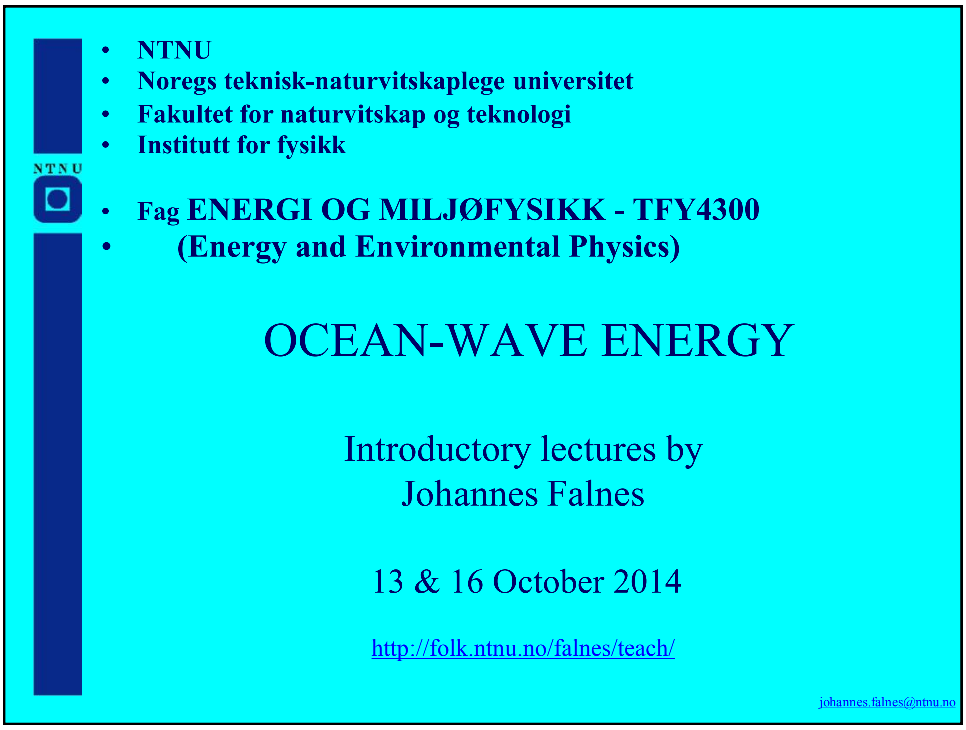
File <“**JF_introduction2010-06-28.pdf** ”>

In the revised version, the third edition (2015), of the textbook «**Renewable Energy Resources**» by John Twidell and Tony Weir, there is, at the end of Chapter 11, a reference to my web page <JF_introduction2010-06-28.pdf> concerning additional information on **ocean-wave-energy** conversion. As I discovered this reference, I was prompted to revise this URL site.

Johannes Falnes

After my retirement in 2001, I have every automn term presented four wave-energy lectures (each 45 min.) within NTNU’s course TFY4300 «Energy and Environmental Physics» -- see my web pages http://folk.ntnu.no/falnes/teach/index.html and http://folk.ntnu.no/falnes/teach/wave/TFY4300/index.html. The following PDF-pages 2-43 (slides 3-85) show slides used during my 2014 presentation in this course. Moreover, PDF-pages 44-63 (slides 87-126) show some of the slides used in my introductory lecture 2010-06-28 for an advanced 2-week «WAVETRAIN-2» course on ocean-wave-energy conversion, where I presented 25 lectures, most of them based on my 2002 textbook «Ocean waves and oscillating systems». JF, 2015-08-10.



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

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

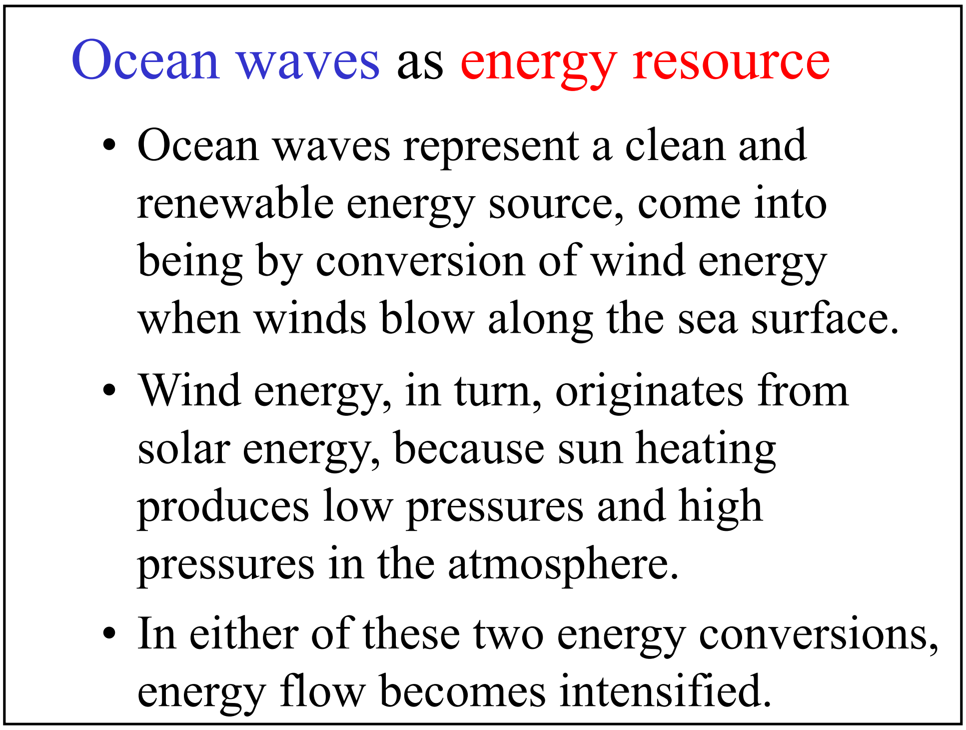
OCEAN-WAVE ENERGY

Introductory lectures by
Johannes Falnes

13 & 16 October 2014

http://folk.ntnu.no/falnes/teach/

johannes.falnes@ntnu.no



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:

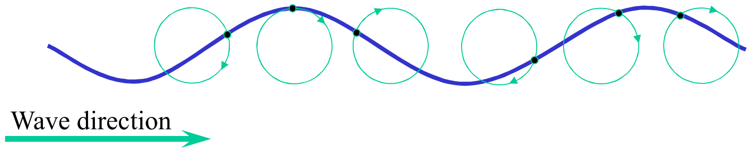
- Solar energy: 100 - 200 W/m^2
- Wind energy: 400 - 600 W/m^2
- Wave energy: 2 - 3 kW/m^2

Ocean waves represent an impressive energy resource.

What is a wave?

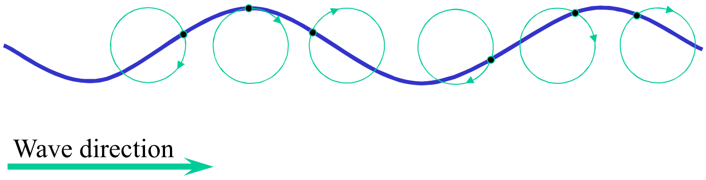
- Everyone has seen waves on lakes or oceans. Waves are actually a form of energy. Energy, not water, moves along the ocean's surface. The water particles only travel in small circles as a wave passes.

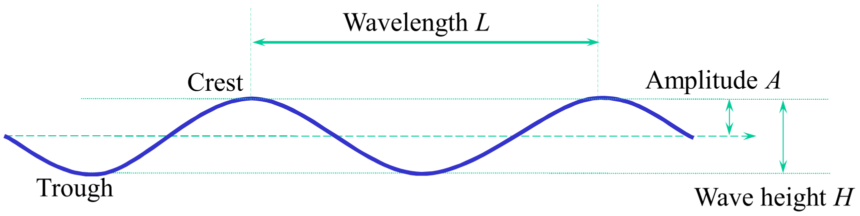
Snapshot of the water surface at a certain instant:



How to describe a wave

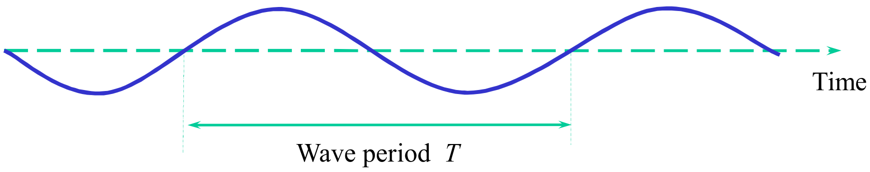
Snapshot of the water surface at a certain instant:





Surface elevation versus time

At a fixed position in space:



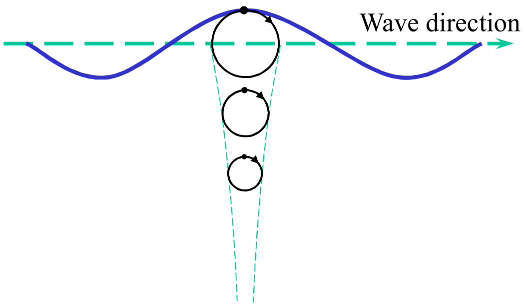
Frequency $f = 1 / T$

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: *dønning*]. Where the water is deep, swells can travel very large distances, for instance across oceans, almost without loss of energy.

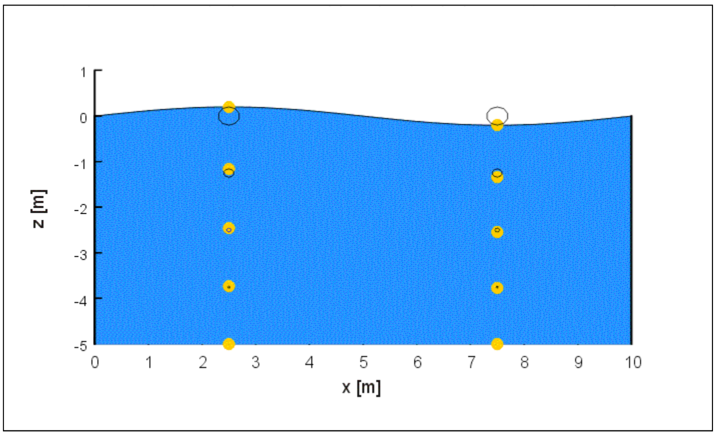
What happens underwater?

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.

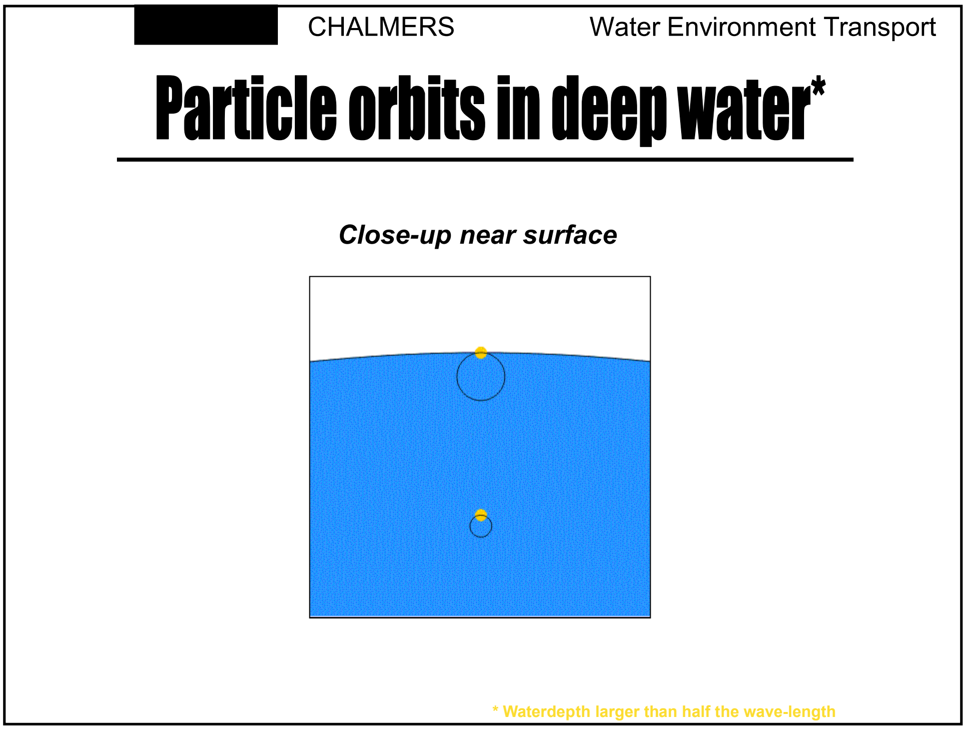


CHALMERS Water Environment Transport

Particle orbits in deep water*



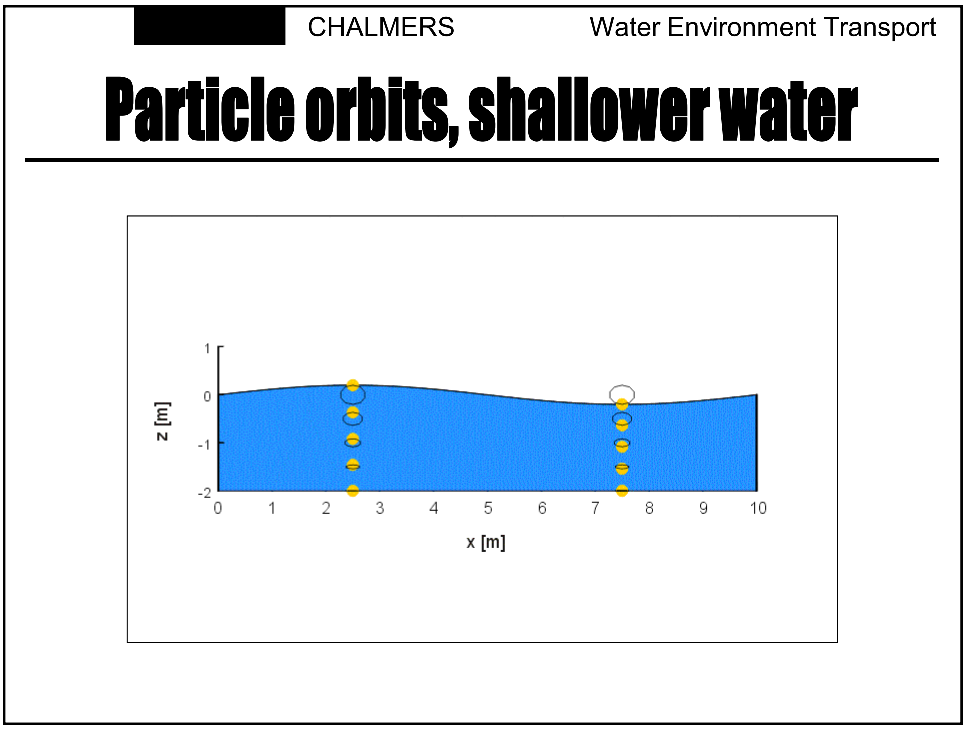
* Waterdepth larger than half the wave-length



Particle orbits in deep water*

Close-up near surface

* Waterdepth larger than half the wave-length

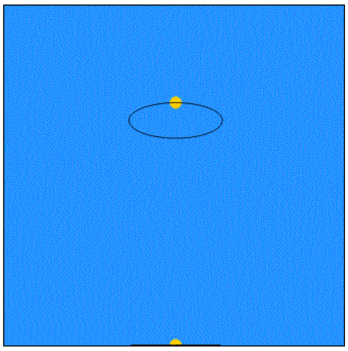


Particle orbits, shallower water

CHALMERS Water Environment Transport

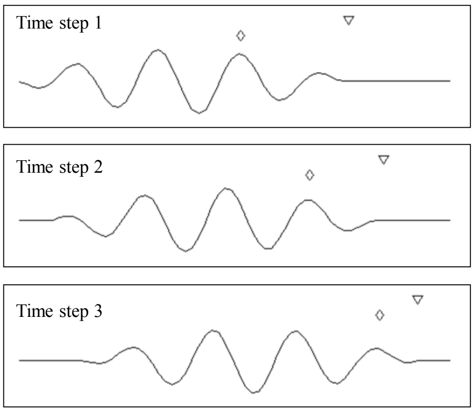
Particle orbits, shallower water

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

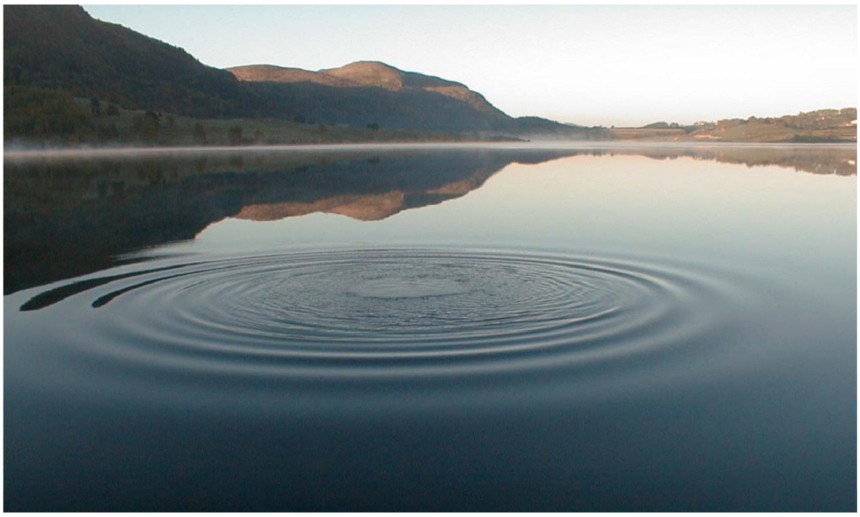
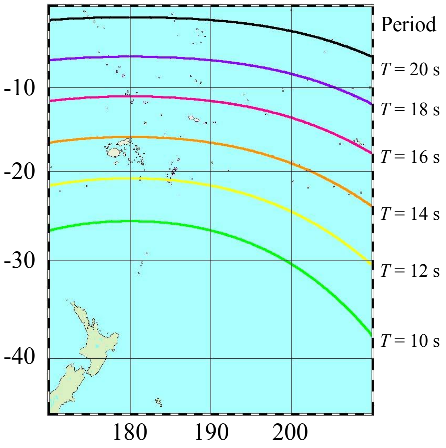


Photo: Magne Falnes, 1999

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 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:

$$E = k_E H^2$$

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

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

g = 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.

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

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

$$J = k_J T H^2$$

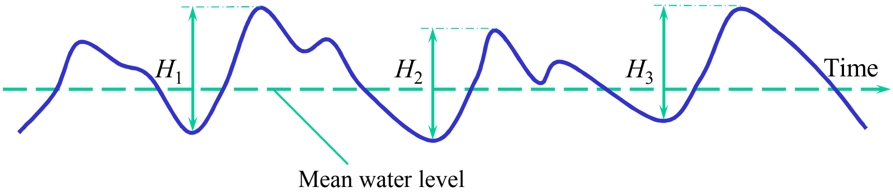
$k_J = \rho g^2 / 32\pi \approx 1\ \text{kW/m}^3\text{s}$

$$\begin{array}{l}\text{Example:}\\ T = 10\,\text{s} \ \text{and} \ H = 2\text{m} \quad \Rightarrow \quad J = 40\ \text{kW/m}\end{array}$$

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 $H_{1/3}$.

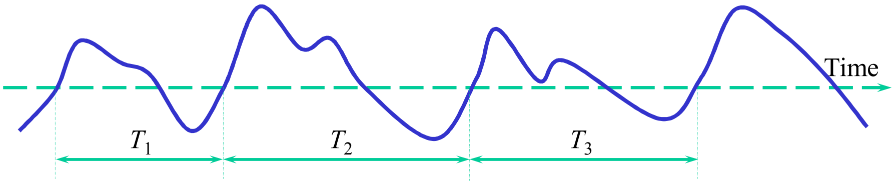
$$H_{1/3} = \frac{H_1 + H_2 + \cdots + H_{N/3}}{N/3}$$



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

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

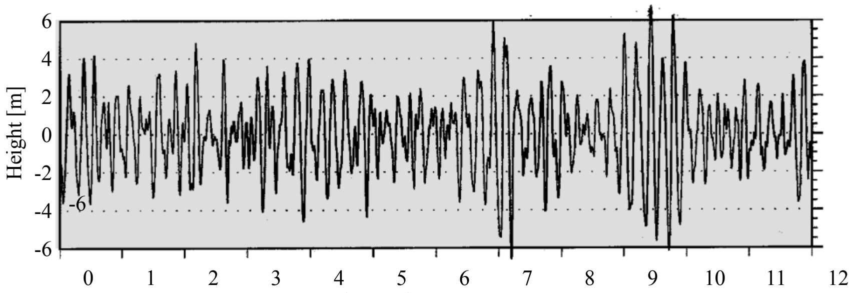
Wave-power level in terms of significant wave height

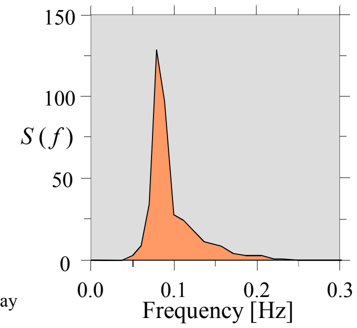
$$\int_0^\infty S(f)\,\mathrm{d}f \equiv H_s^2 / 16$$

•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



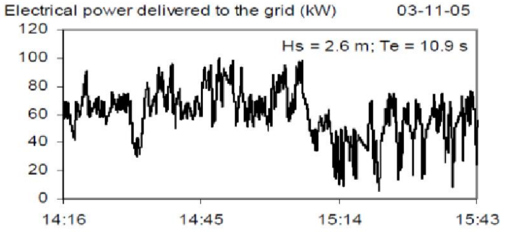


- This time series (above) from high sea shows that individual waves vary greatly in size and form. The corresponding energy spectrum is shown to the right. For this storm wave the significant wave height is $H_s = 8$ m.

Source: OCEANOR, Norway

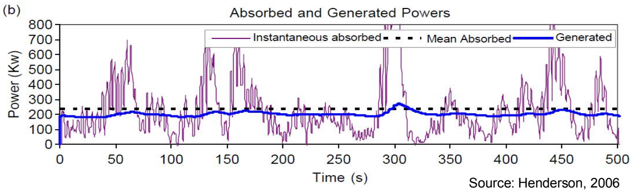
Instantaneous power:

- is this acceptable for the grid?



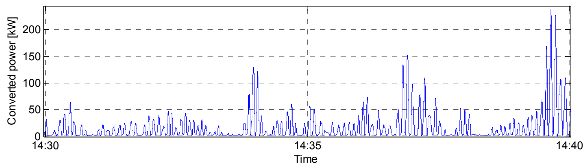
Source: Neumann et al., 2006

Air turbine, Pico plant



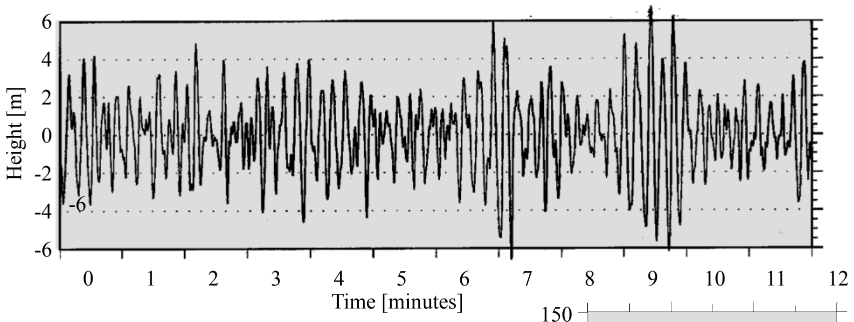
Source: Henderson, 2006

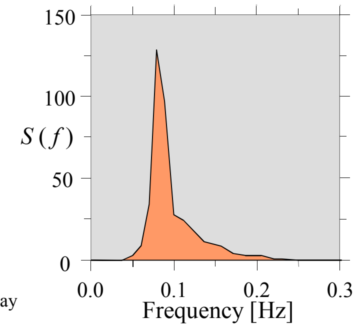
Hydraulic machinery, Pelamis



Directly driven generator, AWS

A measurement example

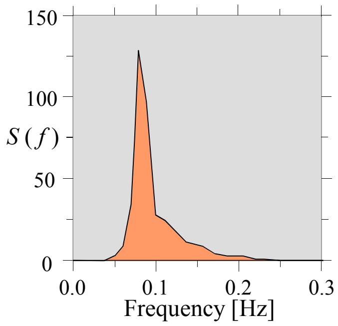


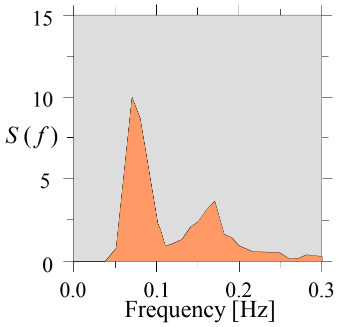


- This time series (above) from high sea shows that individual waves vary greatly in size and form. The corresponding energy spectrum is shown to the right. For this storm wave the significant wave height is $H_s = 8$ m.

Source: OCEANOR, Norway

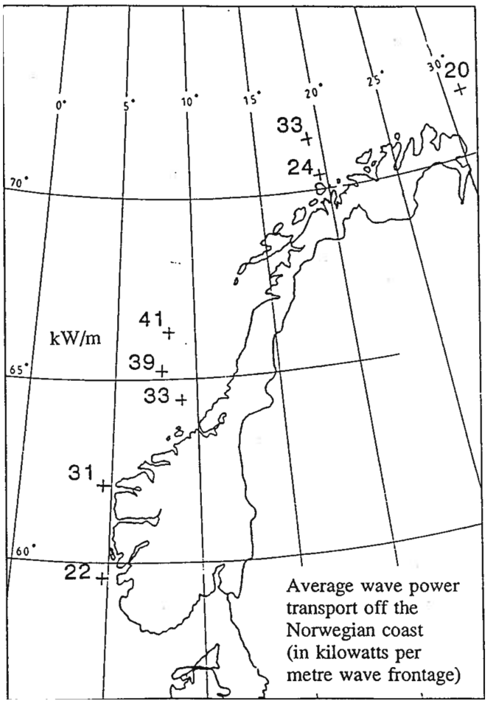
Real-sea spectra





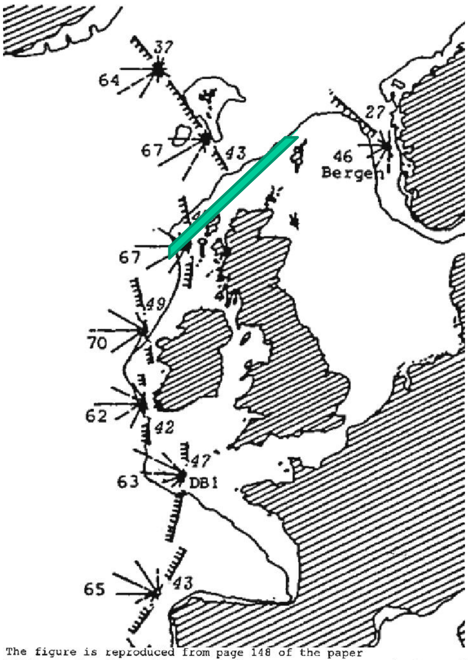
- These are typical energy spectra from wind-sea conditions (top) and mixed wind-sea and swell conditions (bottom).
- The swell contains lower frequencies (high peak) than the the wind waves (low peak).
- Significant wave heights: 8 m (top) and 3 m (bottom)

Source: OCEANOR, Norway



Average wave power transport off the Norwegian coast (in kilowatts per metre wave frontage)

Norwegian wave-power-level [in kW per m wavefront]. (Torsethaugen 1990).



The figure is reproduced from page 148 of the paper Mollison, D.: "Wave climate and the wave power resource". *Proceedings IUTAM Symposium on Hydrodynamics of Ocean Wave-Energy Utilization*, (edited by D.V. Evans and A.F. de Falcão) Lisbon, Portugal, 8-11 July 1985, Springer-Verlag, pp 133-156, 1986.

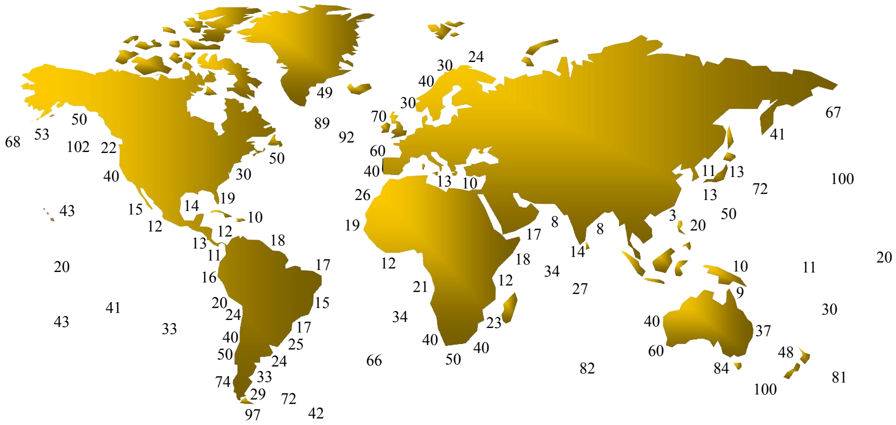
Who (which nations) have the propriety right to exploit the oceans' wave energy?

If wave energy is being exploited by WEC arrays ranging from north of Shetland to south of the Hebrides, there may be reduced wave energy to exploit at the west coast of Denmark and Norway.

Make international agreements before wave-energy has a commercial interest!

Could any country, e.g. Switzerland, exploit wave energy by floating WEC arrays in international waters of the Atlantic?

Distribution of wave energy transport



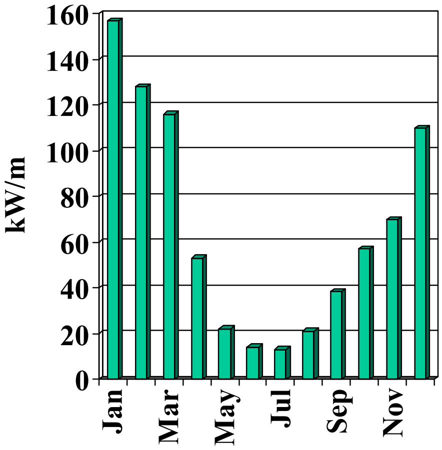
Average wave power levels are approximate and given in kW/m of the wave front.

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

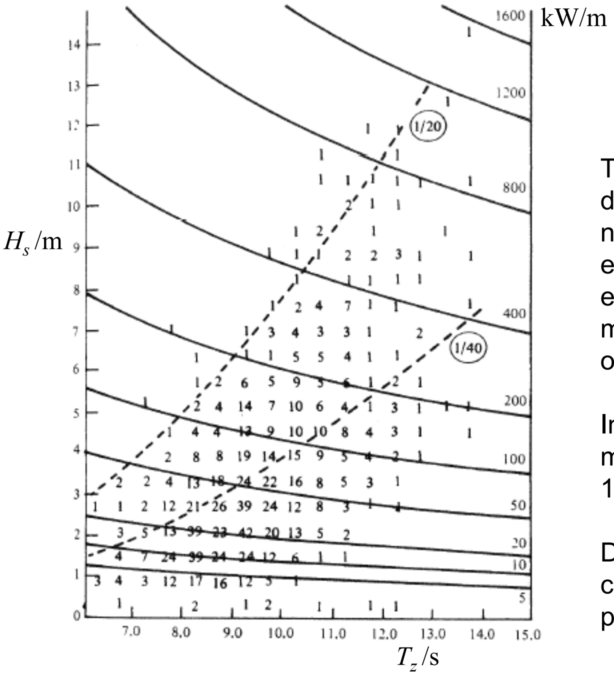


Figure after Ian Glendenning 1978 (cf. book # D6 in the list: http://folk.ntnu.no/falnes/w_e/books_wave_energy.htm).

"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.

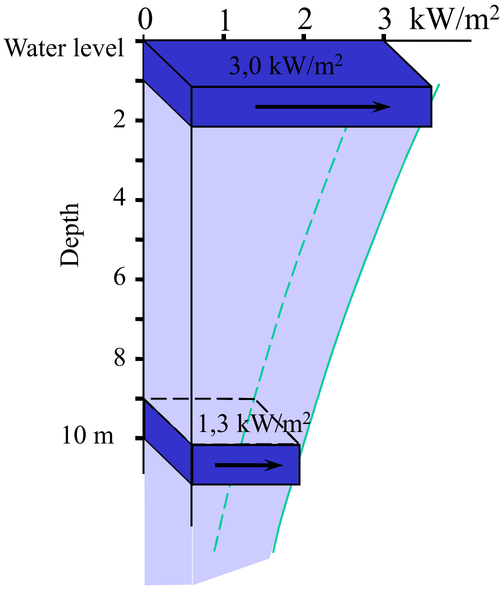
Source : Ian Glendenning, 1977

- Average energy intensity:

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

Vertical distribution of wave-energy transport

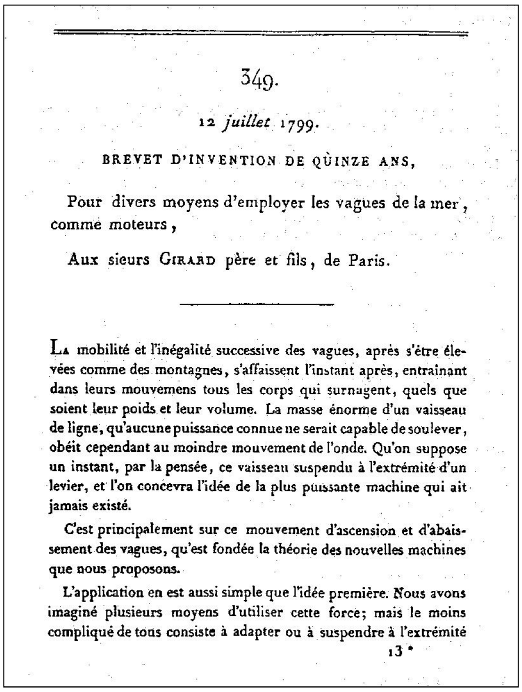
- As we have seen, the water particles move in circles with decreasing radius in the depth. Consequently, the energy flow density decreases as we go deeper in the water. In fact, on deep water, 95 % of the energy transport takes place between the surface and the depth *L*/4. (*L* is the wavelength).



$J = 40$ 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.

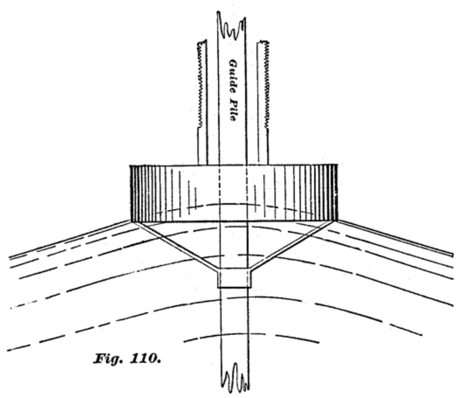
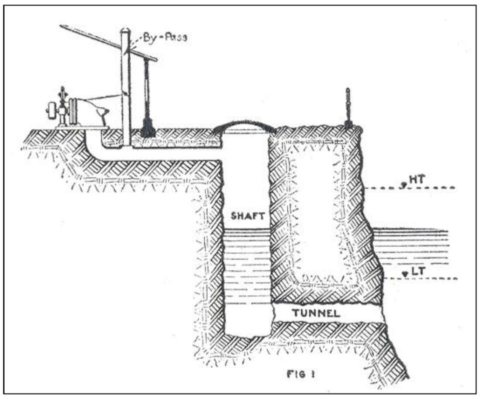


Fig. 110.

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

- 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.

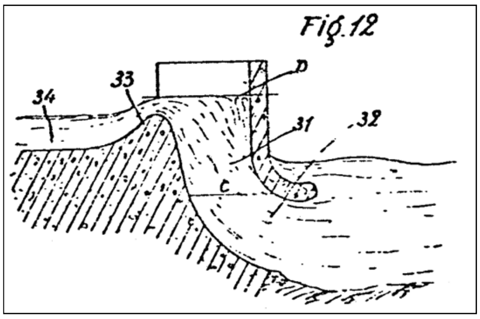


Drawing from 1920 showing Mr. Bochaux-Praceique's device. Reprinted with permission of Power Magazine, The McGraw Hill Companies

- 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)

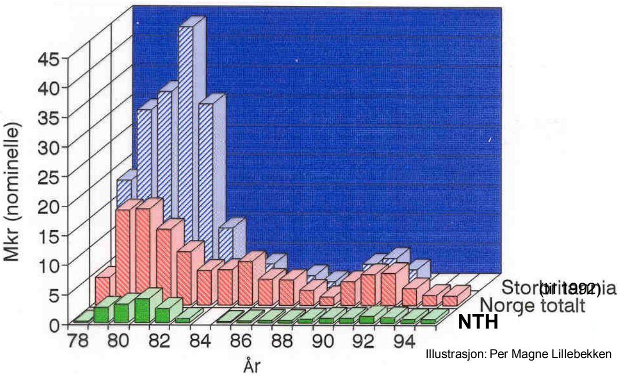
- Sea water enters a hollow structure with its lower opening submerged. Due to wave action the inside "water column" will oscillate. With the shown proposal some water at the upper part of the "column" is drained into an elevated water reservoir.



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.

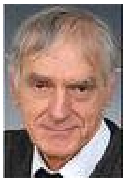
Governmental funding of wave-energy research after 1977, for UK (to 1992) and Norway (to 1995).



Illustrasjon: Per Magne Lillebekken

Three wave-power inventor pioneers

Yoshio Masuda (1925 − 2009)
Started already in 1947 with experiments to test devices for utilising wave energy in Japan.



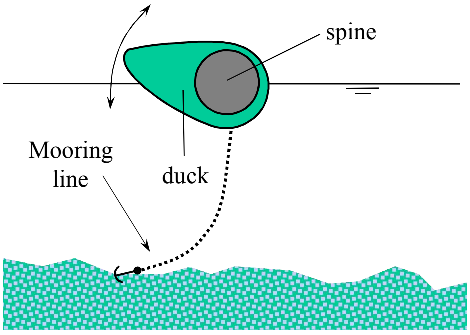
Stephen Salter (1938 −)
started 1973 wave-power research at the University of Edinburgh, Scotland.

Kjell Budal (1933 − 1989)
initiated in 1973 wave-power research at NTH (part of pre-NTNU university), Trondheim, Norway.

80 m long vessel Kaimei (= sea light) for testing various types of wave-activated air turbines. (Japan, late 1970s and early 1980s)

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.



Salter's nodding Duck

Scotland (Stephen Salter, University of Edinburgh)

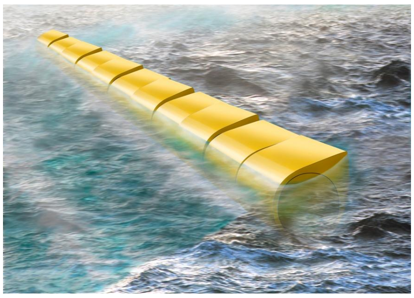


Illustration: Bjarne Stenberg, 2007

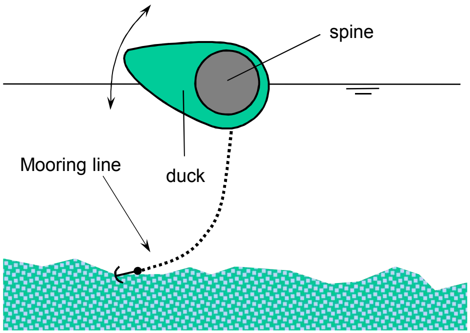


Illustration: Jørgen Hals 1999

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

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

Video clip of "Pelamis"

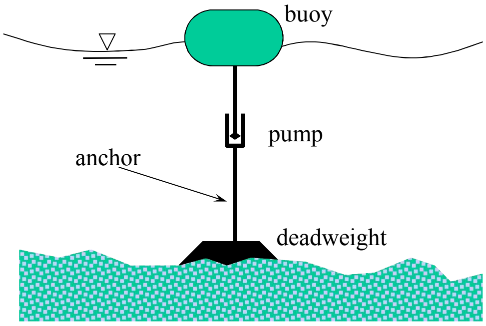
PELAMIS WAVE POWER LTD <http://www.pelamiswave.com/galleryvideo.php>.

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.

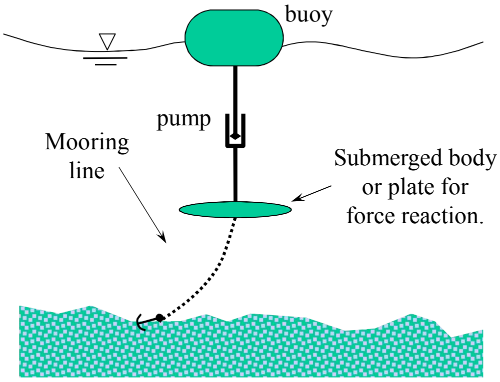
Force reaction

- 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.

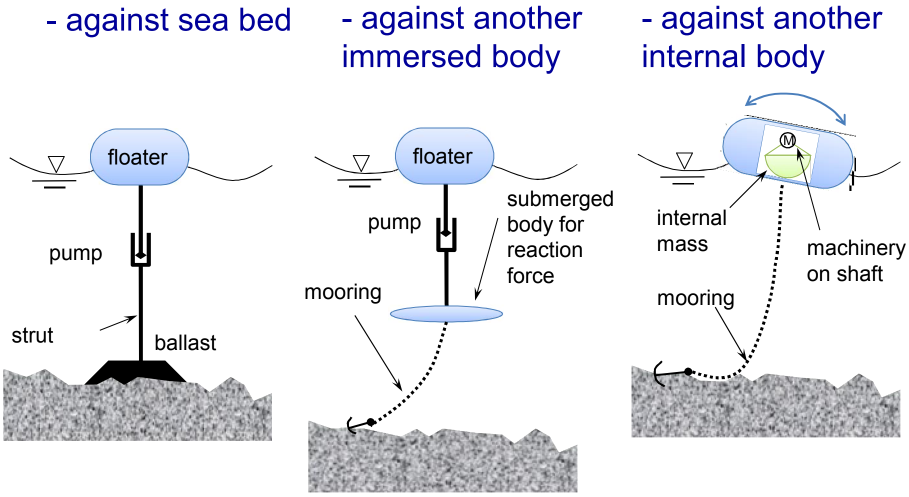


Force reaction by another body

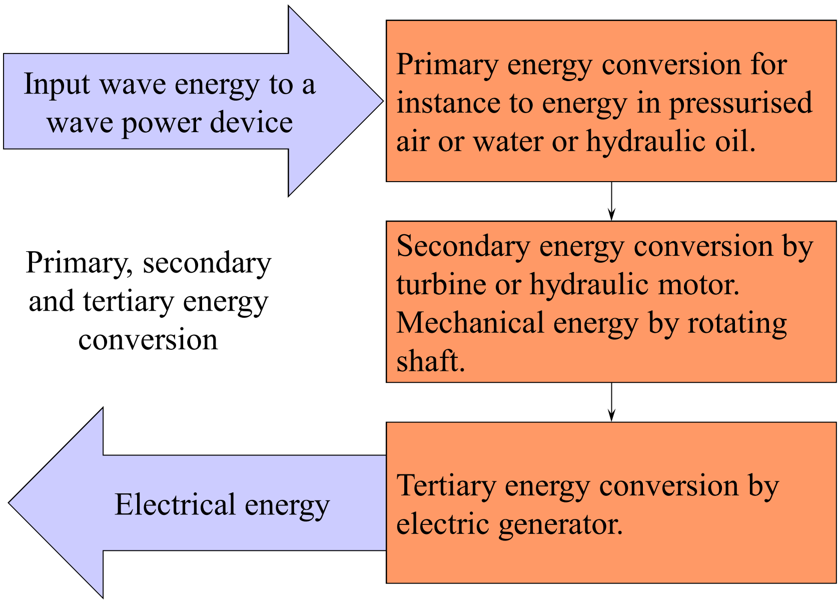
- An alternative is to let the wave force on the float react against another body, such as the shown submerged body. The power take-off pump is activated by the relative motion between the two bodies. A mooring line is required to prevent the system from drifting away from position.



Force reaction



Steps of wave-energy conversion



Input wave energy to a wave power device

Primary energy conversion for instance to energy in pressurised air or water or hydraulic oil.

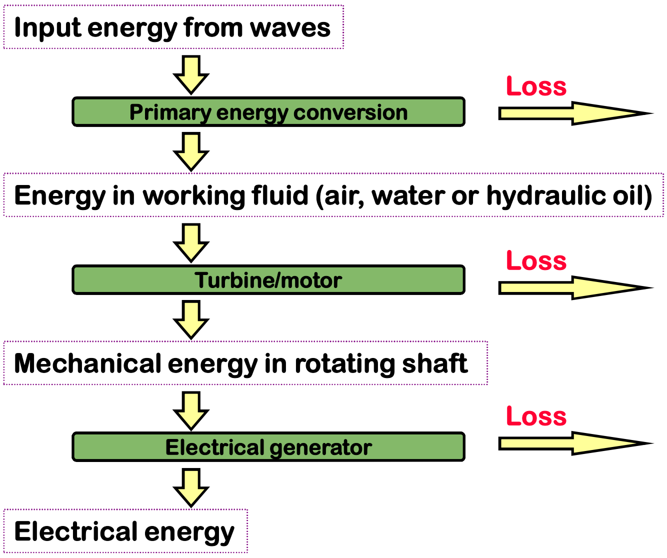
Secondary energy conversion by turbine or hydraulic motor. Mechanical energy by rotating shaft.

Tertiary energy conversion by electric generator.

Electrical energy

Primary, secondary and tertiary energy conversion

Schematic principle for extracting wave energy



Input energy from waves

Primary energy conversion

Loss

Energy in working fluid (air, water or hydraulic oil)

Turbine/motor

Loss

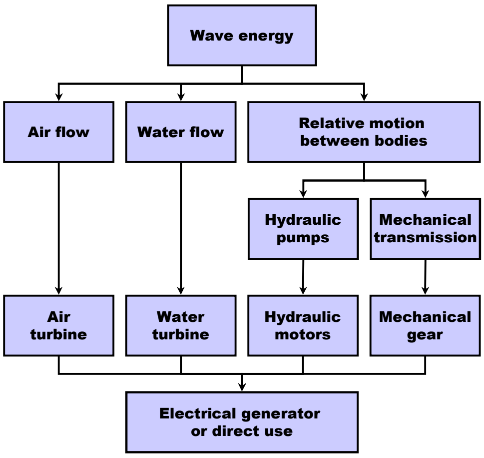
Mechanical energy in rotating shaft

Electrical generator

Loss

Electrical energy

Power take-off alternatives



Wave energy

Air flow

Water flow

Relative motion between bodies

Hydraulic pumps

Mechanical transmission

Air turbine

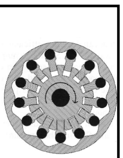
Water turbine

Hydraulic motors

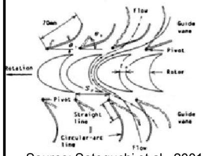
Mechanical gear

Electrical generator or direct use

Power take-off machineries

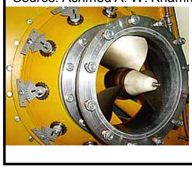


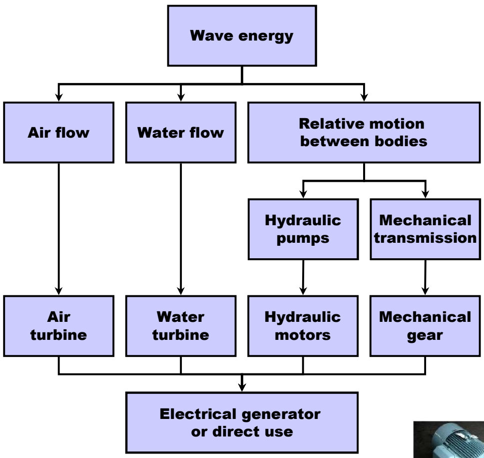
Source: JAMSTEC, Japan



Source: Setoguchi et al., 2001

Source: Achmed A. W. Khammas





Wave energy

Air flow

Water flow

Relative motion between bodies

Hydraulic pumps

Mechanical transmission

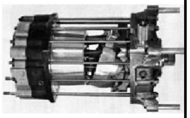
Air turbine

Water turbine

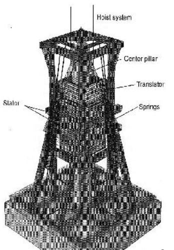
Hydraulic motors

Mechanical gear

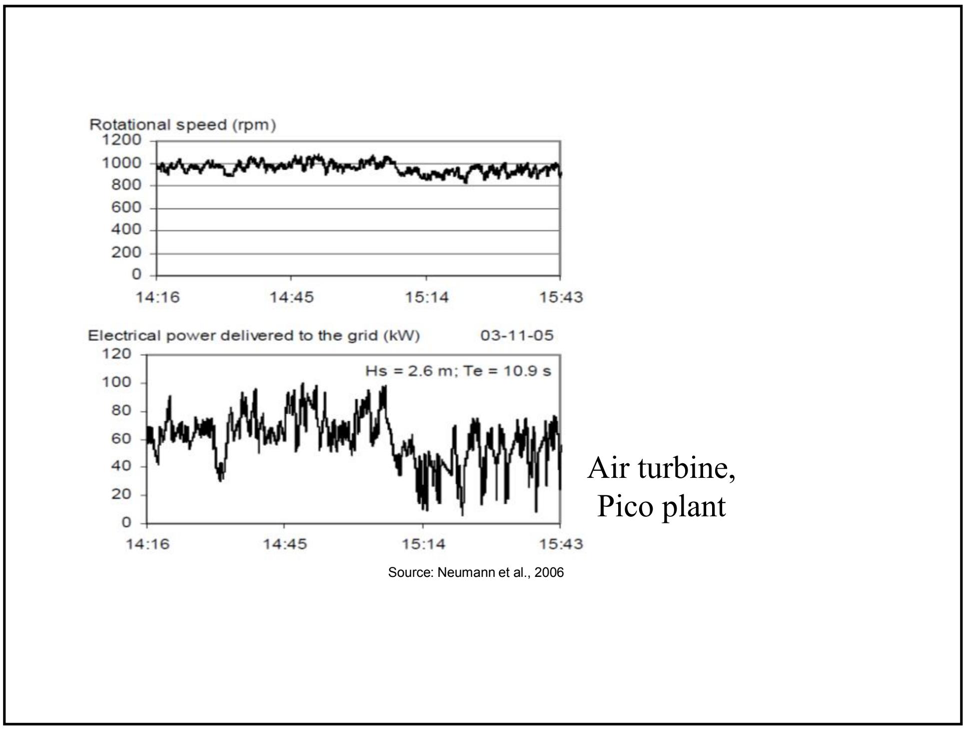
Electrical generator or direct use



Source: Jamie Taylor 2008

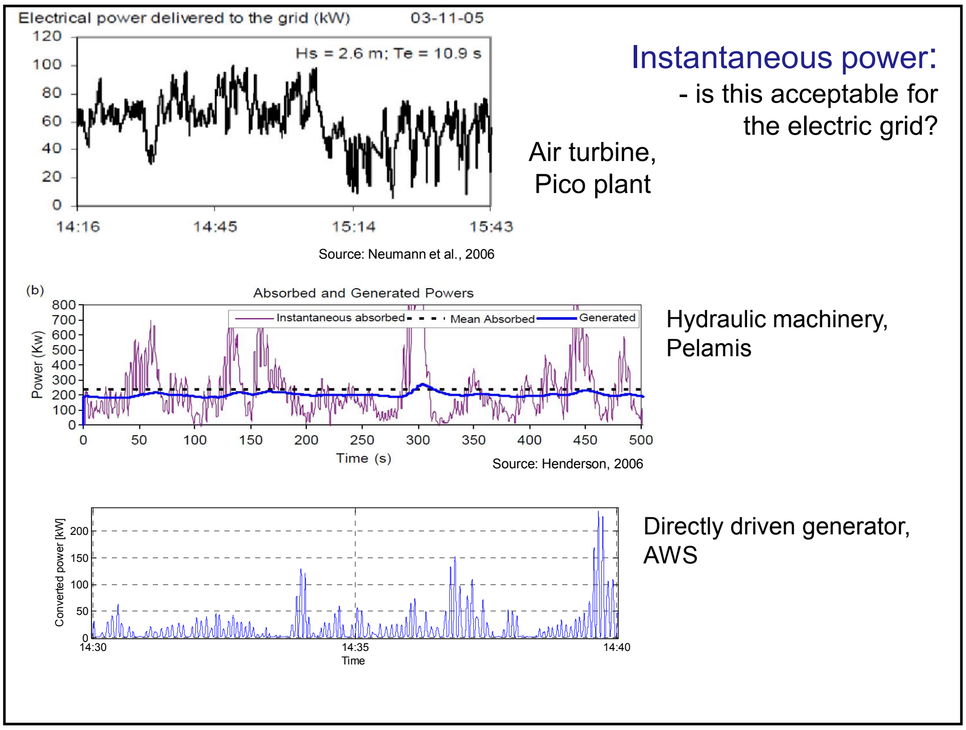


Source: Danielsson et al., 2008



Air turbine,
Pico plant

Source: Neumann et al., 2006



Instantaneous power:

- is this acceptable for the electric grid?

Air turbine,
Pico plant

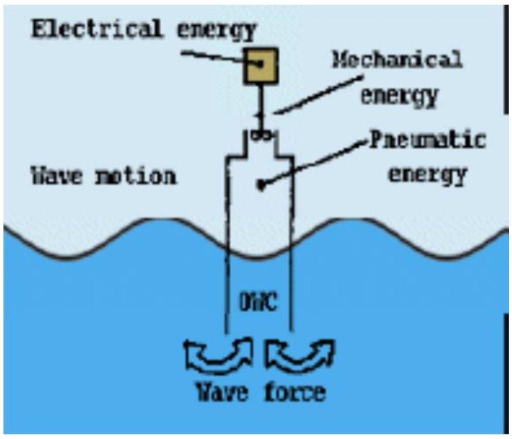
Source: Neumann et al., 2006

Hydraulic machinery,
Pelamis

Source: Henderson, 2006

Directly driven generator,
AWS

Unfortunately, it seems that some inventors do not understand the step of primary energy conversion.



Is this an illustration of a wave-energy converter (WEC) of the oscillating-water-column (OWC) type?

This appears to be an illustration of a perpetual mobile engine.

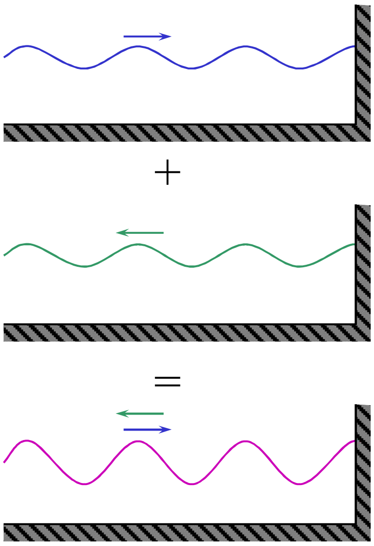
Can this “WEC” deliver electrical energy, when it, apparently, has no influence on the wave?

This illustrates that the development of WEC technology may have suffered from lack of proper understanding of the step of primary energy conversion!

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

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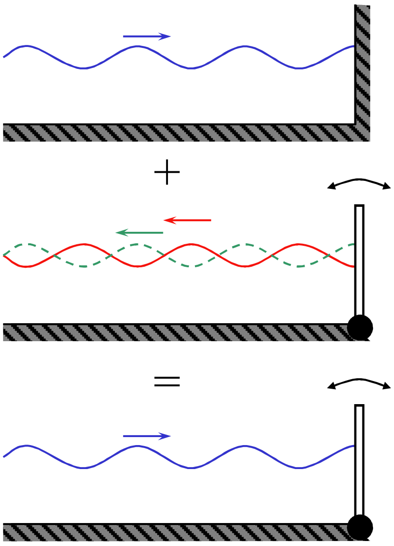
“To absorb a wave means to generate a wave”

- 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.

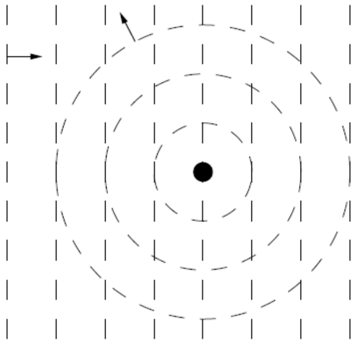
In this simple example, at optimum radiated-wave generation, the maximum absorbed energy equals 100 percent of the incident wave energy. Not also that the required, optimum, radiated wave has the same amplitude as the incident wave. Thus,

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

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*:

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

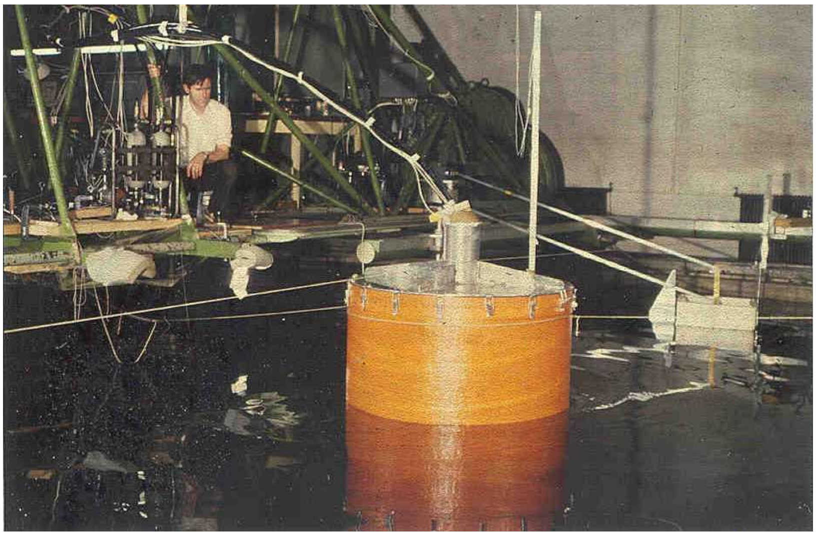
$$P_{r,OPT} = P_{a,MAX}$$

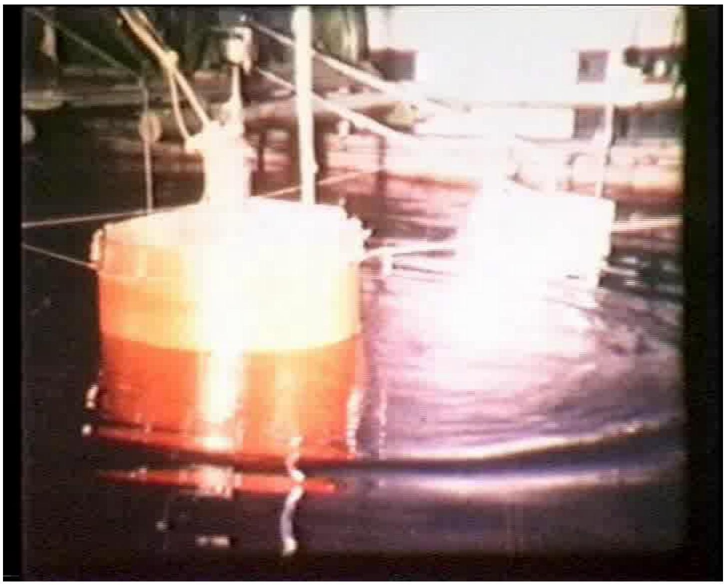
[These theoretical results were derived about 1976, independently, by research teams at NTH (Norway), at University of Bristol (UK) and at MIT (USA).]

A simplified analysis of the wave power that may be absorbed by means of a heaving (i.e. vertically oscillating) immersed body may be seen on:

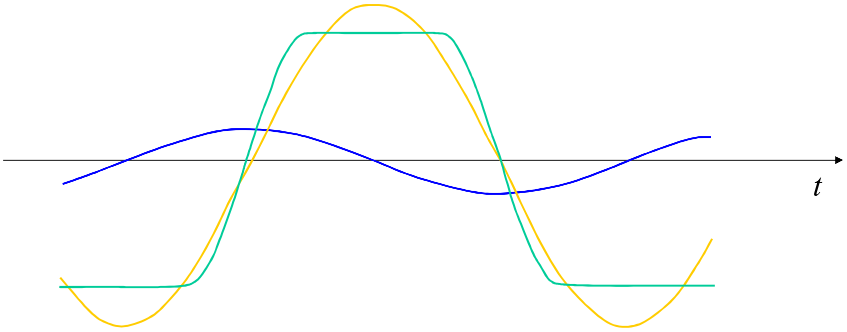
http://folk.ntnu.no/falnes/teach/TEP4175bylgje/bylgjekraftboye.pdf

Kjell Budal with his phase-controlled power-buoy model (type E) in the Trondheim towing tank 1978





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

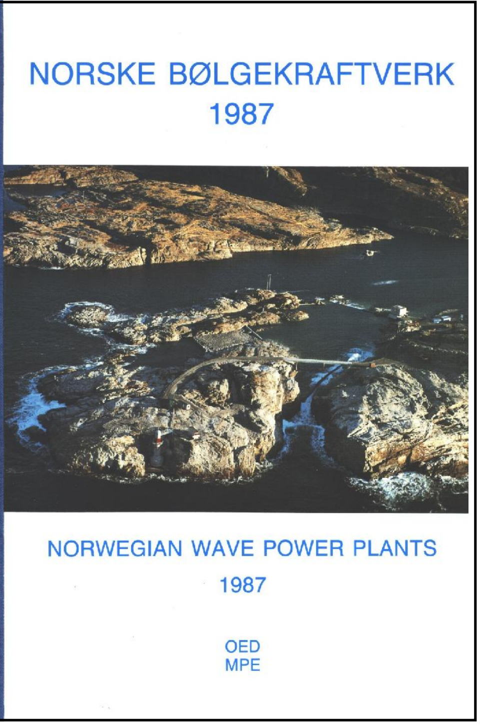


Optimal phase at resonance

Phase control by latching

OED (Ministry of Petroleum and Energy) issued 1987 two reports on NORWAVE's and Kvaerner's wave-power prototypes, 40 km off Bergen. One report, "*Norwegian wave power plants 1987*", with text in Norwegian and English, was open.

The other report, "*Bølgekraftverk Toftestallen: Prosjektkomiteens sluttrapport 31.12.1987*", had only closed distribution. It contained more detailed information, in the Norwegian language, only.



NORSKE BØLGEKRAFTVERK
1987

NORWEGIAN WAVE POWER PLANTS
1987

OED
MPE

OED (Ministry of Petroleum and Energy) issued 1987 two reports on NORWAVE's and Kvaerner's wave-power prototypes, 40 km off Bergen. One report, "*Norwegian wave power plants 1987*", with text in Norwegian and English, was open.

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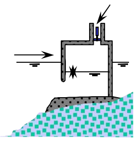
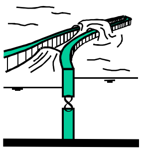
By end of 1988 Kværner's 500 kW OWC prototype had delivered 29 MWh to the local utility Nordhordland Kraftlag.

It seems that the installed power capacity was much too large!





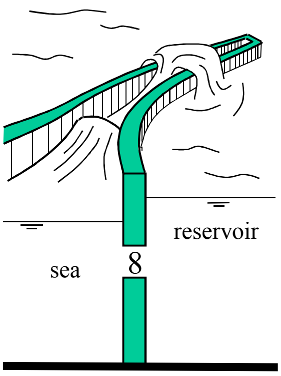
By end of 1991 NORWAVE's 350 kW TapChan prototype had delivered 691 MWh to the local utility Nordhordland Kraftlag.

Energy deliveries as informed by Nordhordland Kraftlag in letter 1993

The tapered channel

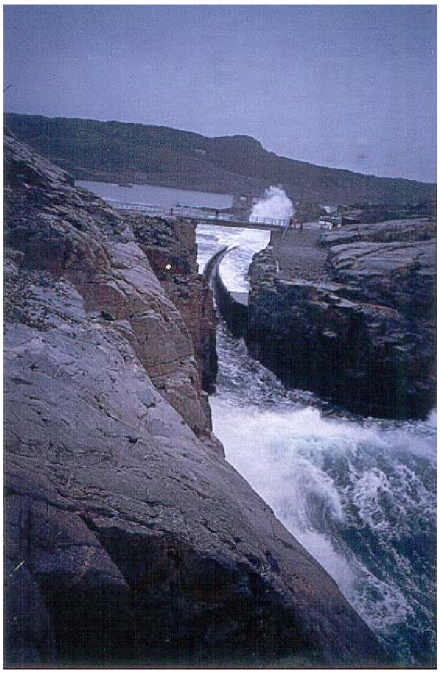
- The tapered channel is a horizontal channel which is wide towards the sea where the waves enter and gradually narrows in a reservoir at the other side. As the waves pass through the channel, water is lifted over the channel wall and into the reservoir due to the shortage of space which occurs as the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

Principle:

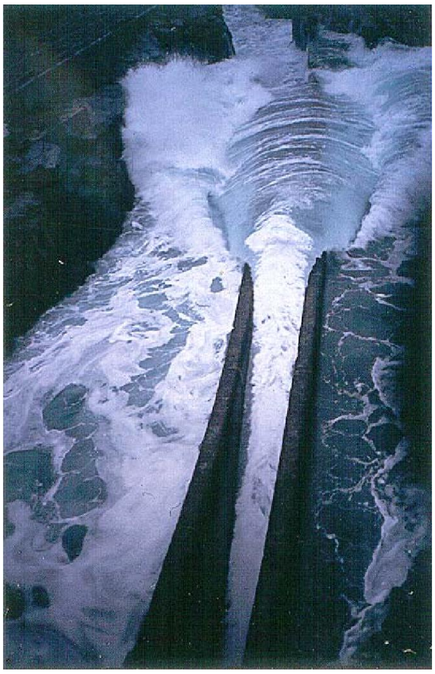


NORWAVE’s TAPCHAN

•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.

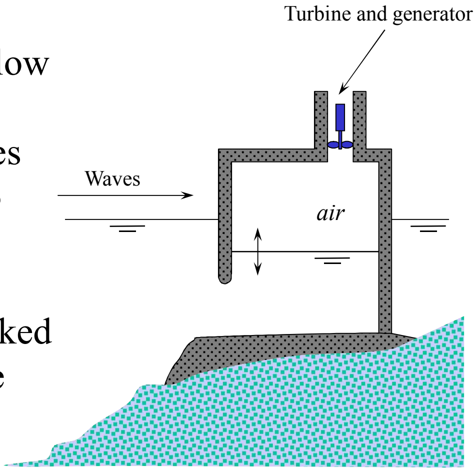


Copyright: NORWAVE AS, Norway, 1986

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).

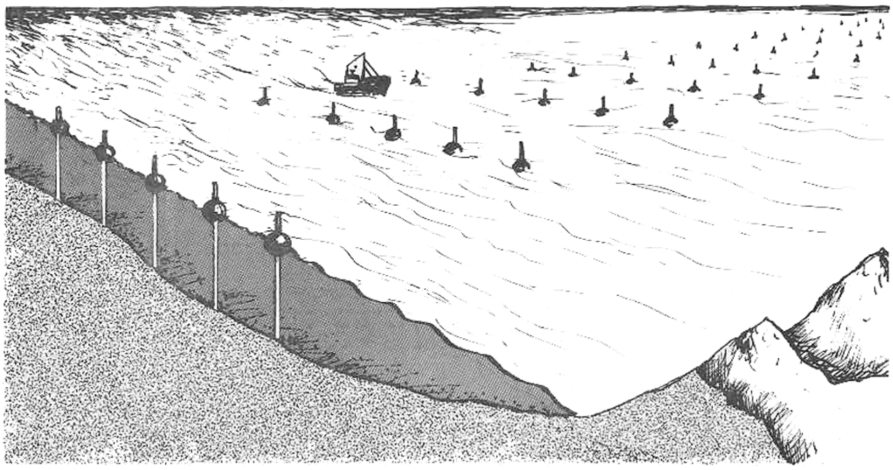
Photo: J. Falnes, 1985.

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).

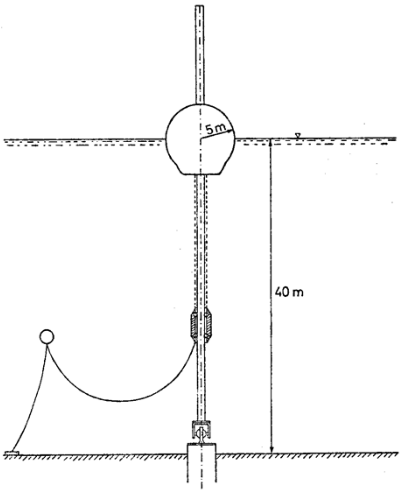
Array of point absorbers



Source: SINTEF, Norway, 1982.

Illustration in:
Stortingsmelding nr. 65 (1981-82): *Om nye fornybare energikilder i Norge.* [White paper No. 65 (1981-82): *On new renewable energy sources in Norway* (in Norwegian).]

The Trondheim point absorber



Source: K. Budal, 1981

Photo: J. Falnes, 1983

Budal's phase-controlled power buoy model (type N2) at the test site in Trondheimsfjorden.

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/.]

Recommendations:

To make large-scale utilisation of ocean-wave energy a future reality,
I recommend a 3-step development program as follows:

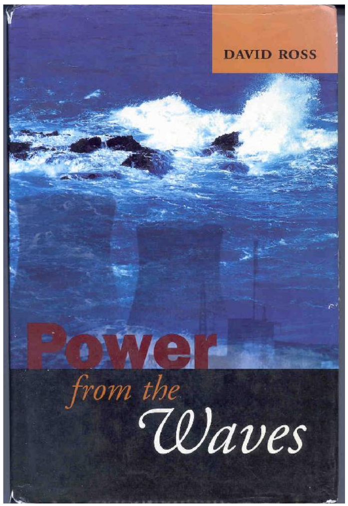
Establish international agreements concerning ownership of the energy that ocean waves may transport, possibly thousands of kilometres, **across offshore national territorial borders**.

R&D&D programmes for various kinds of single wave-energy conversion (WEC) units of power take-off (PTO) capacity in the range of **100-300 kW**.

When such WEC units, deployed in the sea, have demonstrated an annual energy production equal to the PTO's power capacity multiplied by at least 2500 hours, they may become candidates for a R&D&D programme on wave power plants consisting of a huge number of **mass-produced** cooperating WEC units.

Reference to early wave-power projects in Sweden and other countries:

Lennart Claeson et al.: "*Energi från havets vågor*", Efn-rapport nr. 21 ["*Energy from the ocean's waves*", Efn-report No. 21, in Swedish], (Energiforskningsnämnden, Stockholm, Sweden, 1987), ISBN 9138096919.



Reference to early wave-power history in the UK and also in Norway:

David Ross:."*Power from the Waves*", (Oxford University Press, 1995), ISBN 0-19-856511-9)

Some references on 20th-century Norwegian R&D&D activity:

Stortingsmelding nr. 65 (1981-82): *Om nye fornybare energikilder i Norge.* [White paper No. 65 (1981-82): *On new renewable energy sources in Norway* (in Norwegian).]

Falnes, J.: "Research and development in ocean-wave energy in Norway". *Proceedings of International Symposium on Ocean Energy Development*, 26-27 August 1993, Muroran, Hokkaido, Japan, (ed. H. Kondo) pp 27-39.

Christiansen, A.C. and Buen, J., *Managing environmental innovation in the energy sector: the case of photovoltaic and wave power development in Norway*. Internat. J. Innovation Management. 06, 233 (2002)

Ambli, N., *Kværners bølgekraftverk av typen svingende vannsøyle* [*Kvaerner's wave-power plant of the OWC type* (in Norwegian)], Technical report, Kværner Brug AS, MOWC/historikk/3/Ada 1984-09-05.

NTNU
Norwegian University of
Science and Technology

WAVETRAIN2 – Short Course on
Ocean wave energy fundamentals
28 June-8 July 2010, Trondheim, Norway

Norwegian
Centre of
Excellence

Ocean wave energy fundamentals

Introduction 28 June 2010 by

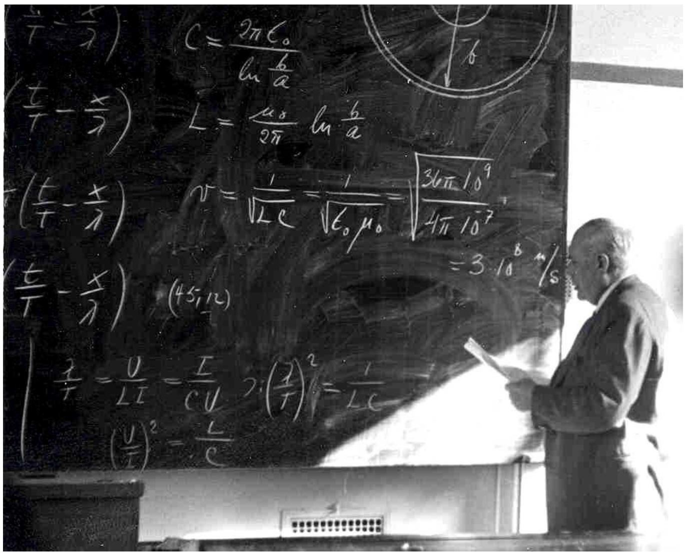
Johannes Falnes

CeSOS & Department of Physics, NTNU

www.cesos.ntnu.no **CeSOS – Centre for Ships and Ocean Structures**

Welcome to the course
and to this lecture room EL2,
where student Johannes Falnes
during 1954-56 received much of
his education in electrical engineering.

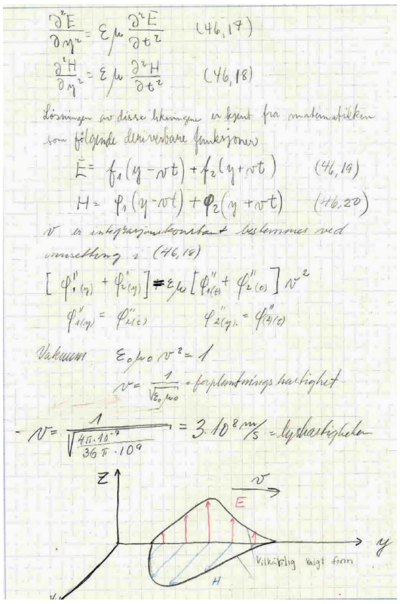
The following two slides illustrates wave teaching here on
29 & 30 March 1954.



[Photo: K. Eidet 1954]

Professor Aksel Aanderud lectures in “Fundamentals of elctrical engineering”, “§45 Wave along a homogeneous lossless coaxial cable”, 29 March 1954.

Notes by student Johannes Falnes when attending lecture 30 March 1954 in subject “Fundamentals of electrical engineering”, “§46 Maxwells equations”



$$\frac{\partial^2 E}{\partial y^2} = \varepsilon\mu\frac{\partial^2 E}{\partial t^2} \quad (46,17)$$

$$\frac{\partial^2 H}{\partial y^2} = \varepsilon\mu\frac{\partial^2 H}{\partial t^2} \quad (46,18)$$

Løsningen av disse likningene er kjent fra matematikken som følgende deriverbare funksjoner

$$E = f_1(y - vt) + f_2(y + vt) \quad (46,19)$$

$$H = \varphi_1(y - vt) + \varphi_2(y + vt) \quad (46,20)$$

v er integrasjonskonstant bestemmes ved innsetting i (46,18)

$$[\varphi''_{1(y)} + \varphi''_{2(y)}] = \varepsilon\mu[\varphi''_{1(t)} + \varphi''_{2(t)}]v^2$$

$$\varphi''_{1(y)} = \varphi''_{2(t)} \qquad \varphi''_{2(y)} = \varphi''_{(2)(t)}$$

Vakuum $\varepsilon_0\mu_0 v^2 = 1$

$v = \frac{1}{\sqrt{\varepsilon_0\mu_0}}$ = forplantnings hastighet

$v = \frac{1}{\sqrt{\frac{4\pi\cdot10^{-7}}{36\pi\cdot10^9}}} = 3\cdot10^8$ m/s = lyshastigheten

Teaching time 9 days: 28 June – 8 July 2010

Morning sessions 9h – 12h: Lectures

Afternoon sessions 13h – 16h: Miscellaneous (mostly exercises, but also some lectures, videos and demonstrations)

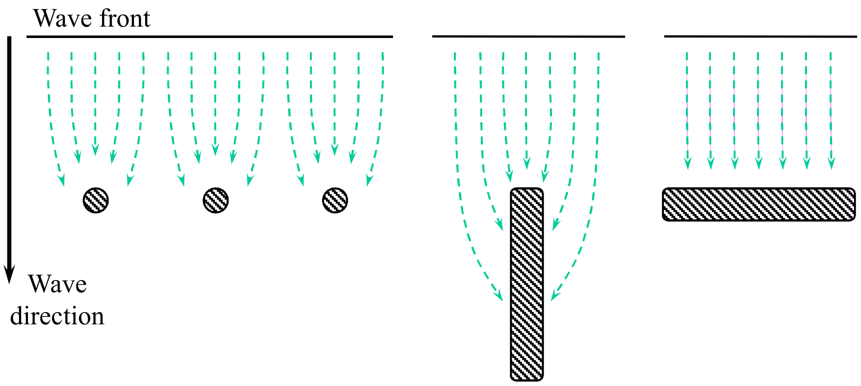
Course content:

Elementary introduction and
various practical matters (~ 3 days)

Central subjects from Falnes' textbook
Ocean Waves and Oscillating Systems,
Chapters 2, 3, 4, 5 & 6 (~ 6 days)

Classification of WECs

- According to size and orientation

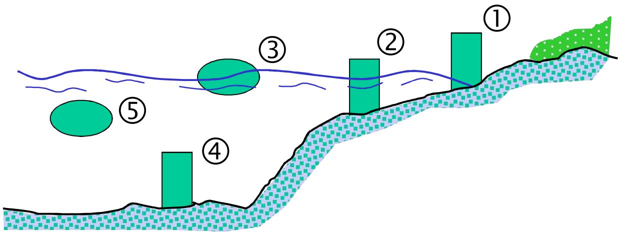


- Point absorbers
- Attenuator
- Terminator

Classification of WECs

- 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.



Classification of WECs

- 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

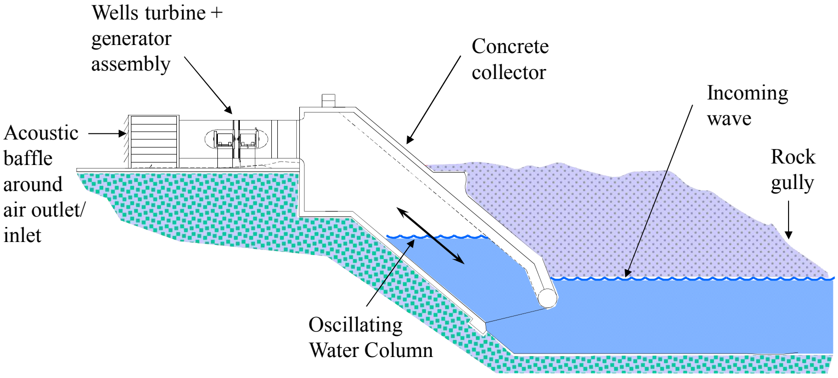
Classification of WECs

- 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)

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

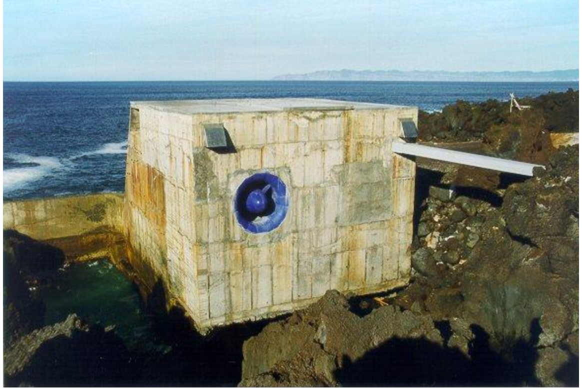


Photo: A. Sarmento, IST, Portugal, 1999

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.

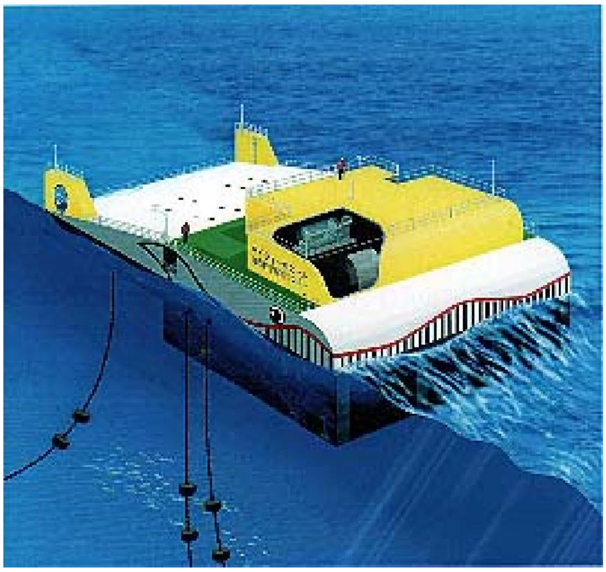


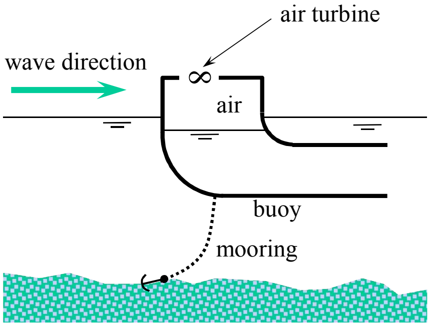
Photo: JAMSTEC, Japan

Backward bent duct buoy

Yoshio Masuda

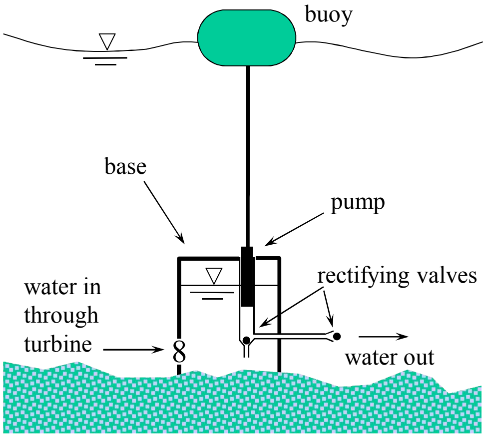
- This buoy shape was proposed by the Japanese inventor Yoshio Masuda. The waves cause the hull to move, thereby giving rise to a change of the water level in the chamber. Results from wave tank tests have been very promising.

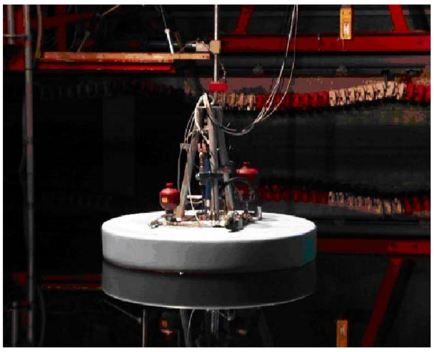
Principle:



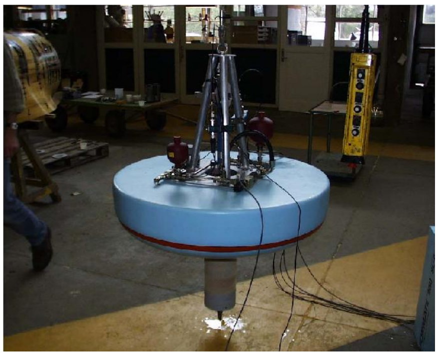
KN’s device

- 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

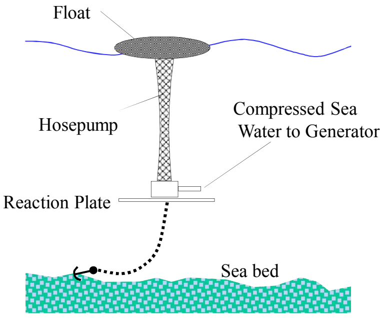


- The Rambøll point absorber represents a continuation of the work with the KN device in Denmark. A difference is that the power take-off is in the floating buoy in stead of a housing on the sea bed

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 in 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.

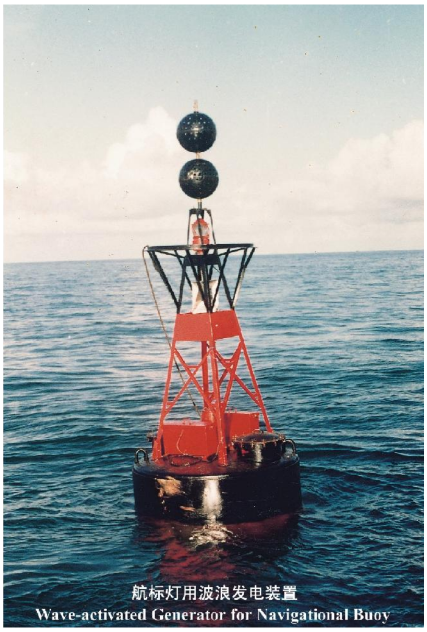


Photo: Niandong Jiang, China, 1987

Upper bounds for power P absorbed from sinusoidal wave of height H and period T by means of an oscillating immersed body of volume V:

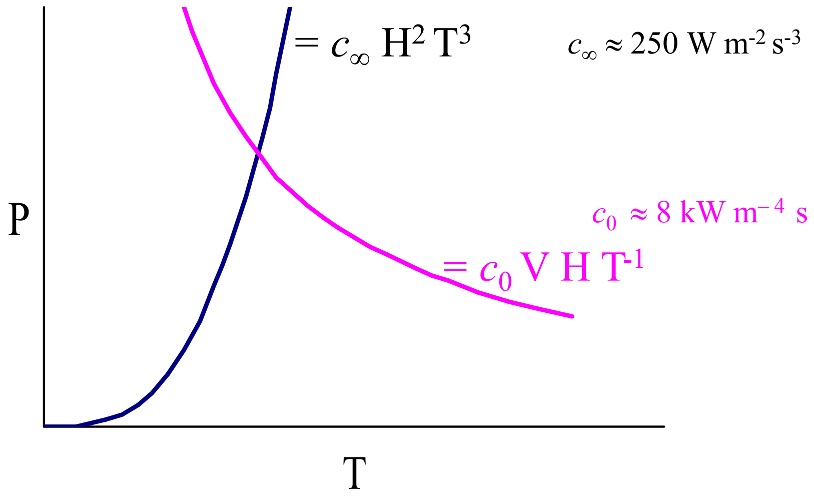
$P \leq c_\infty H^2 T^3$ $\quad$ $c_\infty = \rho(g/\pi)^3/128 \approx 250 \text{ W m}^{-2}\text{ s}^{-3}$

$P < c_0 \, V H / T$ $\quad$ $c_0 = \pi\rho g/4 \approx 8 \text{ kW m}^{-4}\text{ s}$

("Budal's upper bound")

Kjell Budal

Upper bounds for absorbed wave power P



The ConWEC device

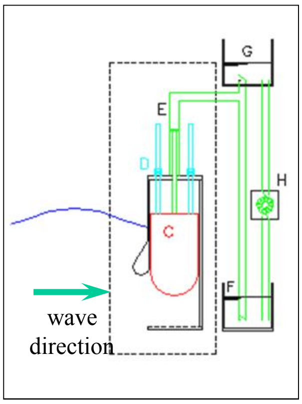
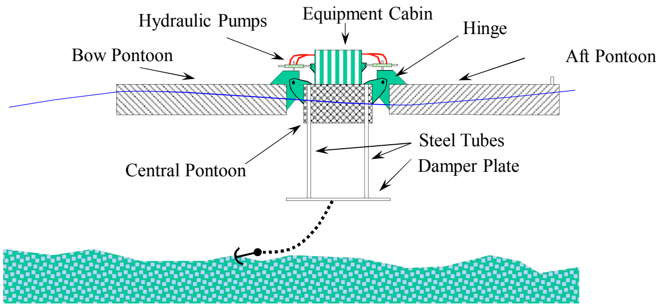


Photo and figure: ConWEC, Norway, 1998

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

Pitching raft

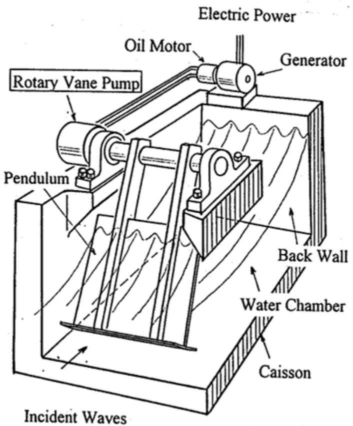
- A system called the McCabe Wave Pump has been designed to produce drinking water or electricity by use of wave energy. It has been developed by Dr. Peter McCabe and a team of engineers from Hydam Technologies Limited in Ireland. The device makes use of the slope change on the water surface due to waves.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



Source: Tom Thorpe, UK

The Pendulor

Photo: Tomiji Watabe, 1999



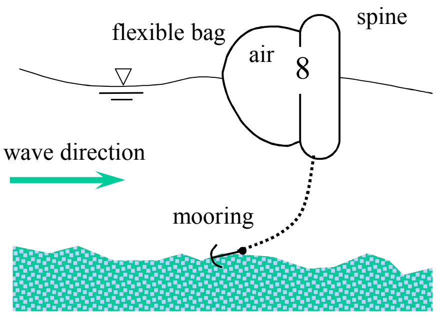
Source: Tomiji Watabe

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

The SEA Clam

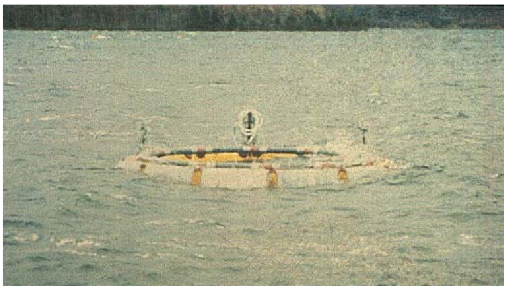
- As a part of the UK Wave Energy Programme, research and development have been carried out by Coventry Polytechnic in England. The result is a flexible bag device called the SEA Clam. A circular design was tested at 1/15th scale in the Scottish lake Loch Ness in 1986.

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.

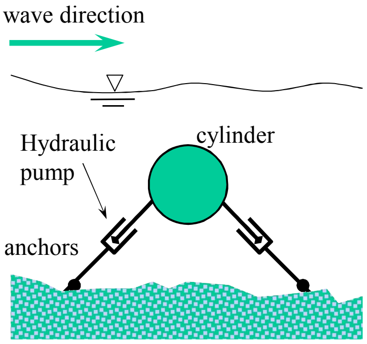


Photos reproduced by permission of L.Duckers/Sea Energy Associates, UK

The Bristol cylinder

Principle:

- 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.



Wave-driven sea-water pump

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

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

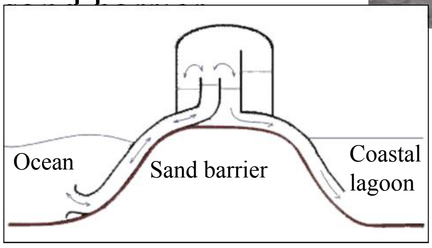


Photo: J. Falnes, 1989

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

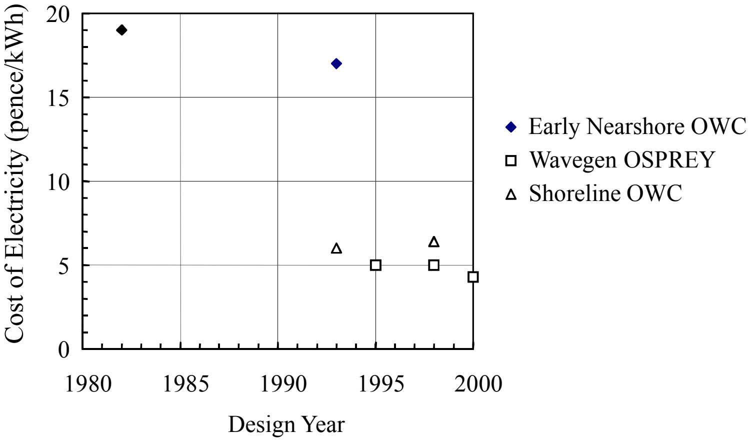
Is wave energy commercial?

- 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

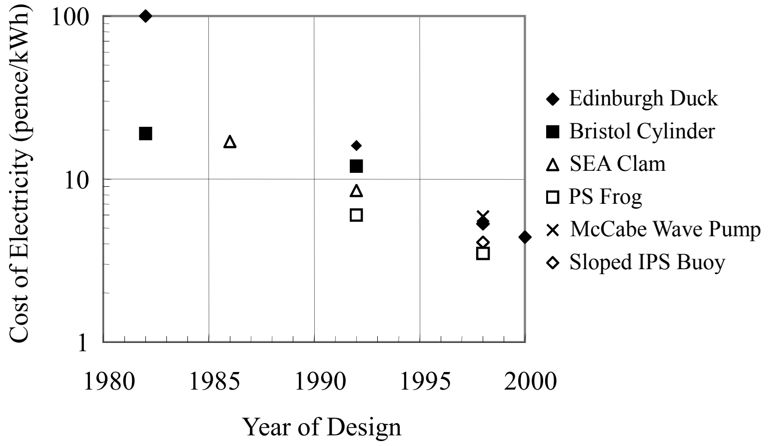
- It is a well-known fact that due to experience and improved methods of production the unit cost of a product usually diminishes as the production volume is increased. Thus, for electricity production in the US during 1926 to 1970 there was a main trend of 25 % decline in the inflation-corrected price 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.)

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



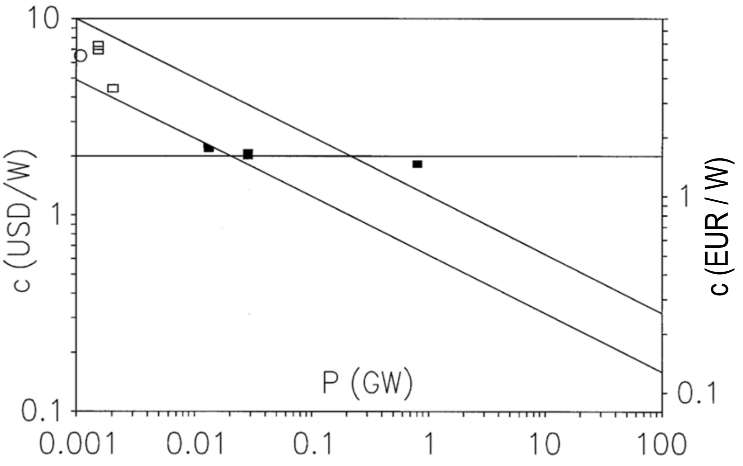
Source: Tom Thorpe, UK, 1998

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. Falnes, *Proc. 2EWEC*, 1996

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.

A renewable-energy/man allegory

- As a human has to grow from conception to an adult person, a new energy production method has to develop from an idea to mature technology. Using this analogy we may perhaps say that wave energy is still in infancy, wind energy is a teenager and conventional energy an adult. Let us care for the children so they may grow up!

ACKNOWLEDGEMENT

Jørgen Hals

drew many of the illustrations of this PPT presentation (see also a 1999 PPT presentation “Wave energy and its utilisation” intended for introductory self study of wave-energy utilisation. It may be downloaded from http://folk.ntnu.no/hals.)