish heaing-body system with bottom-based linear electric generator for power take-off.



www.seabased.com

The ConWEC device

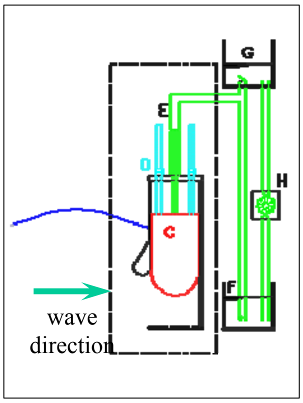
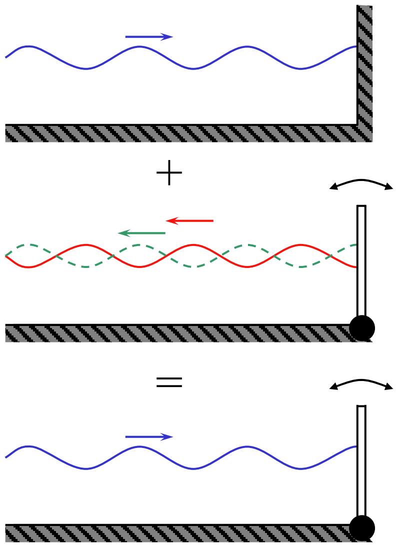


Photo and figure: ConWEC, Norway, 1998

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

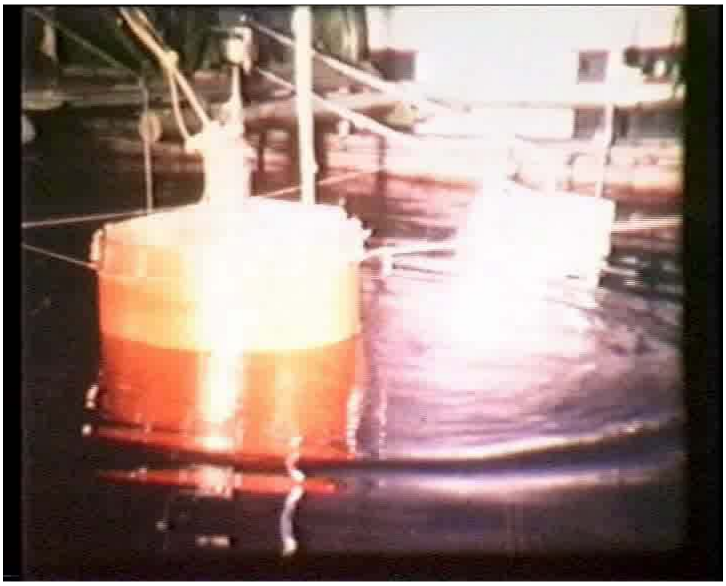
"To absorb a wave means to generate a wave"
- or "to destroy a wave means to create a wave".



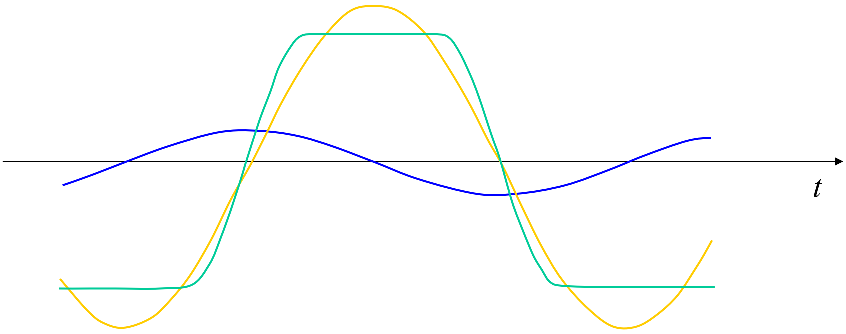
- Incident wave

- Wave reflected from fixed wall
- Wave generation on otherwise calm water (due to wall oscillation)

- The incident wave is absorbed by moving wall because the reflected wave is cancelled by the generated wave.

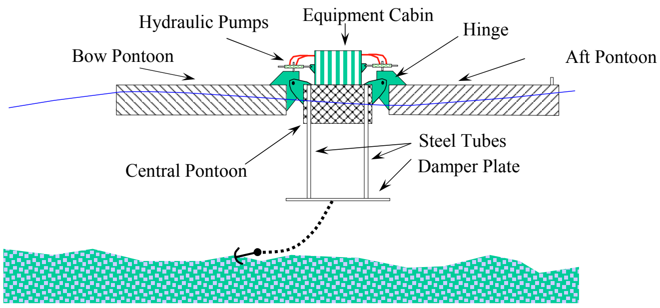


Phase-controlled power-buoy model (type E) under test in Skipsmodelltanken, Trondheim, 1978. Video clip [also on http://folk.ntnu.no/falnes/w_e/.]



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.



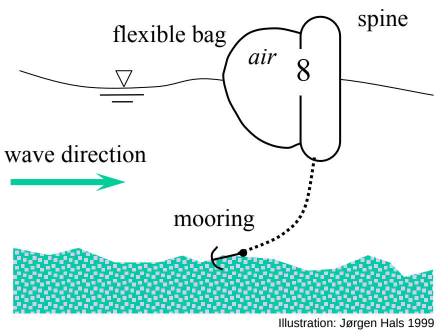
Source: Tom Thorpe, UK

Video clip of "Pelamis" PELAMIS WAVE POWER LTD <http://www.pelamiswave.com/videos>.

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.

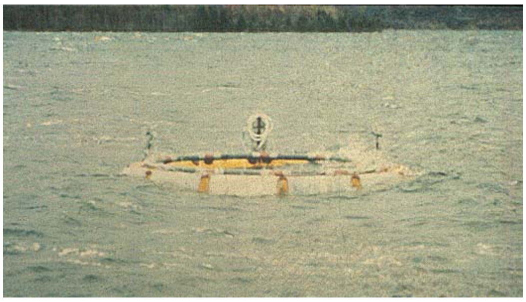
Principle:



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.

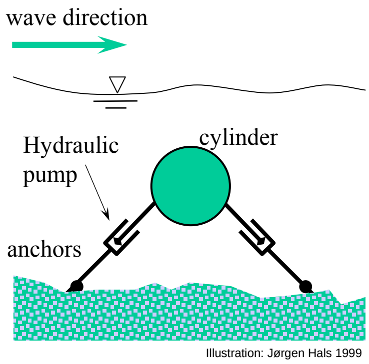


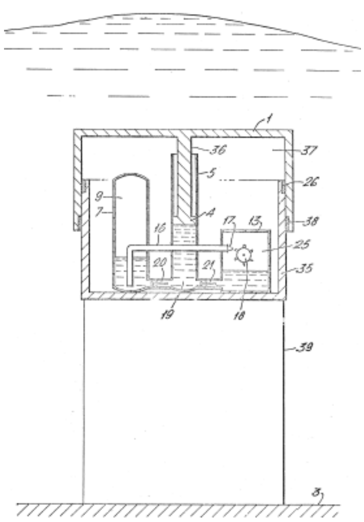
Photos reproduced by permission of L.Duckers/Sea Energy Associates, UK

The Bristol cylinder

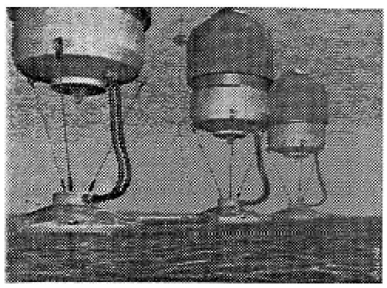
- This wave energy device was proposed by David Evans at the University of Bristol in England. In response to an incident wave the submerged horizontal cylinder oscillates vertically and horizontally. With a sinusoidal wave the combined oscillation results simply in a circular motion whereby all the 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:





A phase-controlled submerged pulsating-volume device with hydraulic power take-off
(Budal patent. Application filed 1977)



Artist impression of a cluster of AWS devices
(in 3EWEC-1998 paper by Rademakers, van Schie, Schuitema, Vriesema and Gardner)

Cf. “Archimedes Installation at EMEC Next Year”, Maritime Journal, 30 July 2008.

AWS

“Archimedes Wave Swing”

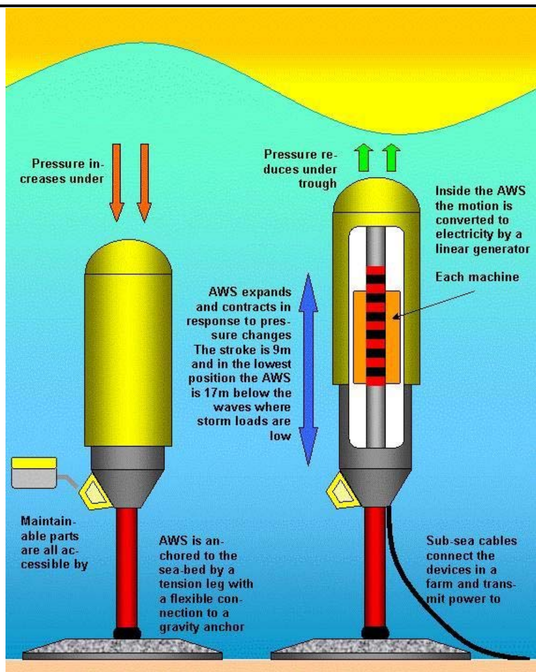
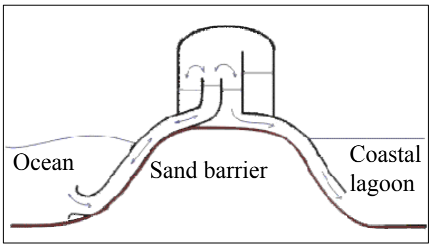


Illustration in the paper “Archimedes Installation at EMEC Next Year”, Maritime Journal, 30 July 2008.

http://www.maritimejournal.com/archive101/2007/september/renewables/archimedes_installation_at_emec_next_year

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

Photo: J. Falnes, 1989

Will these children on Rarotonga later in their lives be able to enjoy the waves in yet another way?

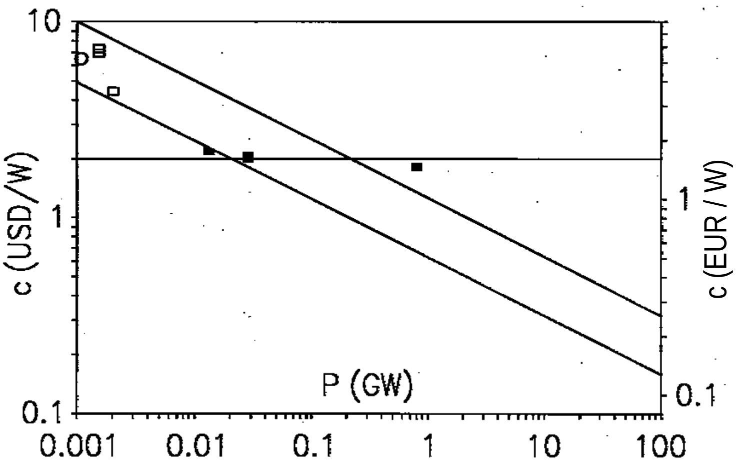
Is wave energy commercial?

- 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.)

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. Falnes, 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.