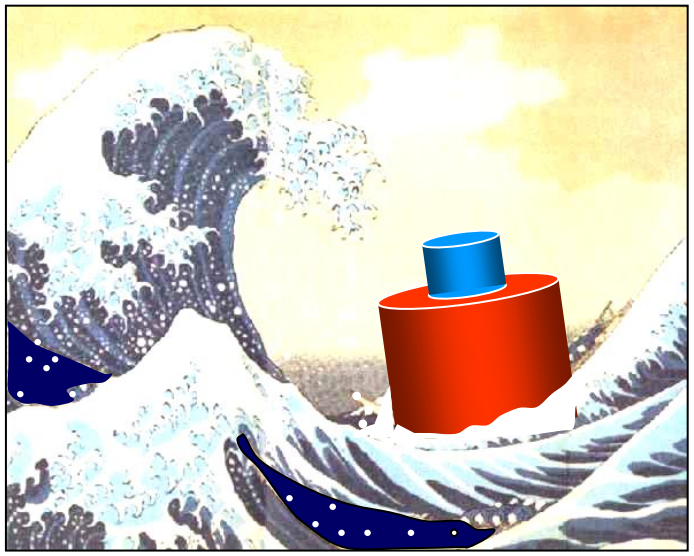
Università degli Studi di Firenze, 18-19 April 2012



WAVE ENERGY UTILIZATION

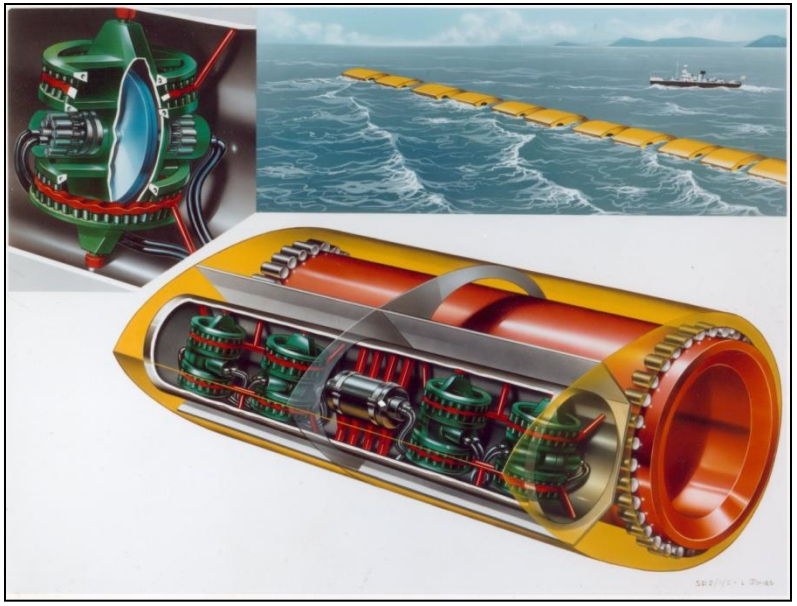
António F. O. Falcão

Instituto Superior Técnico,
Universidade Técnica de Lisboa

Part 2

Introduction to Wave Energy Conversion

- **Historical review.**
- **Types of wave energy converters and how they can be classified.**



Historical Review

- **THE WAVES:**
  the most conspicuous form of Ocean Energy !

- **How it began …**

- **The first patent for wave energy utilization: 1799, Messrs GIRARD, father and son, from Paris**

- **This patent was followed by thousands of others, …**

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 elevés comme montagnes, s'affaisent l'instant aprés, entrai-

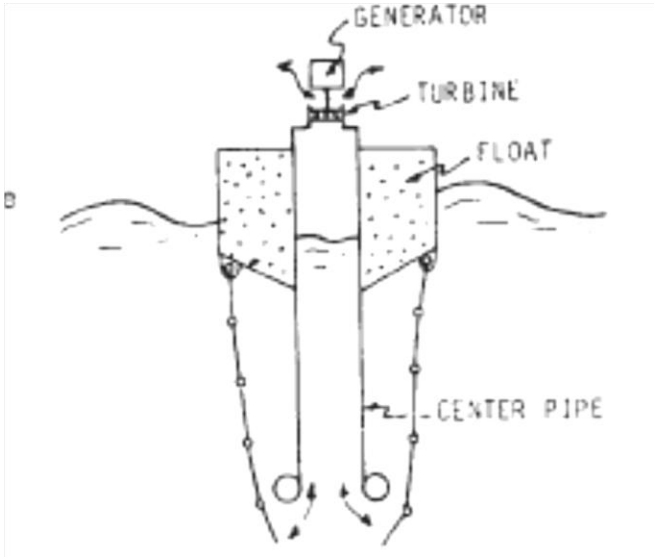
Historical Review

… but the father of modern wave power technology was ...

Yoshio Masuda, (1925-2009) a Navy officer from Japan, with studies in wave energy utilization since the 1940s.

- **Masuda invented the Oscillating Water Column (OWC) converter.**

- **Developed a navigation buoy with an air turbine (1964-65), of which more than one thousand were produced.**



Historical Review

- **In 1976, at JAMSTEC, Masuda promoted the construction of the first large wave energy converter to be deployed in the open sea:**

… the KAIMEI, a large barge (80m x 12m), used as a testing platform housing several OWCs equipped with different types of air turbines.

Historical Review

- **Another pioneer was Michael E. McCormick, who, in the US Naval Academy, did work on Oscillating-Water-Column devices in the early 1970s.**

- **McCormick developed self-rectifying air-turbines for OWCs, and was the author of some of the earliest journal papers on wave energy conversion:**

M.E. McCormick, Analysis of a Wave-Energy Conversion Buoy. *AIAA Journal of Hydronautics*, 8, 77-82, 1974.

- **He was the author of the first book devoted to wave energy conversion:**

M.E. McCormick, Ocean Wave Energy Conversion. Wiley, New York, 1981.

Historical Review

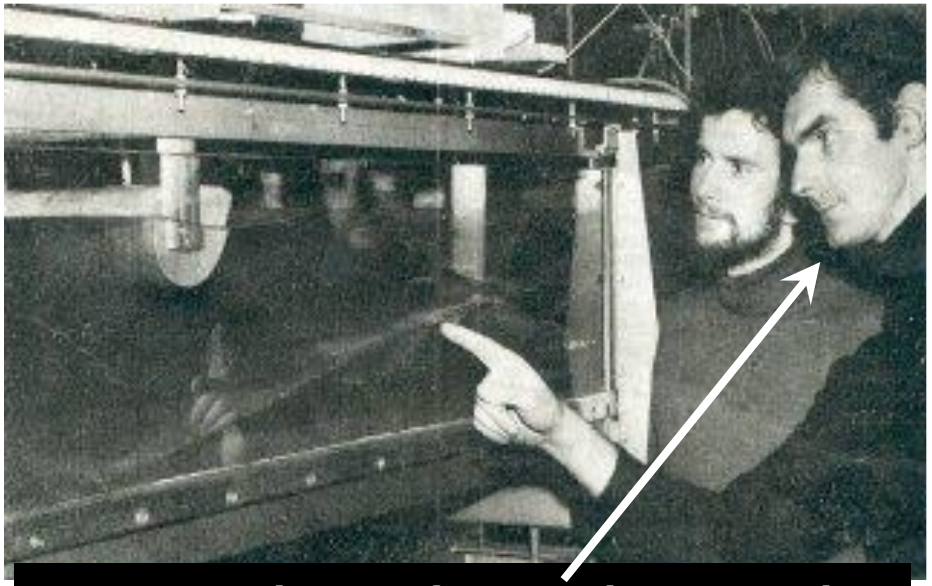
- **In the mean time, in the early 1970s, in Europe, Stephen Salter, from the**

University of Edinburgh, UK, invented and developed a very different wave energy converter:

… the Duck, a nodding floater, of which several versions would appear later.

Salter's 1974 paper in the influencial journal NATURE brought the wave energy to the attention of the international scientific community:

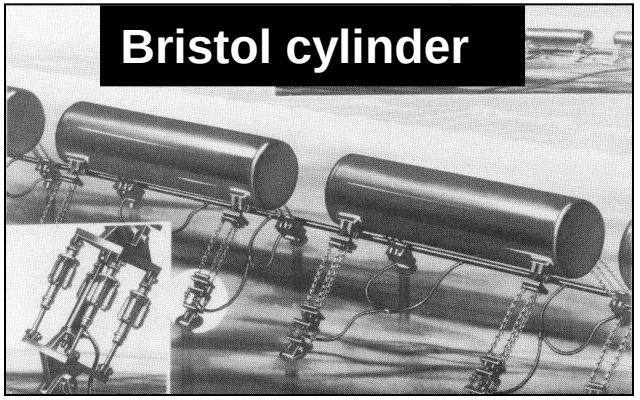
S.H. Salter, Wave Power. *Nature*, 249, 720-724, 1974.

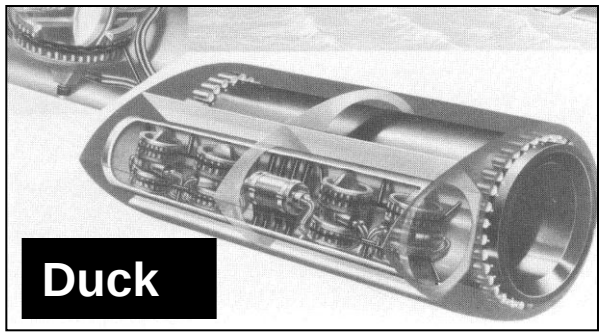


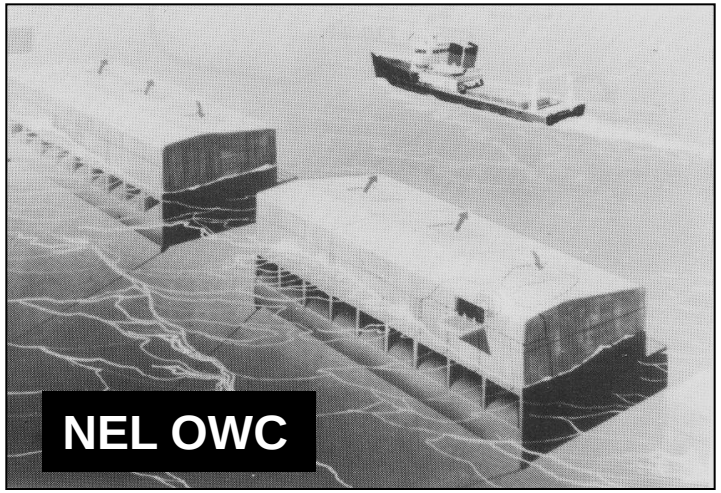
1974: Stephen Salter testing a Duck model in a wave flume at the University of Edinburgh.

Historical Review

- **An ambitious Research & Development program on wave energy was set up by the British Government in 1975, and run by Clive Grove-Palmer (1920-2002).**
- **Target: a cost-effective 2000 MW wave power plant.**
- **Several projects were funded:**

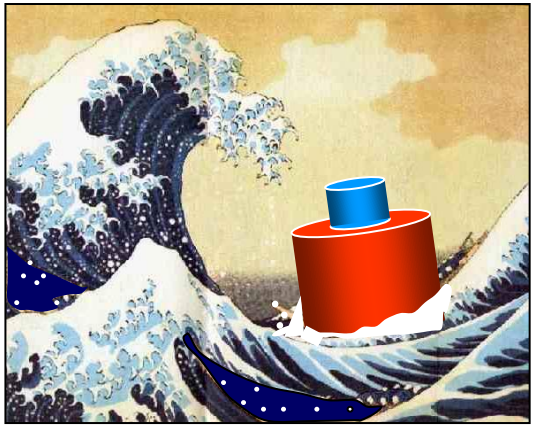






Historical Review

Hydrodynamics of wave energy absorbers



The wave energy absorption is a complex hydrodynamic process that often illudes intuition.

Ignoring it undelies many failures by inventors and technology developers.

The hydrodynamical theory of wave energy converters as a sub-area of surface-wave hydrodynamics was initiated in the mid-1970s, with important contributions from applied mathematicians and other scientists.

These developments could benefit from previous studies on the dynamics of ships in wavy seas.

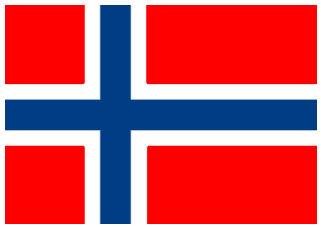
The energy extraction and its maximization introduced new issues.

Historical Review

Pioneers in hydrodynamics of wave energy absorbers

- David V. Evans, UK
- Brian M. Count, UK
- E. Richard Jefferyes, UK
- Martin Greenhow, UK

- Johannes Falnes, Norway
- Kjell Budal (1933-89), Norway



- John Nicholas Newman, USA
- Chiang C. Mei, USA

… and others !

Historical Review
Control

Maximum wave energy absoption by oscillating-body or OWC converters occurs at near-resonance conditions.

This requires tuning and control.

Remember that sea waves are irregular.

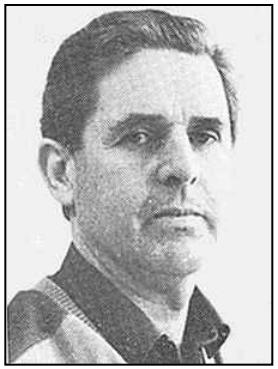
Control is essencial, but is one of the most difficult problems in hydrodynamics of wave energy conversion.

Optimal control remains an unsolved problem.

Historical Review

Pioneers in control theory of wave energy converters.

Johannes Falnes

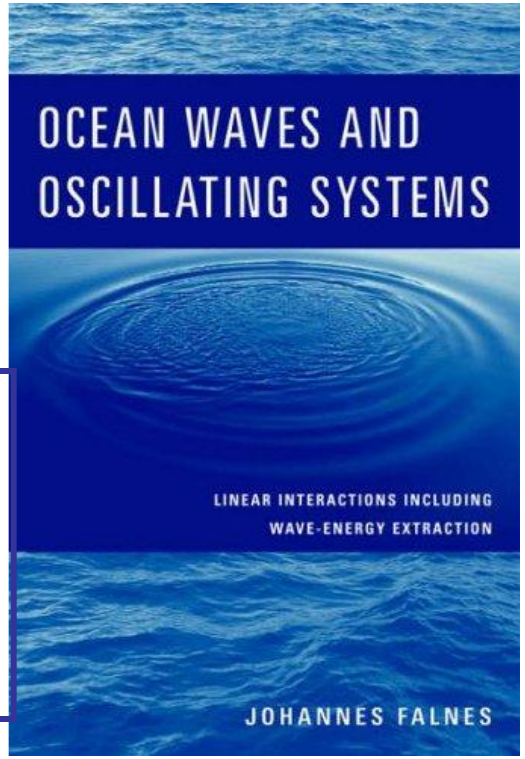


Kjell Budall (1933-89)

They introduced the concept of phase-control by latching:

J. Falnes, K. Budal, Wave-power conversion by power absorbers. *Norwegian Maritime Research*, 6, 2-11, 1978.

25 years of theoretical developments in hydrodynamics of wave energy conversion are embodied in the book (2002) by Johannes Falnes, that is now the reference textbook.

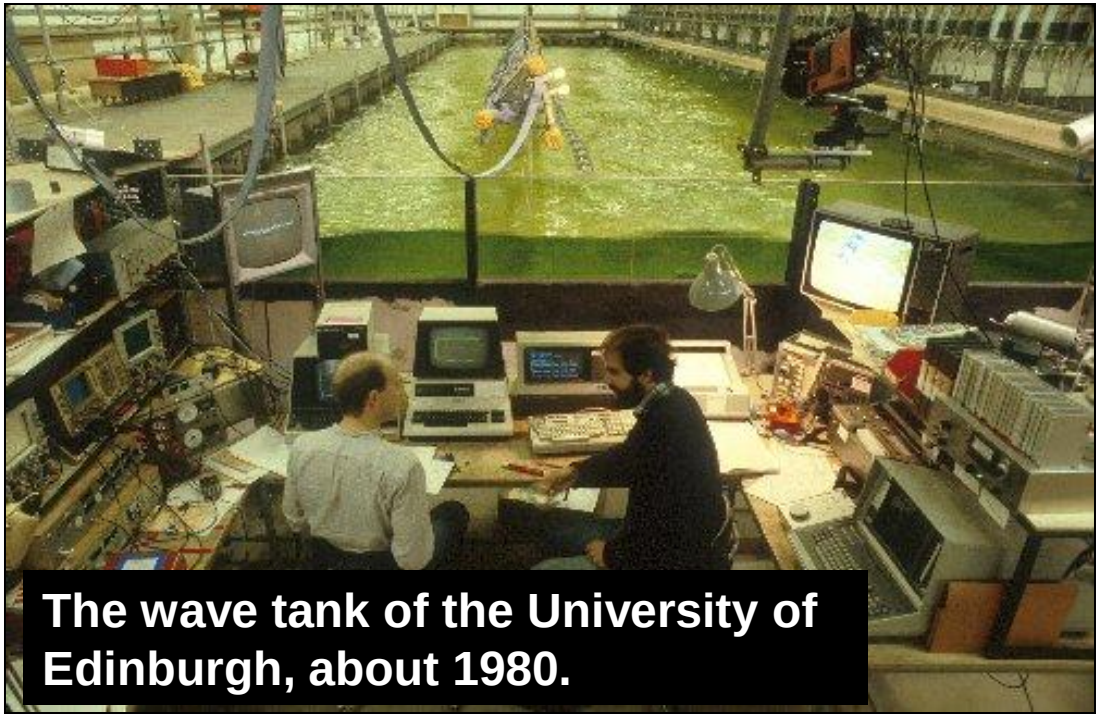


Historical Review
Model testing

- **The theoretical studies had to be complemented with model testing in wave tank.**

Stephen Salter was one of the pioneers of this approach.

At Edinburgh he created his own irregular-wave tank, in which he introduced several innovations, and tested wave energy device models.

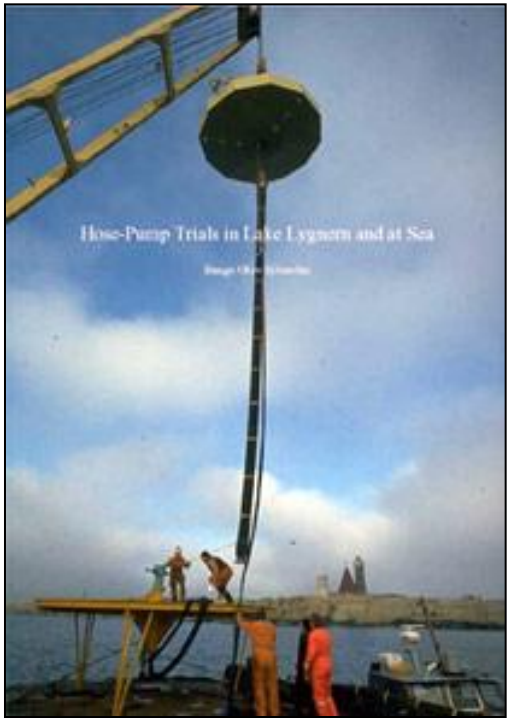


The wave tank of the University of Edinburgh, about 1980.

Historical Review

- **The concept of "point absorber", usually a "small buoy" oscillating in heave, was developped especially in Scandinavia.**

IPS buoy, Sweden, about 1982.



Hose pump device, Sweden, about 1982.

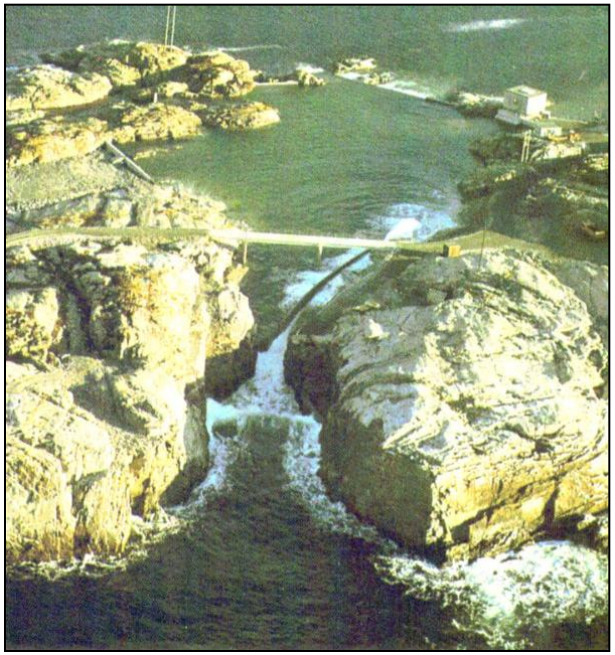
Heaving buoy, Norway, 1983.

Historical Review

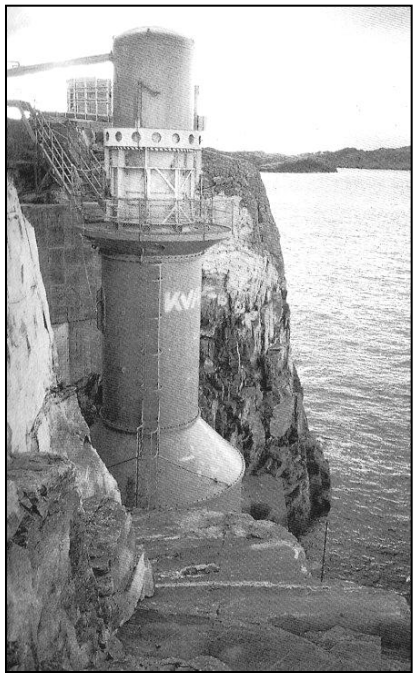
Due to a change in Government policy, the British Wave Energy Program came practically to a halt in 1982, …

… without any full-sized prototype having been constructed and tested.

The less ambitious Norwegian program went on to the construction, in 1985, of two shoreline prototypes, deployed on the coast, near Bergen.



The TAPCHAN, an over-topping device with a converging channel, a reservoir and a low-head hydraulic turbine,



… and an OWC with a vertical axis air turbine.

Historical Review

The two Norwegian plants at Toftestallen, 1985.

Historical Review

The Oscillating Water Column (OWC) was the first wave energy device to be developed and to reach the full-sized stage.

Several bottom-standing OWCs were built in 1985-90.

OWC integrated into a breakwater, Sakata, Japan, 1990.

Small OWC at Sanze, Japan, 1985.

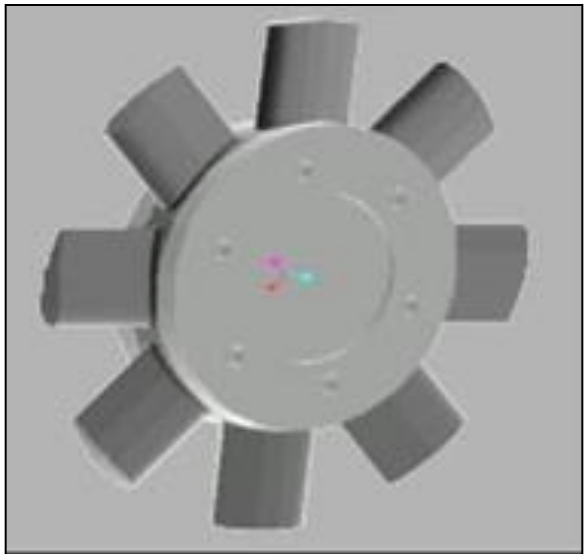
Trivandrum, India, 1990.

Historical Review

All the OWC prototypes built so far use a self-rectifying air turbine.

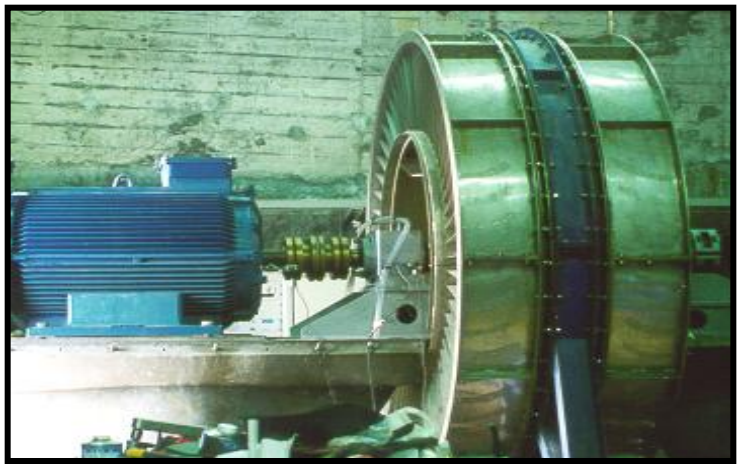
The most popular one is the <u>Wells turbine</u>, invented in 1976 by Allan Wells, in Northern Ireland.

Allan Wells
1924 - 2005



Rotor of Wells turbine

Wells turbine-generator set, 400 kW, Pico OWC plant. 1999.



Historical Review

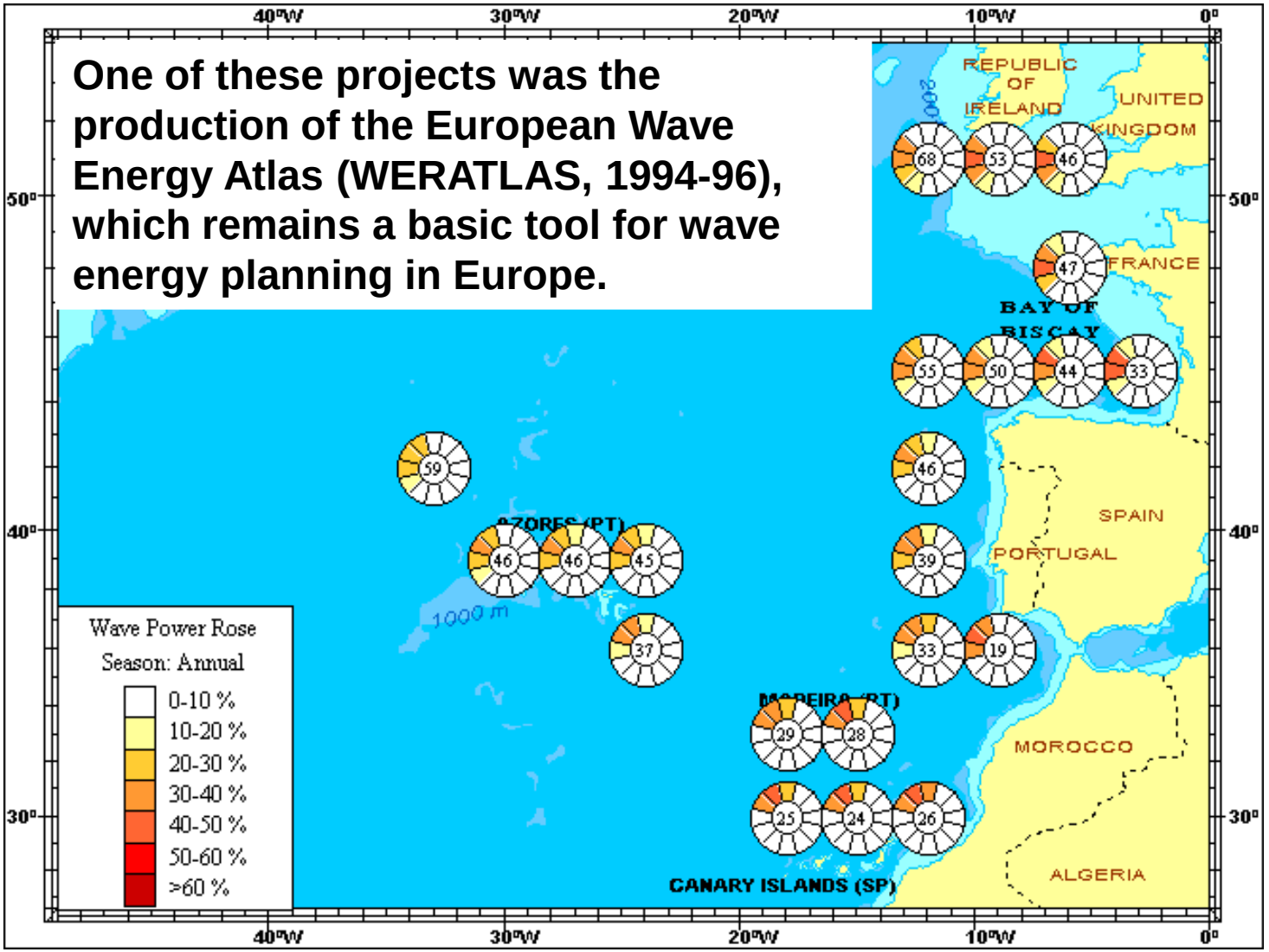
After 1982, and until the early 1990s, R & D on wave energy in Europe remained mostly academic, except for the two Norwegian protypes (1985) …

… and the construction of a small (75 kW) OWC on Islay, Scotland, in 1991.

The situation in Europe changed dramatically with the decision made, in 1991, by the European Commission, of including Wave Energy in their R & D programme on Renewable Energies

Since then, many projects have been funded by the European Commission, involving a large number of European teams.

Historical Review



One of these projects was the production of the European Wave Energy Atlas (WERATLAS, 1994-96), which remains a basic tool for wave energy planning in Europe.

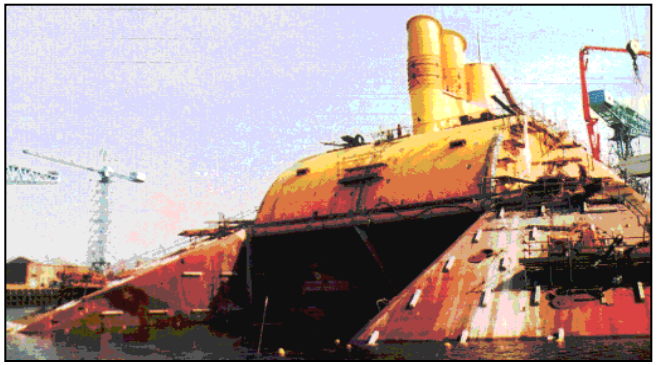
Historical Review

Other European Commission projects supported the design and construction of prototypes, like the two European OWC Pilot Plants, on the shoreline of …

… the island of Pico, Azores, Portugal, in 1999 (400 kW) …

… and the island of Islay, Scotland, in 2000 (500 kW).

The much larger (2 MW) Osprey plant (also an OWC) was destroyed by sea action during the deployment operation (Scotland, 1995).



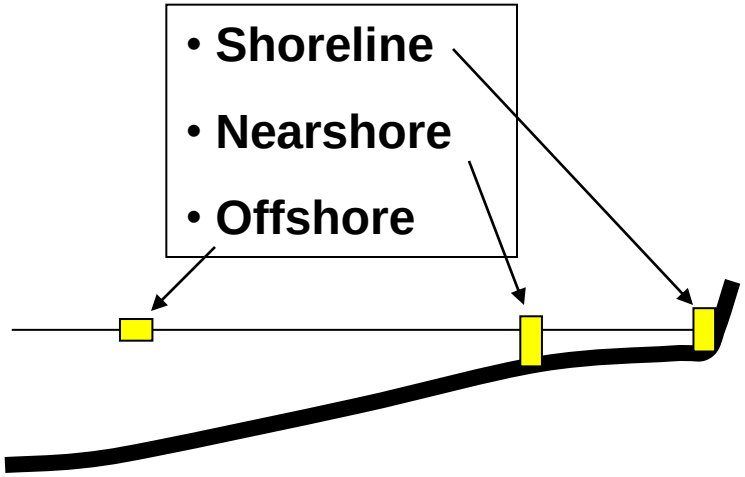
Wave Energy Converter Types

Unlike the case of large wind turbines …

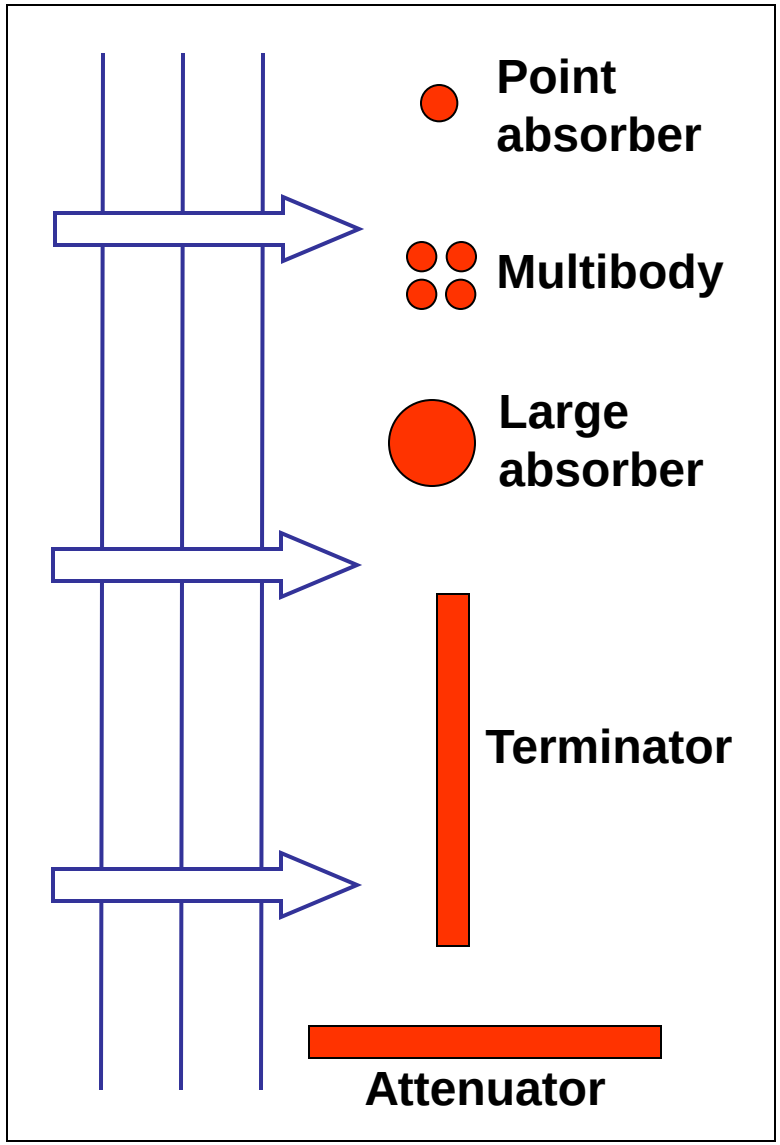
… there is a wide range of wave energy devices, at different development stages, competing against each other.

Wave Energy Converter Types

Different ways of classifying WECs:



According to working principle



Wave Energy Converter Types

- **Oscillating Water Column** (with air turbine)
  - **Fixed structure**
    - **Isolated:** Pico, LIMPET, Oceanlinx
    - **In breakwater:** Sakata, Mutriku
  - **Floating:** Mighty Whale, BBDB
- **Oscillating body** (hydraulic motor, hydraulic turbine, linear electric generator)
  - **Floating**
    - **Heaving:** Aquabuoy, IPS Buoy, Wavebob, PowerBuoy, FO3
    - **Pitching:** Pelamis, PS Frog, Searev
  - **Submerged**
    - **Heaving:** AWS
    - **Bottom-hinged:** Oyster, Waveroller
- **Overtopping** (low head water turbine)
  - **Fixed structure**
    - **Shoreline (with concentration):** TAPCHAN
    - **In breakwater (without concentration):** SSG
  - **Floating structure (with concentration):** Wave Dragon

Wave Energy Converter Types

OWC (Oscillating Water Column)

The most developed type of wave energy converter:

- **Europe (UK, Norway, Portugal, Ireland)**
- **Japan, USA, India, China, Australia**

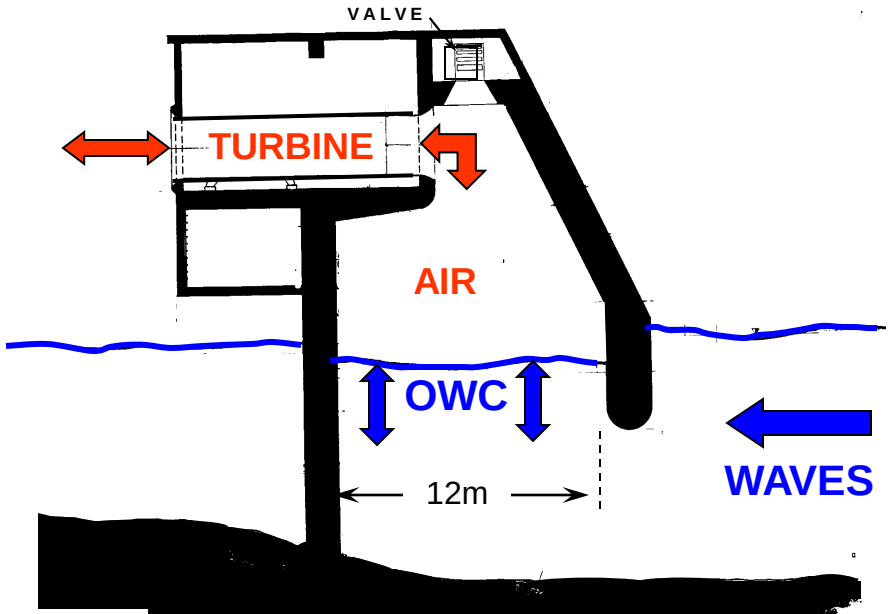
Structure (concrete, …) { **OWC** / **Air chamber**

Air turbine (several types)

Valves (air) (for protection, control)

Electrical generator

Electrical and control equipment



Cross-section of bottom-standing OWC plant.

Wave Energy Converter Types

OWC: shoreline and nearshore (bottom standing)

Material: CONCRETE

Construction method dependent on site, integration, and local facilities

Construction in yard; towed and sunk into place (India), 1990

In situ construction (Azores), 1999.

16 OWCs integrated into breakwater, Mutriku (Spain), 2008.

Wave Energy Converter Types

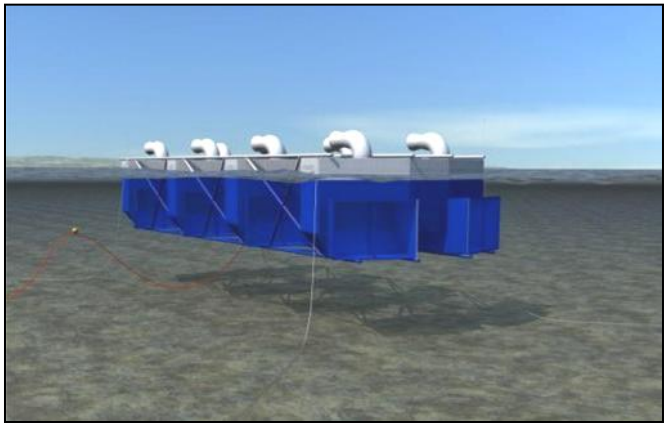
OWC: shoreline and nearshore (bottom standing)

Material: STEEL

Port Kembla (Australia), 2005.

Wave Energy Converter Types

OWC: floating

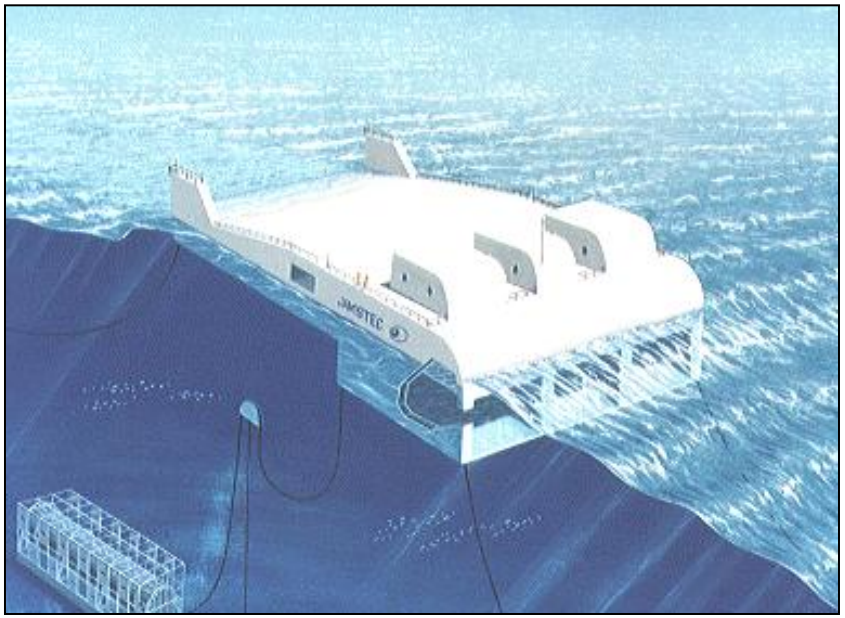


Oceanlinx, Australia. Floating platform with 8 air chambers.

1:3rd scale model with 2 installed air turbines tested in 2010.

Wave Energy Converter Types

OWC: floating

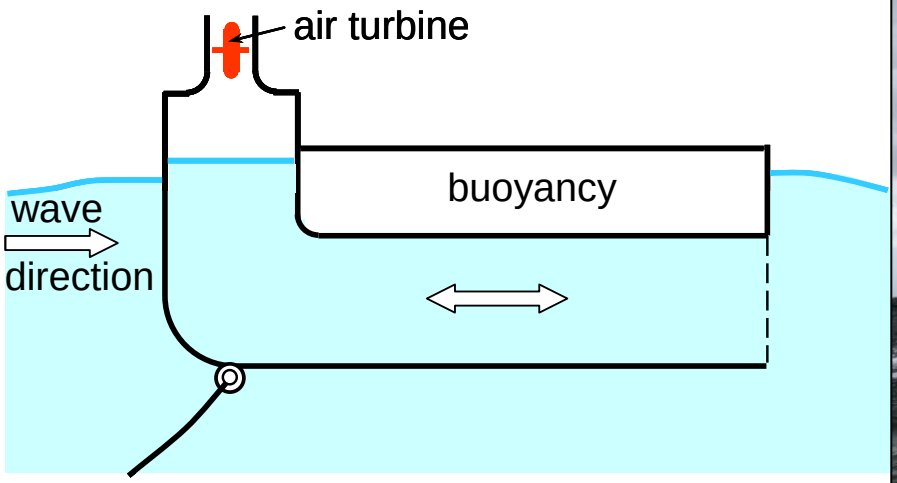


“Mighty Whale”, Gokasho Bay (Japan), 1998. Three OWCs with frontward facing opening.

Wave Energy Converter Types

OWC: floating

Backward Bent Duct Buoy (BBDB).



Concept: Japan, about 1985.

1/4th scale model testing, Galway Bay (Ireland), 2008.

Wave Energy Converter Types

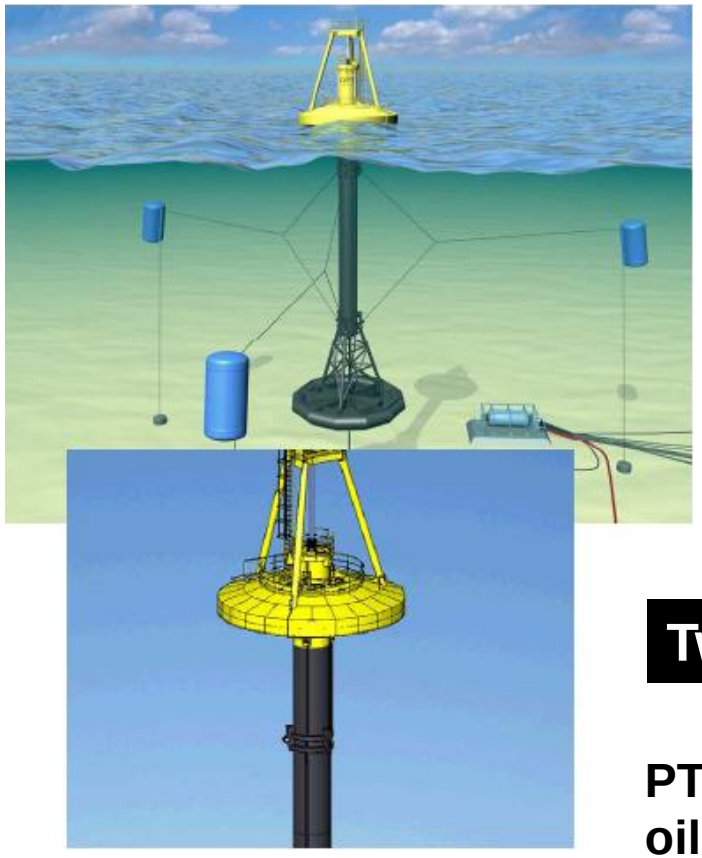
Floating Oscillating Body, Heaving

BOLT, Norway (Fred Olsen)

Single body WEC

Wave Energy Converter Types

Floating Oscillating Body, Heaving



PowerBuoy, USA

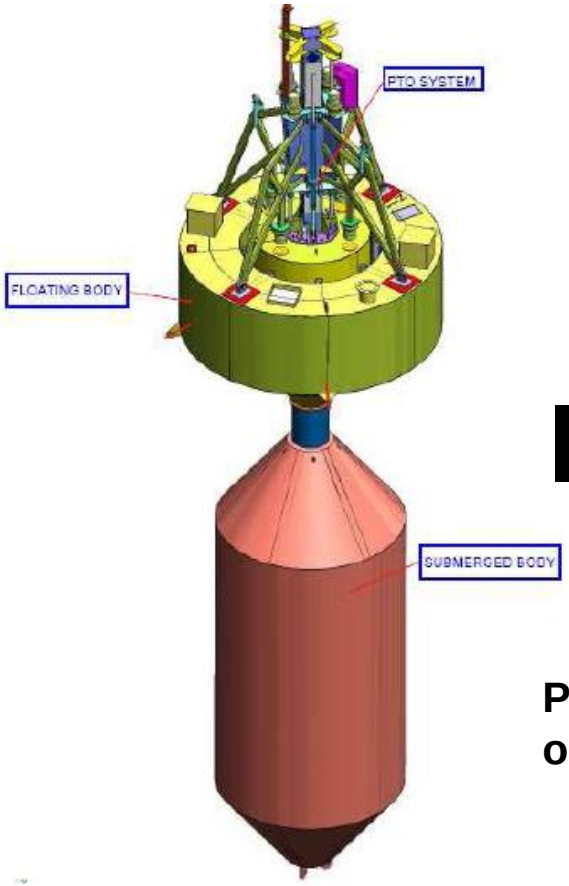
40 kW, Santoño (Spain), 2008

Two-body WEC

PTO: high-pressure-oil hydraulic circuit

Wave Energy Converter Types

Floating Oscillating Body, Heaving



Wavebob, Ireland

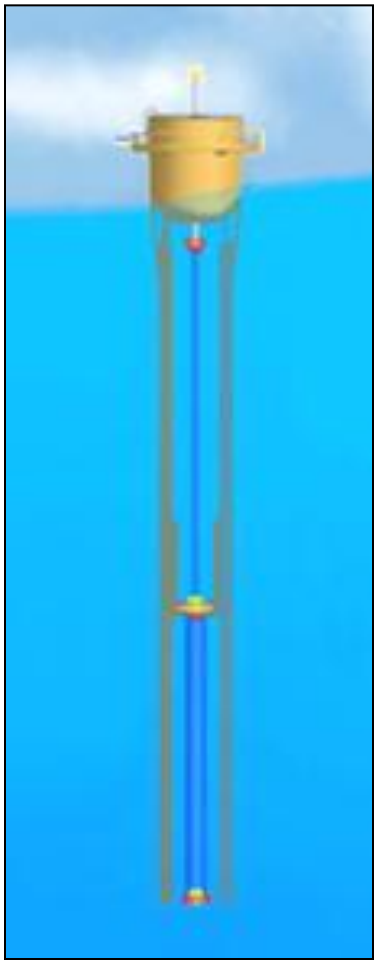
Two-body WEC

PTO: high-pressure-oil hydraulic circuit

1/4th scale model testing, Galway Bay (Ireland), 2008.

Wave Energy Converter Types

Floating Oscillating Body, Heaving



Aquabuoy,
Sweden, USA

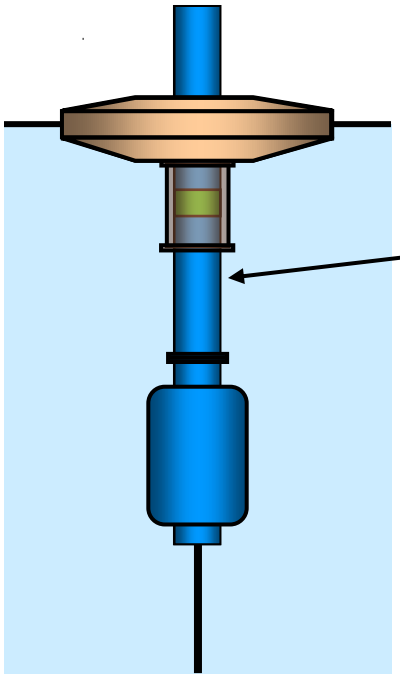
Two-body WEC

PTO: high-head hydraulic turbine

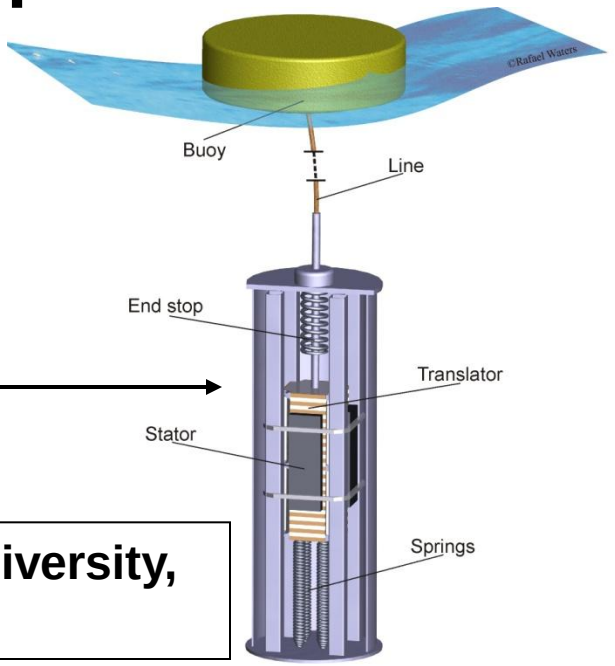
Oregon, USA, 2007

Wave Energy Converter Types

Floating Oscillating Body, Heaving

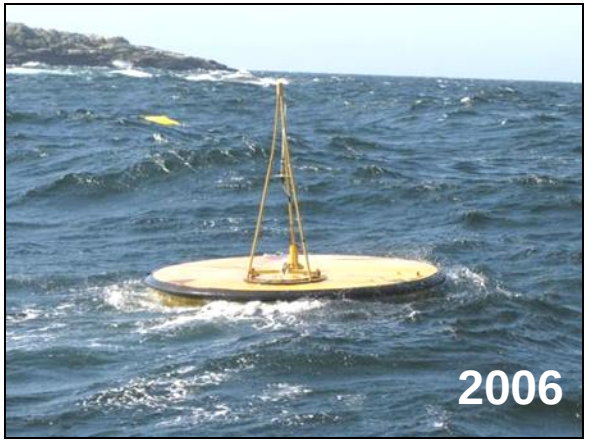


With linear electric generator



Oregon State University, USA

Uppsala University, Sweden

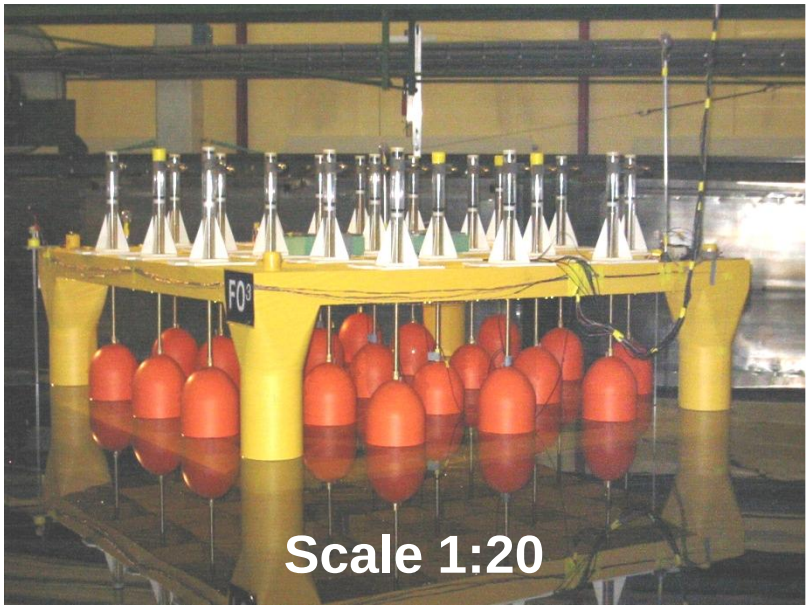


Wave Energy Converter Types

Floating Multibody, Heaving

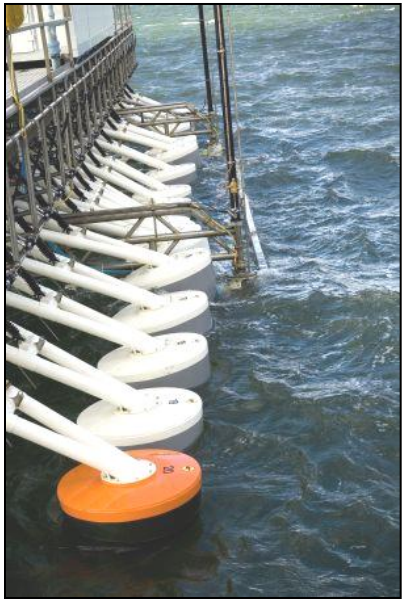
FO3, Norway

1/3rd scale model testing, Norway



Wave Energy Converter Types

Floating Multibody, Heaving



Wave Star (Denmark)

Hydraulic circuit (oil)

Hyperbaric WEC (Brazil)

Hydraulic circuit (sea water)

Wave Energy Converter Types

Wave Star (Denmark)

Tests of a section (2 floats) of full-sized machine (20 floats)

Water depth: 7 m
Height of legs: 25 m
Number of floats: 2 (out of 20)
Float diameter: 5 m
Power per float: 25 kW

North Sea off Hanstholm

Wave Energy Converter Types

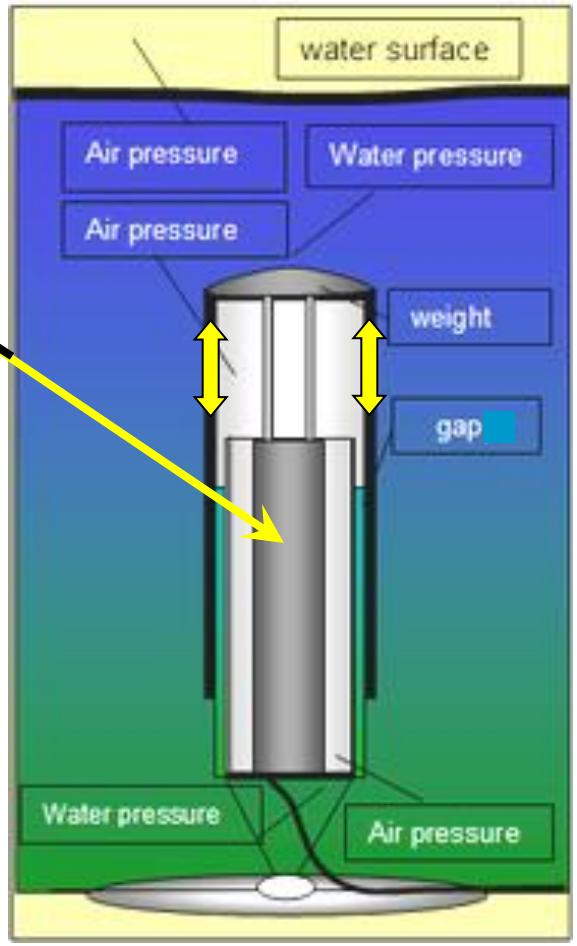
Submerged Oscillating Body, Heaving

Archimedes Wave Swing (AWS), Holland

With linear electric generator

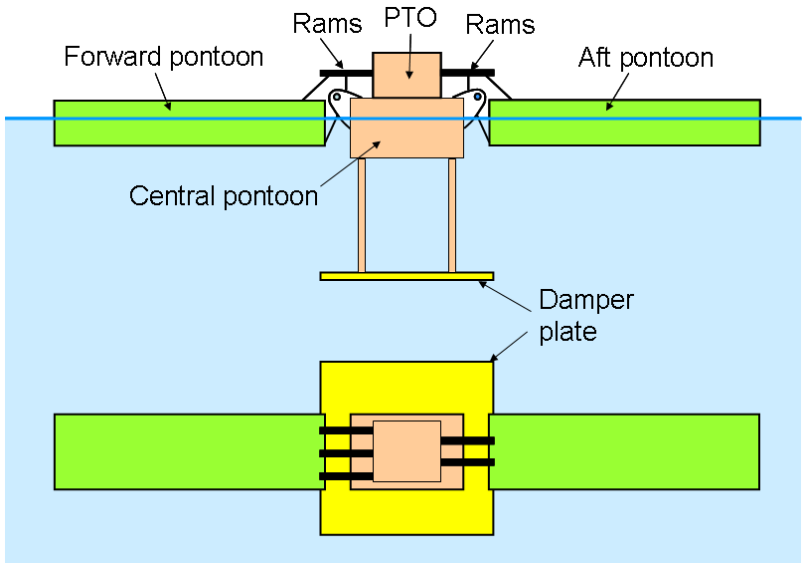
AWS being sunk into place

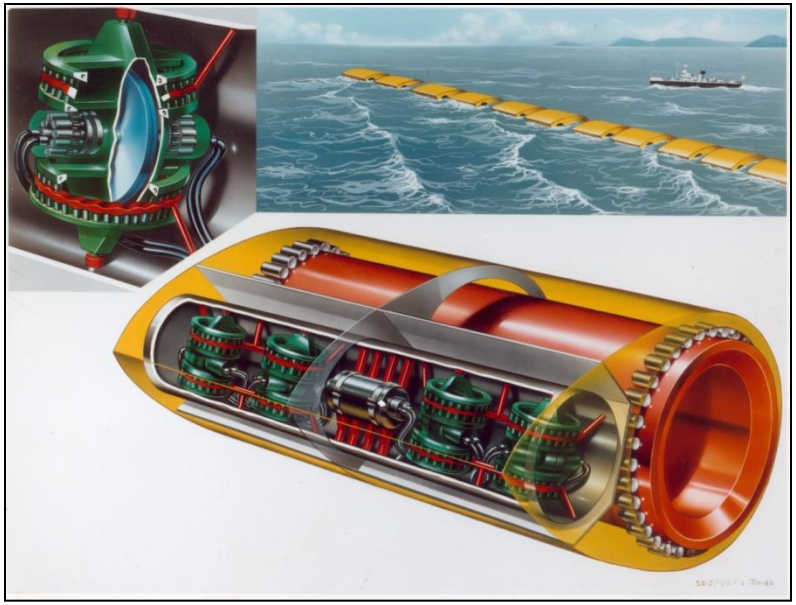
Aguçadoura, Portugal, 2004.



Wave Energy Converter Types

Floating Oscillating Body Pitching





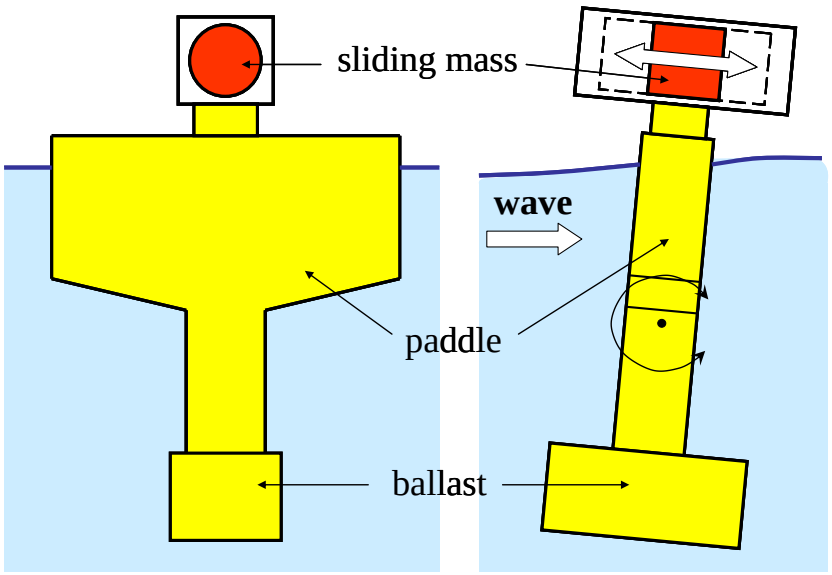
Duck, UK, 1979, with gyroscopes

McCabe Wave Pump, UK

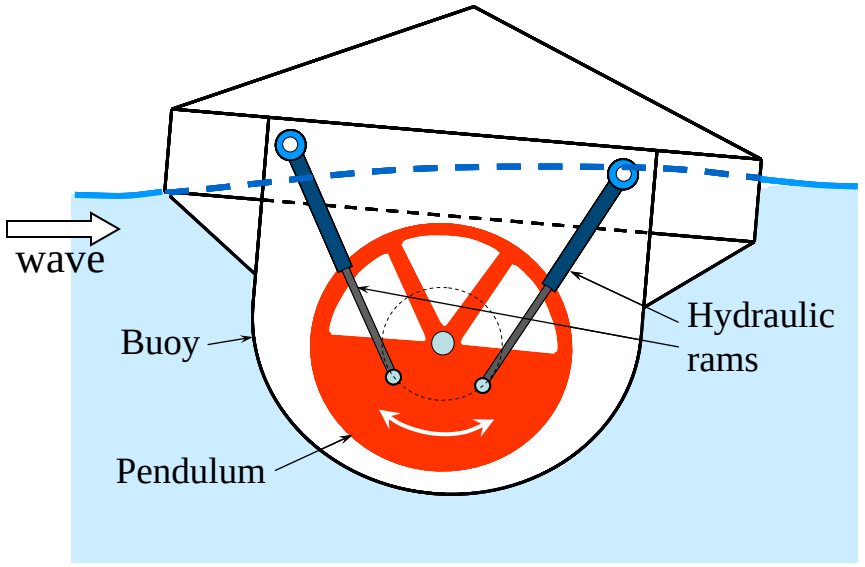
Wave Energy Converter Types

Floating Oscillating Body, Pitching

Floater reacts against an internal body



PS Frog Mk 5, UK

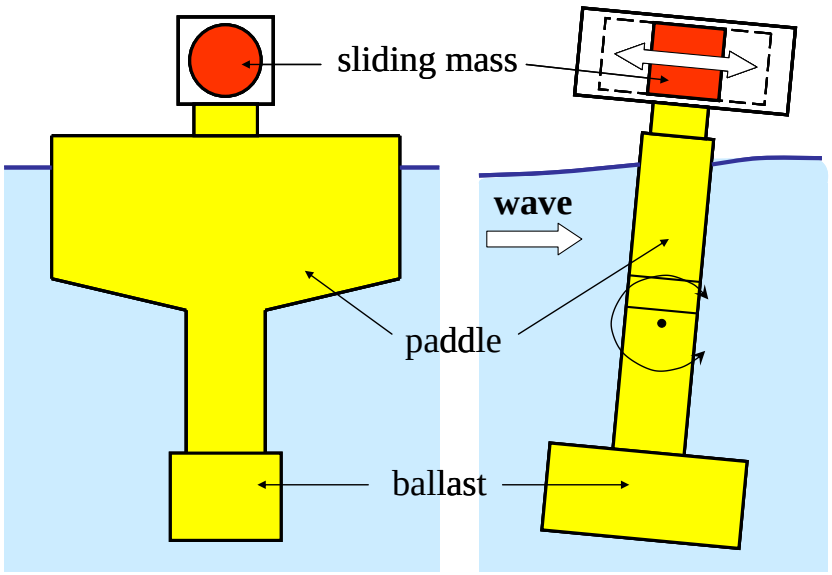


Searev, France

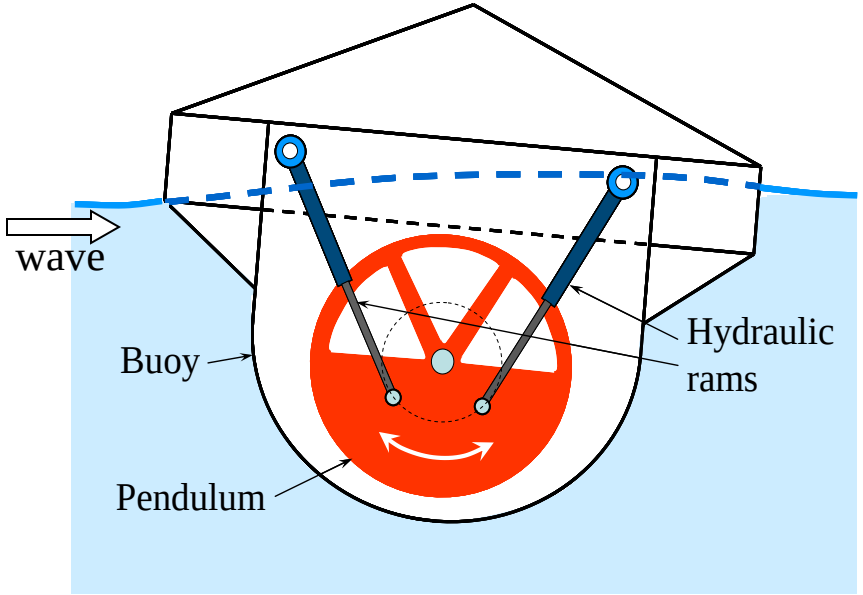
Wave Energy Converter Types

Floating Oscillating Body, Pitching

Floater reacts against an internal body



PS Frog Mk 5, UK

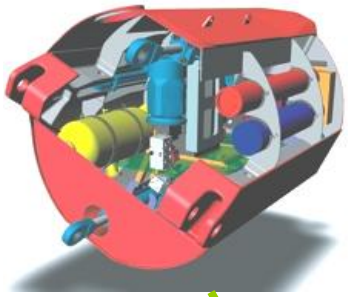


Searev, France

Wave Energy Converter Types

Floating, Multibody, Pitching and Yawing

Pelamis, UK



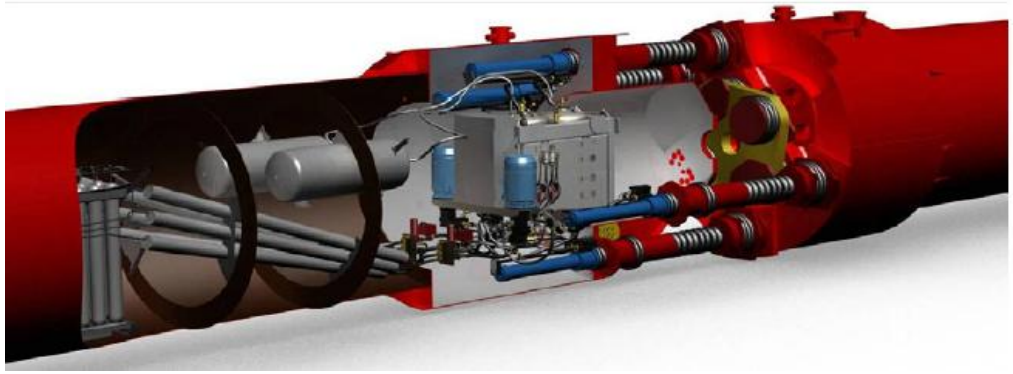
Hydraulic PTO

3-unit farm, Portugal, 2008.

Wave Energy Converter Types

Pelamis, UK

New Mark 2 version

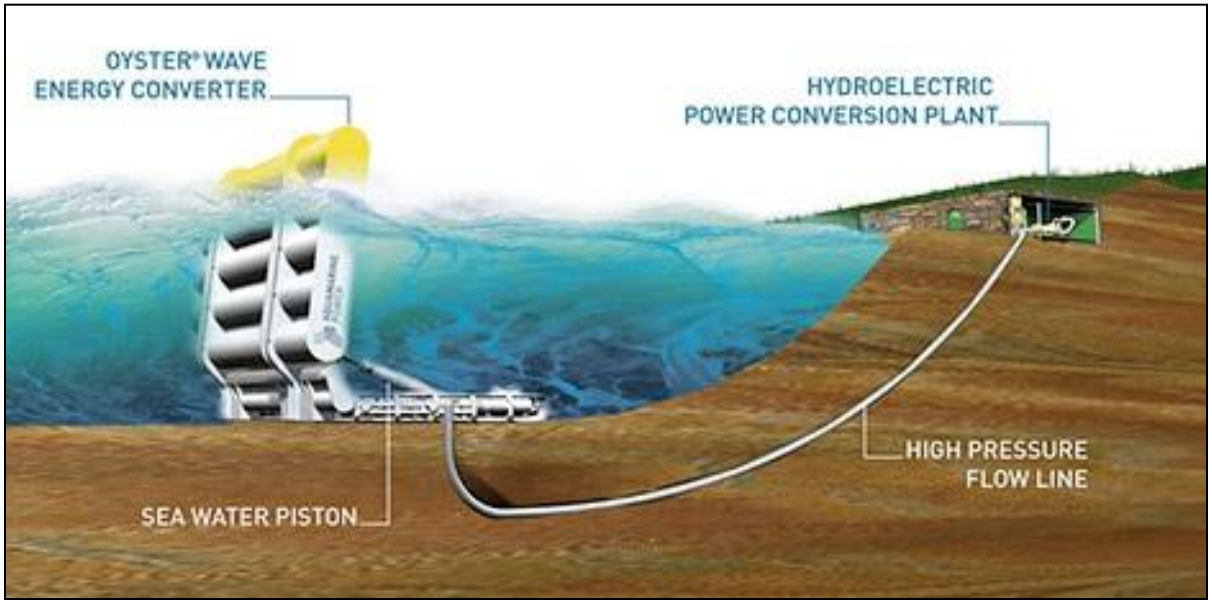


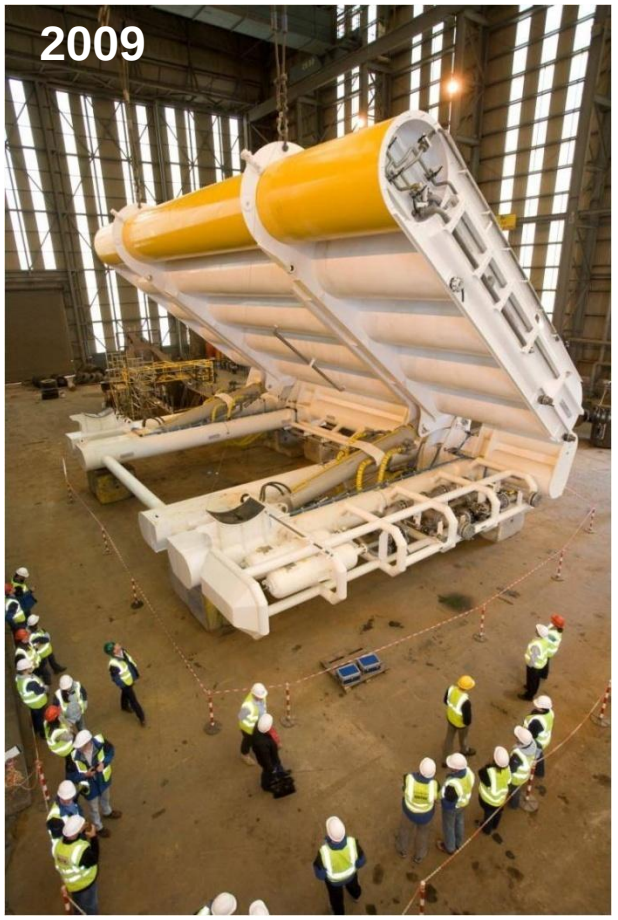
Wave Energy Converter Types

Submerged Body, Bottom-hinged, Pitching, Nearshore

Oyster, UK

High-pressure sea water PTO





Wave Energy Converter Types

Submerged Body, Bottom-hinged, Pitching, Nearshore

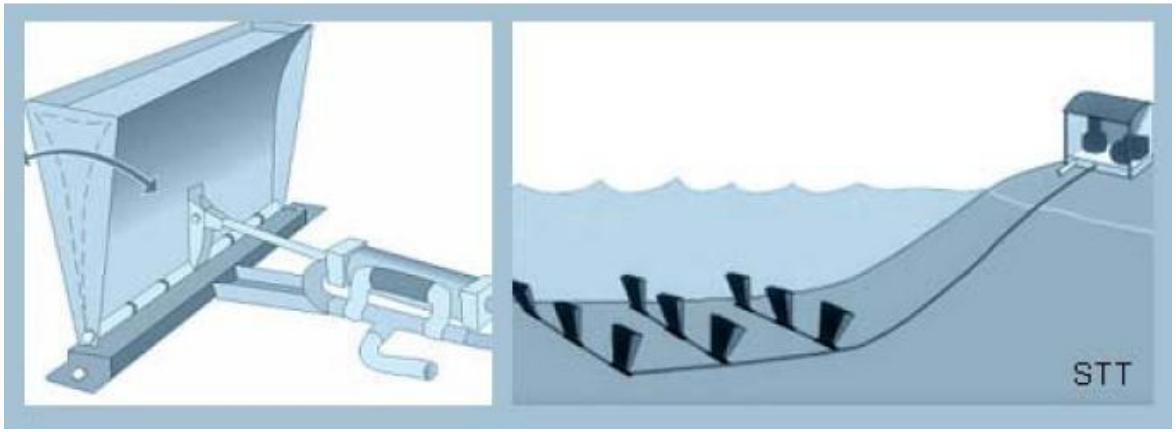
Oyster prototype being tested at EMEC, Scotland, 2010

Wave Energy Converter Types

Submerged body, Bottom-hinged, pitching, nearshore

Waveroller, Finland

High-pressure oil PTO



Peniche, Portugal, 2007

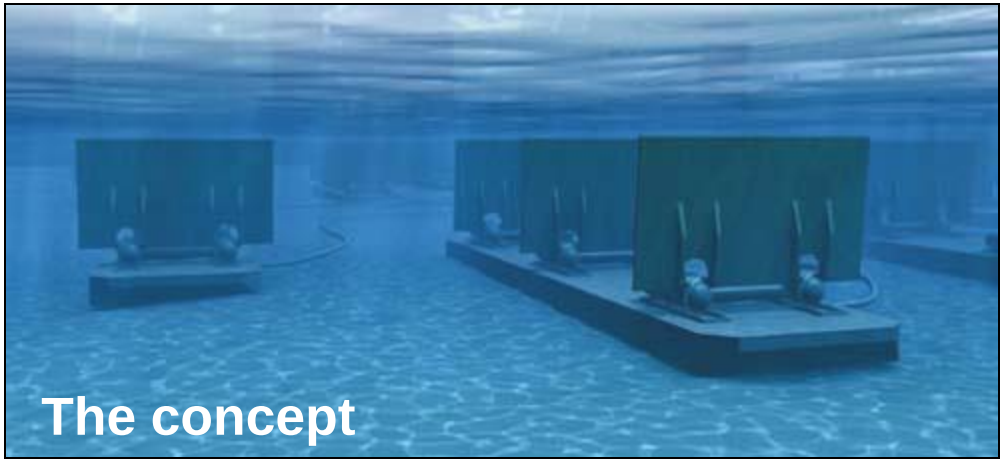
Wave Energy Converter Types

Fully submerged body, Bottom-hinged, pitching, nearshore

Waveroller, Finland

Peniche, Portugal, 2007

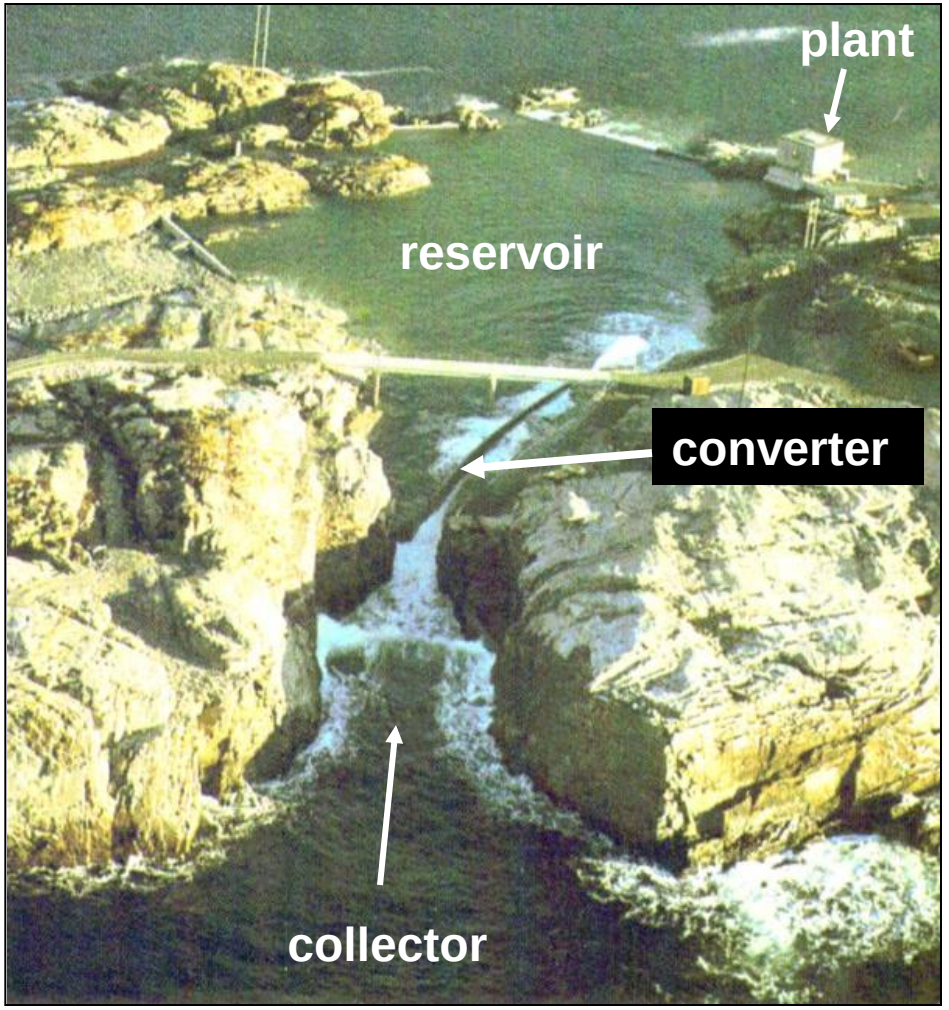
High-pressure oil PTO



Peniche, Portugal, 2012, 3 x 100 kW

Wave Energy Converter Types
Overtopping, shoreline, with concentration

TAPCHAN (Tapered Channel Wave Power Device), Norway



Toftestallen, Norway, 1985.

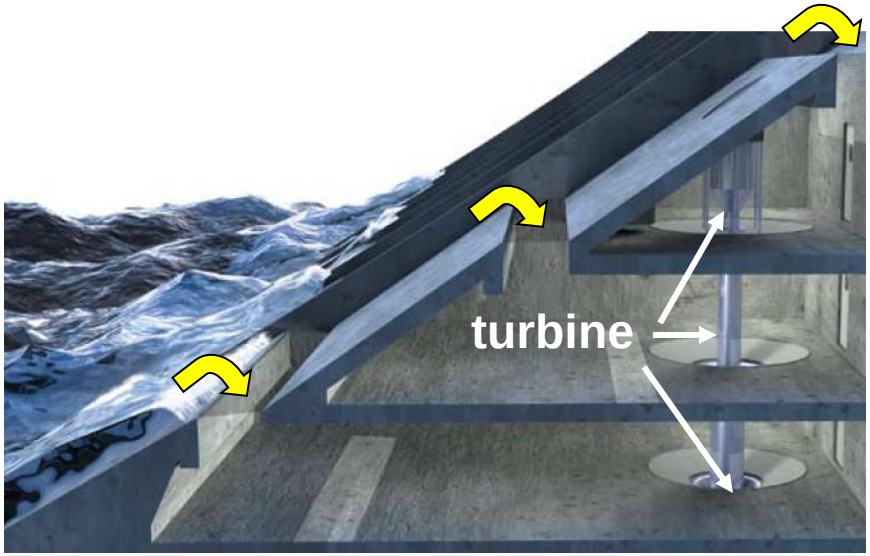
With 350kW vertical-axis water turbine.

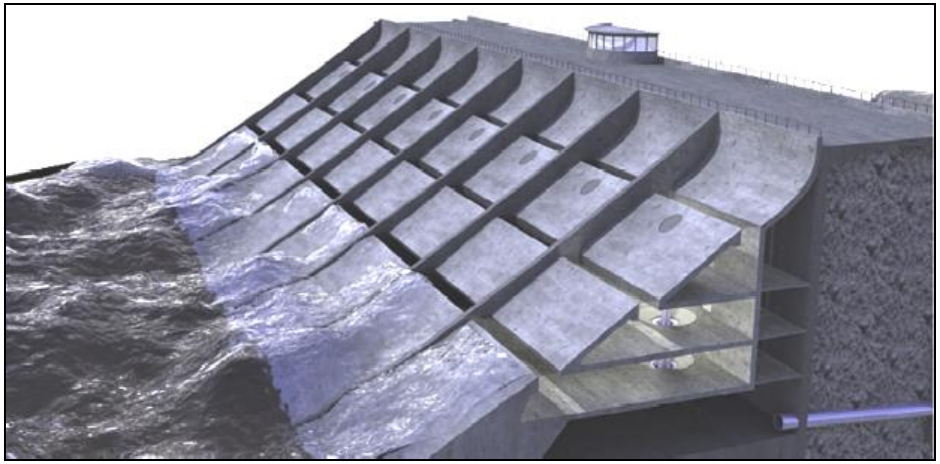
Wave Energy Converter Types

Overtopping, in breakwater, without concentration

Seawave Slot-Cone Generator (SSG), Norway

Considered for construction at several sites



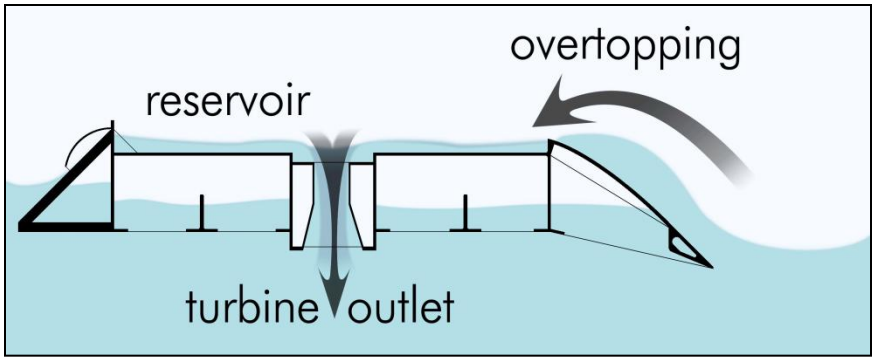


Wave Energy Converter Types

Overtopping, floating, with concentration

Wave Dragon, Denmark

1/4th scale model tests, Denmark, 2005.



END OF PART 2. INTRODUCTION TO WAVE ENERGY CONVERSION