Chapter Outline

Wave Energy Conversion

- Introduction
- Classification of wave energy converters WECs
- Fundamentals of wave energy conversion theory
- Tidal Energy Extraction Systems

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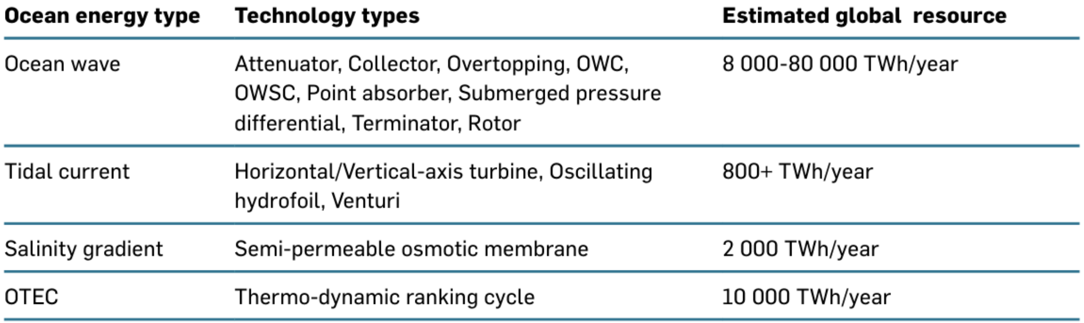
Introduction

Ocean energy technologies, including ocean wave, tidal current, ocean thermal energy conversion (OTEC) and salinity gradient, are at the early stages of development compared with other, more well-established renewable and conventional generation technologies.

The International Energy Agency’s Implementing Agreement on Ocean Energy Systems commenced in October 2001. The Agreement’s mission is to enhance international collaboration to make ocean energy technologies a significant energy option in the medium-term future.

Historically, global research into ocean wave energy began in the 1970s; however, the majority of those technologies currently in development started in the 1990s. Development of tidal current technology began in the 1990s, although the number of RD&D projects has increased significantly over the last three years.



Ocean energy type	**Technology types**	**Estimated global resource**
Ocean wave	Attenuator, Collector, Overtopping, OWC, OWSC, Point absorber, Submerged pressure differential, Terminator, Rotor	8 000-80 000 TWh/year
Tidal current	Horizontal/Vertical-axis turbine, Oscillating hydrofoil, Venturi	800+ TWh/year
Salinity gradient	Semi-permeable osmotic membrane	2 000 TWh/year
OTEC	Thermo-dynamic ranking cycle	10 000 TWh/year

Types of ocean energy and technologies, plus estimated resource

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Introduction

The possibility of converting wave energy into usable energy has inspired numerous inventors: more than one thousand patents had been registered by 1980, and the number has increased markedly since then.

Yoshio Masuda may be regarded as the father of modern wave energy technology, with studies in Japan since the 1940s. He developed a navigation buoy powered by wave energy, equipped with an air turbine, which was in fact what was later named as a (floating) oscillating water column. Probably because this was done at an early stage when the theoretical knowledge of wave energy absorption was in its infancy, the power output levels achieved were not a great success.

The oil crisis of 1973 induced a major change in the renewable energies scenario and raised the interest in large-scale energy production from the waves. A paper published in 1974 in the prestigious journal Nature by Stephen Salte, of the University of Edinburgh, became a landmark and brought wave energy to the attention of the international scientific community.

The British Government started in 1975 an important research and development program in wave energy, followed shortly afterwards by the Norwegian Government. The first conferences devoted to wave energy took place in England (Canterbury, 1976, and Heathrow, 1978). This was followed in 1979 by two more genuinely international conferences: Power from Sea Waves (Edinburgh, June) and the First Symposium on Wave Energy Utilization (Gothenburg, October-November).

Introduction

In Norway the activity went on to the construction, in 1985, of two full-sized (350 and 500 kW rated power) shoreline prototypes near Bergen. In the following years, until the early 1990s, the activity in Europe remained mainly at the academic level, the most visible achievement being a small (75 kW) OWC shoreline prototype deployed at the island of Islay, Scotland (commissioned in 1991).
At about the same time, two OWC prototypes were constructed in Asia: a 60 kW converter integrated into a break water at the port of Sakata, Japan and a bottom-standing 125 kW plant at Trivandrum, India.

The wave energy absorption is a hydrodynamic process of considerable theoretical difficulty, in which relatively complex diffraction and radiation wave phenomena take place. This explains why a large part of the work on wave energy published in the second half of the 1970s was on theoretical hydrodynamics, in which several distinguished applied mathematicians took leading roles. An additional difficulty is related to the conception of the power take-off mechanism (PTO) (air turbine, power hydraulics, electrical generator or other) which should allow the production of usable energy. The problem here lies in the variability of the energy flux absorbed from the waves, in several time-scales: wave-to-wave (a few seconds), sea states (hours or days) and seasonable variations. Naturally, the survivability in extreme conditions is another major issue.

The situation in Europe was dramatically changed by the decision made in 1991 by the European Commission of including wave energy in their R&D program on renewable energies. The first projects started in 1992. Since then, about thirty projects on wave energy were funded by the European Commission involving a large number of teams active in Europe.

Introduction

The main disadvantage of wave power, as with the wind from which is originates, is its (largely random) variability in several time-scales: from wave- to - wave, with sea state, and from month to month (although patterns of seasonal variation can be recognized).

The assessment of the wave energy resource is a basic prerequisite for the strategic planning of its utilization and for the design of wave energy devices. The characterization of the wave climate had been done before for other purposes, namely navigation, and harbour, coastal and offshore engineering, for which, however, the required information does not coincide with what is needed in wave energy utilization planning and design. The studies aiming at the characterization of the wave energy resource, having in view its utilization, started naturally in those countries where the wave energy technology was developed first.

The wave energy level is usually expressed as power per unit length (along the wave crest or along the shoreline direction); typical values for ‘‘good’’ offshore locations (annual average) range between 20 and 70 kW/m and occur mostly in moderate to high latitudes. Seasonal variations are in general considerably larger in the northern than in the southern hemisphere, which makes the southern coasts of South America, Africa and Australia particularly attractive for wave energy exploitation.

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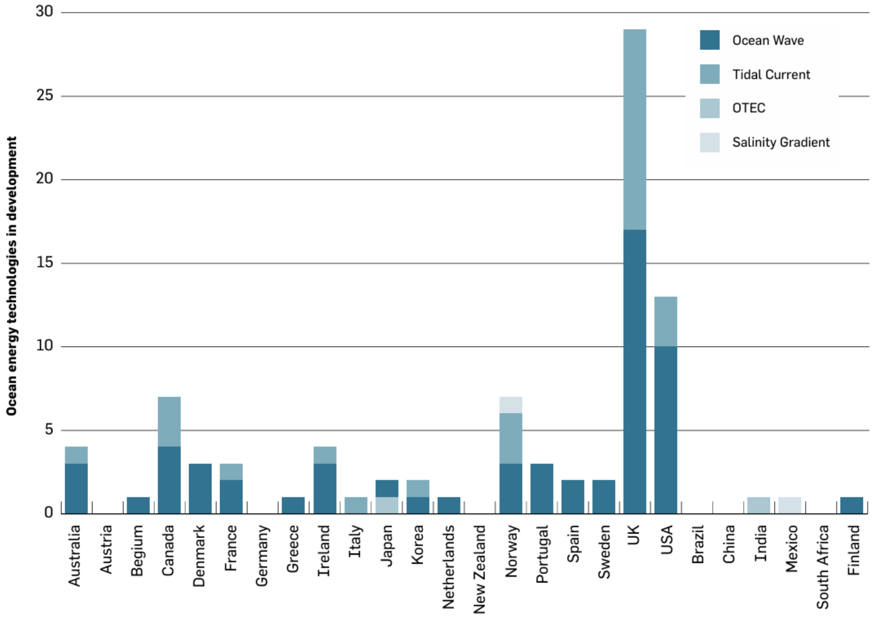
Introduction

Typically, an ocean energy concept is developed by one of the types of team listed below:

- Small team of academics within a university department or research institute.
- Small start-up company.
- Specialist equipment manufacturer.
- Large energy company monitoring and assessing the feasibility of concepts.
- Combination of the above within a consortium.

A pattern observed is the tendency for smaller developers to form partnerships with various companies, including:

- Engineering consultants.
- Energy generation and transmission specialist companies.
- Companies involved in the marine and offshore industry.



The ocean energy technology RD&D projects in March 2006.

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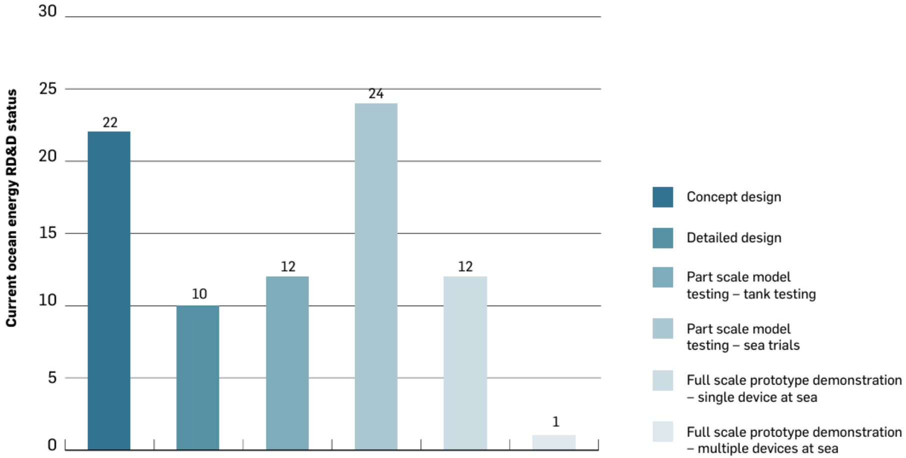
Introduction

Current development status of ocean energy technologies is varied. There are a relatively high number of emerging designs at the conceptual stage. Several concepts have advanced to detailed designs. Many device developers have constructed more advanced models and are performing simulated testing of part-scale models in wave, flume or tow tanks.
Part-scale prototypes are currently being tested at sea, and prototypes are then undergoing sea trials at full or near full-scale.

There are still several relatively new devices at the concept stage, indicating that the total number being developed is still growing. Generally, the greater the number of technology developments, the greater the level of competition within the sector. Increased competition should lead to better cost-competitiveness longer term, however the growing number of concepts in development at this stage also indicates that RD&D is not yet close to converging on an optimum design.



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Introduction

Attenuator

Collector

Overtopping

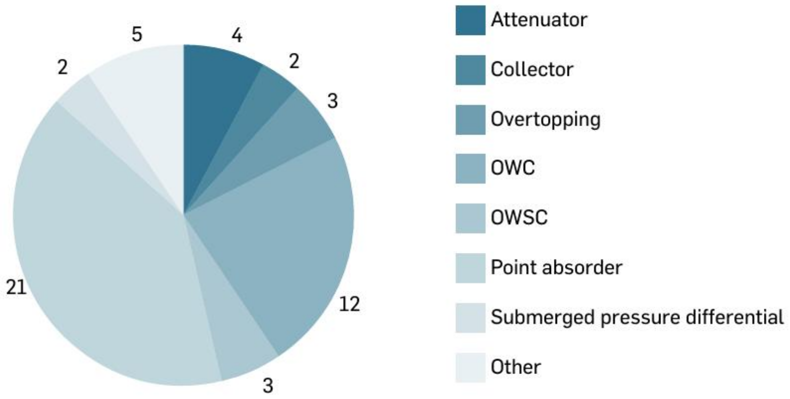
Oscillating Water Column (OWC)

Oscillating Wave Surge Converter (OWSC)

Point absorber

Submerged pressure differential

Terminator



Introduction

- Attenuator
- Collector
- Overtopping
- Oscillating Water Column (OWC)
- Oscillating Wave Surge Converter (OWSC)
- Point absorber
- Submerged pressure differential
- Terminator

An attenuator is a long floating structure aligned in parallel with wave direction, which effectively rides the waves. Movements along its length can be selectively constrained to produce energy. It has a lower area perpendicular to the waves in comparison to a terminator, so the device experiences lower forces.

A collector is a floating device which captures waves to concentrate the energy into various power take-off systems.

An overtopping device is a wave surge/focusing device, and contains a wall over which waves topple into a storage reservoir. The reservoir creates a head of water, which is released through hydro turbines as the water flows back out to sea. An overtopping device may use collectors to concentrate the wave energy.

An OWC comprises a partly submerged, resonantly tuned collector, open to the sea below the water surface and effectively containing air trapped above a column of water. This column of water moves up and down in sympathy with the wave movements, behaving like a piston, compressing and de-compressing the air. This is then channelled through an air turbine, usually a bi-directional Wells turbine making use of airflow in both directions, on the compression and decompression of the air.

An OWSC is also a wave surge/focusing device, but extracts the energy that exists in waves caused by the movement of water particles within them. It comprises a near-surface collector mounted on an arm pivoted near the seabed. The arm oscillates like an inverted pendulum in sympathy with the movement of water in the waves, allowing the transmission of power.

A point absorber is a floating structure absorbing energy in all directions through its movements at/near the water surface. The absorber can be designed to resonate to maximise the power available for capture. The power take-off system may take a number of forms, depending on the configuration of displacers/reactors.

This is a submerged device typically located nearshore and attached to the seabed. The motion of the waves causes the sea level to rise and fall above the device, inducing a pressure differential in the device. The alternating pressure can then pump fluid through a system to generate useful energy.

A terminator is a near-surface floating structure similar to a point absorber, but absorbing energy in only one direction. The device extends perpendicular to the wave direction, restraining waves as they arrive. Again, resonance may be employed and the power take-off system may take a variety of forms.

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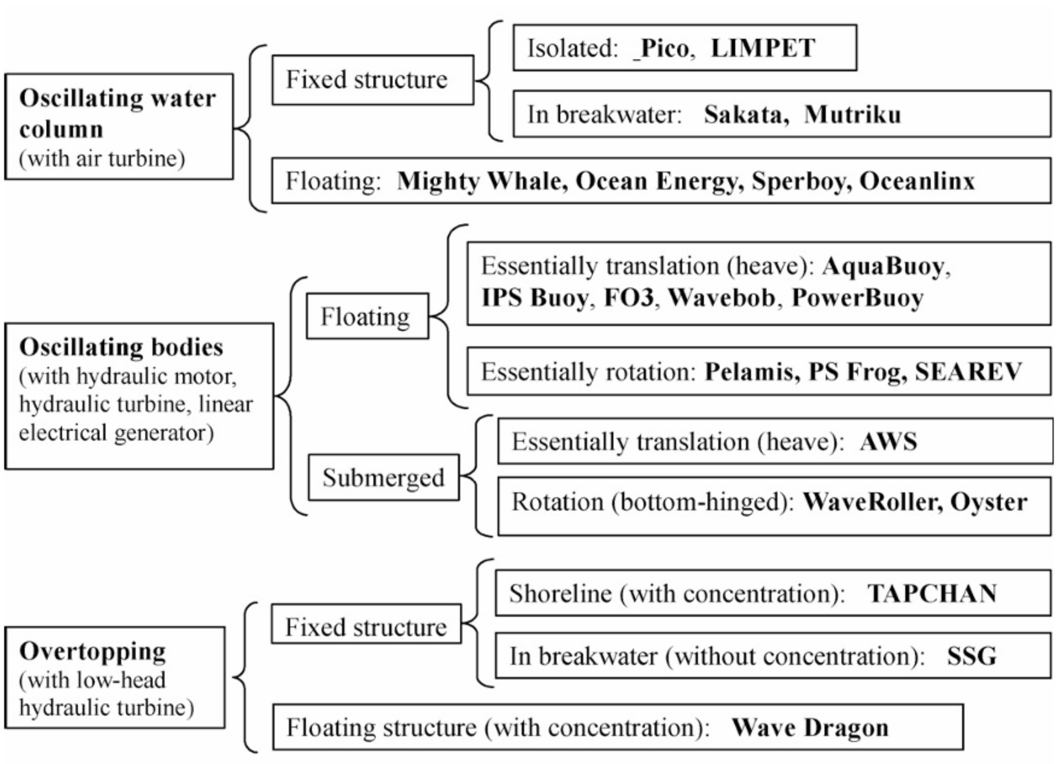
Classification of wave energy converters WECs



- **Oscillating water column** (with air turbine)
  - Fixed structure
    - Isolated: **Pico, LIMPET**
    - In breakwater: **Sakata, Mutriku**
  - Floating: **Mighty Whale, Ocean Energy, Sperboy, Oceanlinx**
- **Oscillating bodies** (with hydraulic motor, hydraulic turbine, linear electrical generator)
  - Floating
    - Essentially translation (heave): **AquaBuoy, IPS Buoy, FO3, Wavebob, PowerBuoy**
    - Essentially rotation: **Pelamis, PS Frog, SEAREV**
  - Submerged
    - Essentially translation (heave): **AWS**
    - Rotation (bottom-hinged): **WaveRoller, Oyster**
- **Overtopping** (with low-head hydraulic turbine)
  - Fixed structure
    - Shoreline (with concentration): **TAPCHAN**
    - In breakwater (without concentration): **SSG**
  - Floating structure (with concentration): **Wave Dragon**

Falcao et al. 2010

Unlike large wind turbines, there is a wide variety of wave energy technologies, resulting from the different ways in which energy can be absorbed from the waves, and also depending on the water depth and on the location (shoreline, near-shore, offshore).

Recent reviews identified about one hundred projects at various stages of development. The number does not seem to be decreasing: new concepts and technologies replace or outnumber those that are being abandoned.

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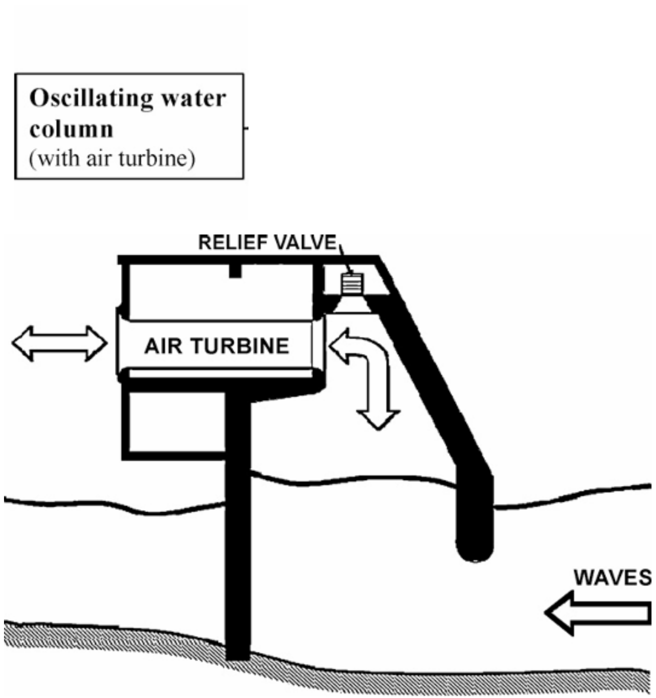
Classification of wave energy converters WECs

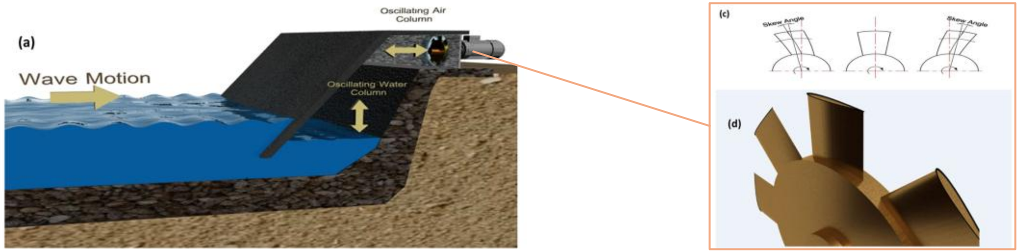


Falcao et al. 2010

The oscillating water column (OWC) device comprises a partly submerged concrete or steel structure, open below the water surface, inside which air is trapped above the water free surface.

The oscillating motion of the internal free surface produced by the incident waves makes the air to flow through a turbine that drives an electrical generator. The axial-flow **Wells turbine**, invented in the mid 1970s, has the advantage of not requiring rectifying valves.

It has been used in most prototypes. Full sized OWC prototypes were built in Norway (in Toftestallen, near Bergen, 1985), Japan (Sakata, 1990), India (Vizhinjam, near Trivandrum, Kerala state, 1990), Portugal (Pico, Azores, 1999, [62]), UK (the LIMPET plant in Islay island, Scotland, 2000).



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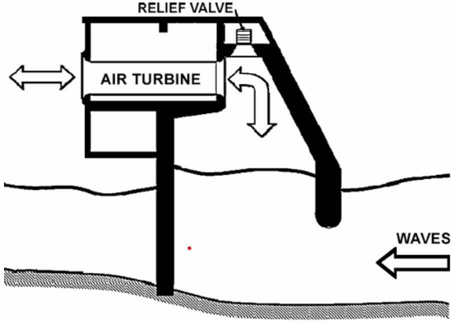
Classification of wave energy converters WECs

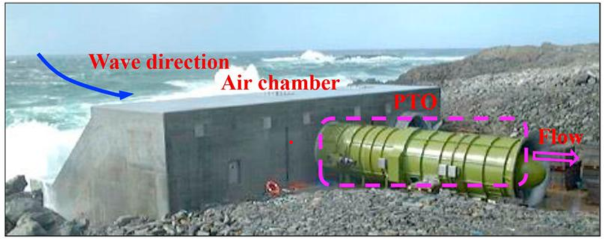
Oscillating water column
(with air turbine)

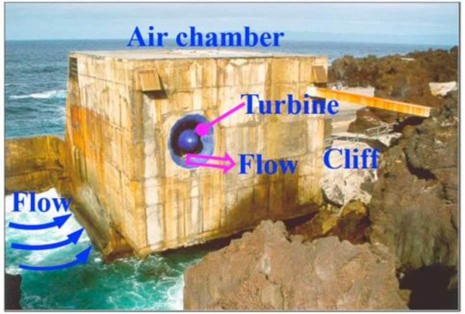


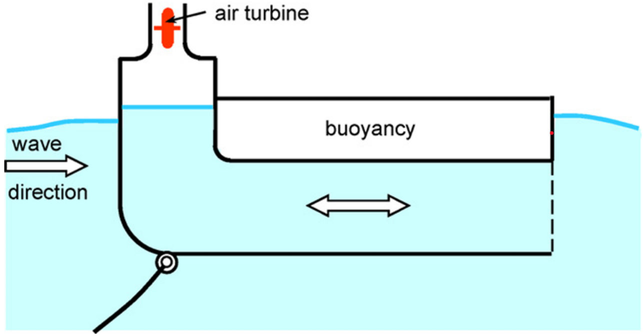
The cross-sectional area of these OWCs (at mid water-free-surface level) lies in the range 80-250 m^2.Their installed power capacity is in the range 60-500 kW.

The design and construction of the structure (apart from the air turbine) are the most critical issues in OWC technology, and the most influential on the economics of energy produced from the waves.

The integration of the plant structure into a breakwater has several advantages: the constructional costs are shared, and the access for construction, operation and maintenance of the wave energy plant become much easier.







Floating OWC: Backward Bent Duct Buoy

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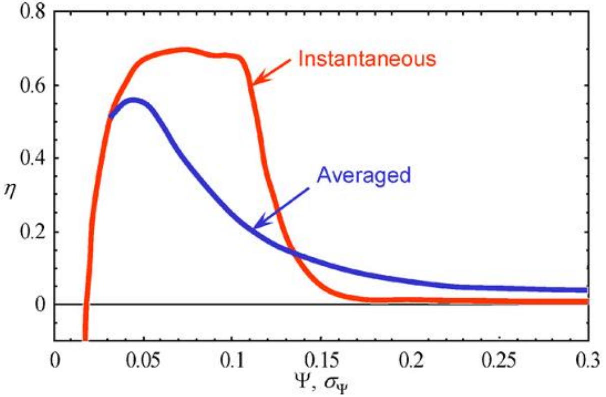
Classification of wave energy converters WECs

Air turbines equipped most of the early (small and large) wave energy converters and are still the favoured PTO for many development teams. Conventional turbines are not appropriate for reciprocating flows, and so new types of turbines had to be devised and developed. Self-rectifying air turbines were probably the object of more published papers than any other piece of equipment for wave energy converters.

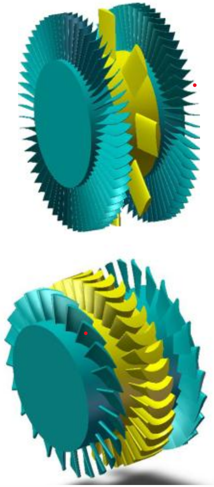
The air turbine of an OWC is subject to much more demanding conditions than the turbines in any other application, including wind turbines. Indeed, the flow through the turbine is reciprocating, and is random and highly variable over several time scales, ranging from a few seconds to seasonal variations. It is not surprising that the time-averaged efficiency of an air turbine in an OWC is substantially lower than that of a (water, steam, gas, wind) turbine working in nearly steady conditions. Several types of air turbines have been proposed, and in some cases used, in wave energy conversion.

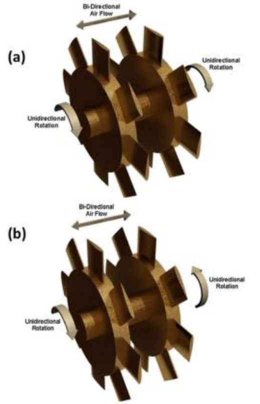
The **Wells turbine** was invented in the mid-1970s by Dr. Allan Wells (1924–2005) (at that time Professor at Queen’s University of Belfast). It is an axial-flow turbine that is self-rectifying, i.e. its torque is not sensitive to the direction of the air flow. Several versions have been studied since then (UK, Portugal, Ireland, Japan, India and China).

$$\boxed{\boldsymbol{E = \int_0^T \eta \, \Delta p \, Q}}$$



$$\Psi = \frac{\Delta p}{\rho_a \, N^2 \, D^2}$$





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Classification of wave energy converters WECs

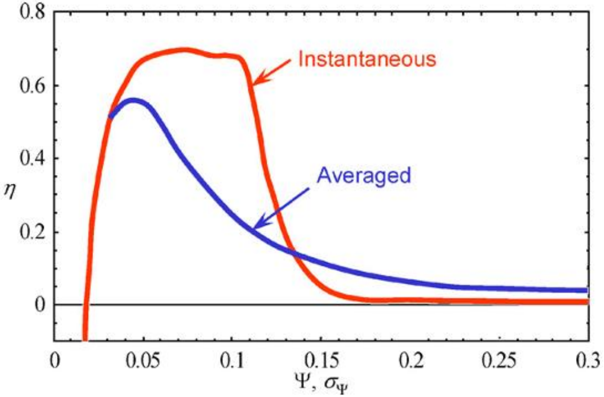
The Wells turbine is clearly the most frequently proposed to equip OWC plants. Its favourable features are:

- (i) high blade to air-flow velocity ratio, which means that a relatively high rotational speed may be attained for a low velocity of air flowing through the turbine
- (ii) a fairly good peak efficiency (0.7–0.8 for a full sized turbine);
- (iii) relatively cheap to construct.

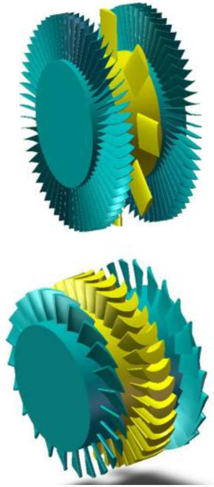
The weak points of the Wells turbine are:

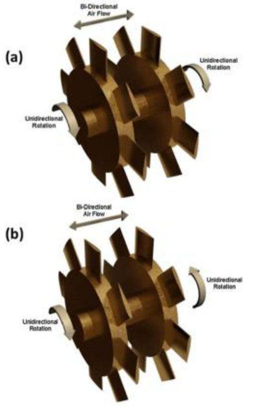
- (i) low or even negative torque at (relatively) small flow rates;
- (ii) drop (possibly sharp drop) in power output due to aerodynamic losses at flow rates exceeding the stall-free critical value;
- (iii) aerodynamic noise;
- (iv) relatively large diameter for its power (2.3 m for the single-rotor 400 kW turbine of the Pico OWC plant, 2.6 m for the counter-rotating 500 kW turbine of the LIMPET Islay II plant, 3.5 m for the Osprey plant).

$$\boxed{\boldsymbol{E = \int_{0}^{T} \eta \, \Delta p \, Q}}$$

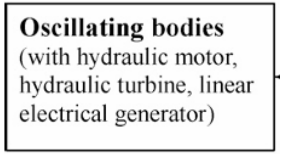


$$\Psi = \frac{\Delta p}{\rho_a \, N^2 \, D^2}$$





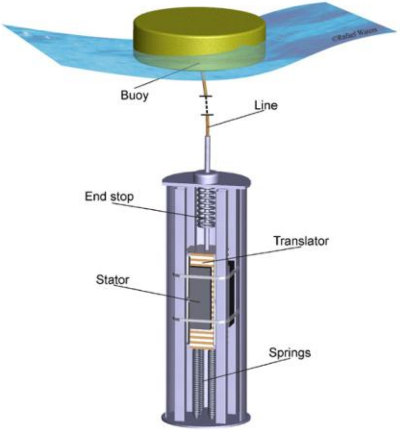
Classification of wave energy converters WECs

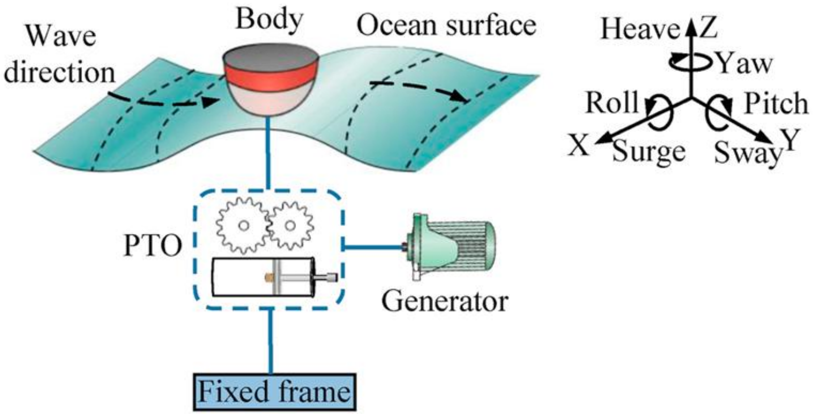


Oscillating bodies
(with hydraulic motor, hydraulic turbine, linear electrical generator)

The simplest oscillating-body device is the heaving buoy reacting against a fixed frame of reference (the sea bottom or a bottom-fixed structure).
In most cases, such systems are conceived as point absorbers (i.e. their horizontal dimensions are much smaller than the wavelength).

The relative motion between the wave-activated float on the sea surface and the seabed structure activates a PTO system. In the device that was tested in Denmark in the 1990s, the PTO (housed in a bottom-fixed structure) consisted in a piston pump supplying high-pressure water to a hydraulic turbine





A version of the taut-moored buoy concept is being developed at Uppsala University, Sweden, and uses a linear electrical generator (rather than a piston pump) placed on the ocean floor.

A line from the top of the generator is connected to a buoy located at the ocean surface, acting as power takeoff. Springs attached to the translator of the generator store energy during half a wave cycle and simultaneously act as a restoring force in the wave troughs.

Classification of wave energy converters WECs

Oscillating bodies
(with hydraulic motor, hydraulic turbine, linear electrical generator)

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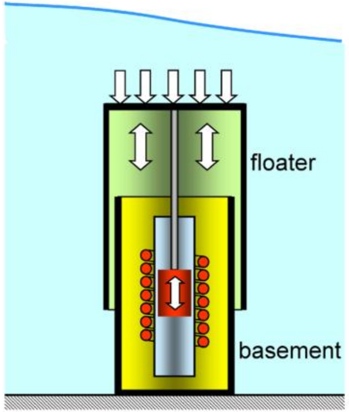

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The Archimedes Wave Swing (AWS), a fully submerged heaving device, was basically developed in Holland, and consists of an oscillating upper part (the floater) and a bottom-fixed lower part (the basement).

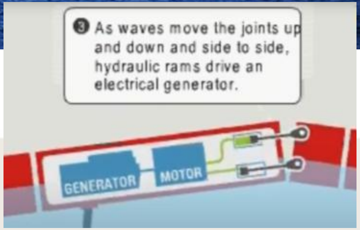
The floater is pushed down under a wave crest and moves up under a wave trough. This motion is resisted by a linear electrical generator, with the interior air pressure acting as a spring. The AWS device went for several years through a programme of theoretical and physical modelling. A prototype was built, rated 2 MW (maximum instantaneous power). After unsuccessful trials in 2001 and 2002 to sink it into position off the northern coast of Portugal, it was finally deployed and tested in the second half of 2004.

The AWS was the first converter using a linear electrical generator.

Classification of wave energy converters WECs

Oscillating bodies
(with hydraulic motor, hydraulic turbine, linear electrical generator)

The oscillating-body wave energy converters briefly described in previous slides are nominally heaving systems, i.e. the energy conversion is associated with a relative translational motion. (It should be noted that, in some of them the mooring system allows other oscillation modes, namely surge and pitch).
There are other oscillating-body systems in which the energy conversion is based on relative rotation (mostly pitch) rather than translation.


③ As waves move the joints up and down and side to side, hydraulic rams drive an electrical generator.

Falcao et al. 2010

The Pelamis, developed in UK, is a snake-like slack-moored articulated structure composed of four cylindrical sections linked by hinged joints, and aligned with the wave direction. The wave Induced motion of these joints is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors driving three electrical generators. Gas accumulators provide some energy storage.

Sea trials of a full-sized prototype (120 m long, 3.5 m diameter, 750kW rated power) took place in 2004 in Scotland. A set of three Pelamis devices was deployed off the Portuguese northern coast in the second half of 2008, making it the first grid-connected wave farm worldwide

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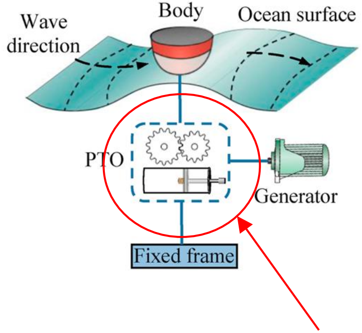
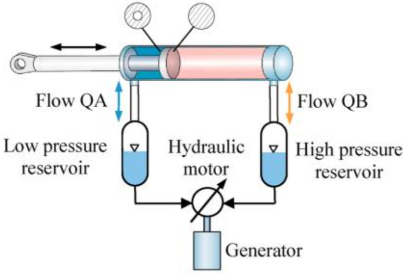
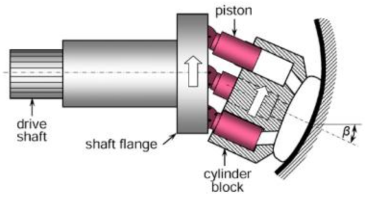
Classification of wave energy converters WECs

Oscillating bodies
(with hydraulic motor, hydraulic turbine, linear electrical generator)

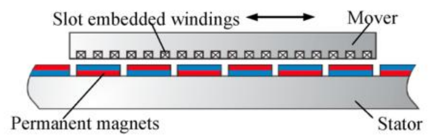
High-pressure oil systems are particularly suitable to convert energy from the very large forces or moments applied by the waves on slowly oscillating bodies (in translation or rotation).
The hydraulic circuit usually includes a gas accumulator system capable of storing energy over a few wave periods, which can smooth out the very irregular power absorbed from the waves. The body motion is converted into hydraulic energy by a hydraulic cylinder or ram (or a set of them).
Energy can be stored in, and released from, a gas accumulator system, consisting of a high-pressure accumulator and a low pressure reservoir. The gas, usually nitrogen, is separated from the oil by a bladder or by a free piston. High-pressure gas accumulators are designed to withstand pressures up to about 500–600 bar. The amount of energy stored per unit mass of gas is $\Delta E = C_c \Delta T$,where Cv is the specific heat at constant volume and T is absolute temperature. Over small time intervals (not exceeding, say, a few minutes) the compression/ decompression process may be regarded as approximately isentropic.

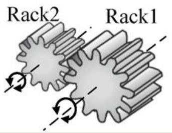


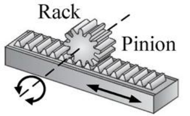


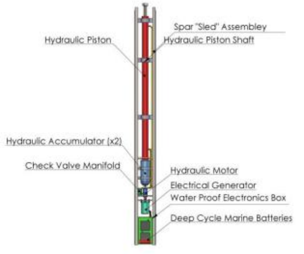


$$\Delta T = T\left\{\left(\frac{p + \Delta p}{p}\right)^{(\gamma - 1)/\gamma} - 1\right\}$$









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Classification of wave energy converters WECs

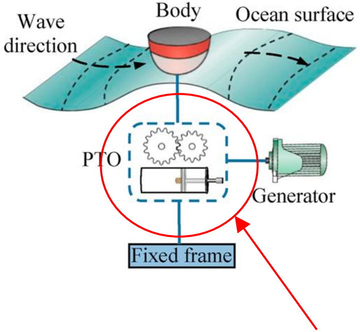
Oscillating bodies
(with hydraulic motor,
hydraulic turbine, linear
electrical generator)

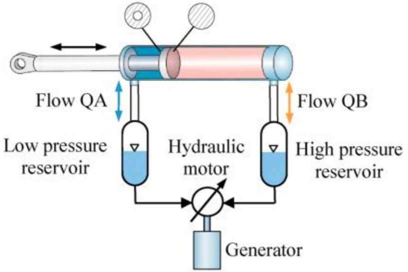
The hydraulic/pneumatic system has flexible transmission, stable energy storage and large torque, which is suitable for the random characteristics of wave energy change amplitude and large change frequency.

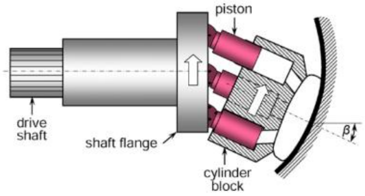
Direct drive transmission uses the undulating motion of waves in the vertical direction to push the generator to make a reciprocating linear motion. Compared to other PTO methods, the advantage of direct drive is that it generates electricity directly without transmission, thereby reducing design complexity, operation requirement and maintenance cost.

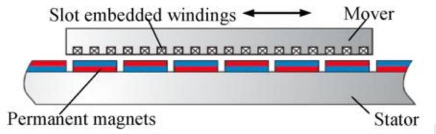
→ Column of magnets moves up and down, with the waves, inside the generator coils. An electrict current is induced in the coils of wire.

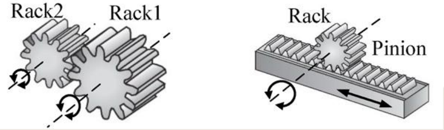
Also, mechanical gear type is commonly used PTO method in oscillating bodies.

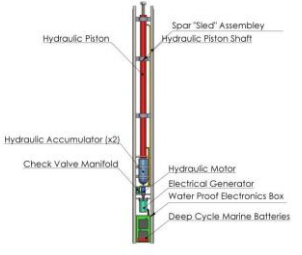








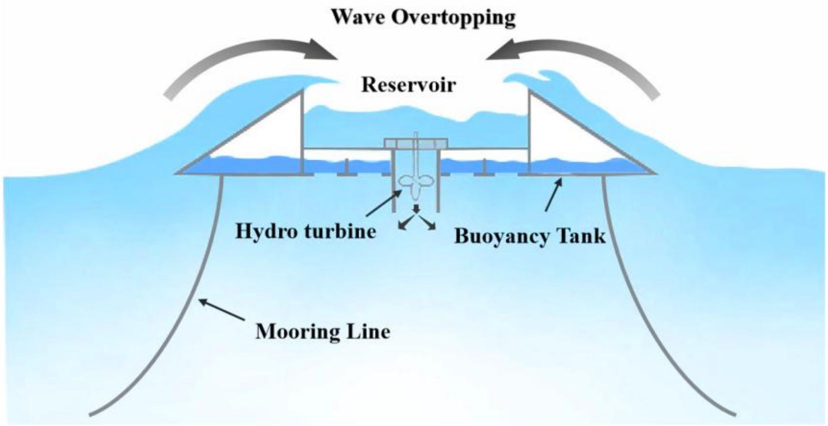




Classification of wave energy converters WECs

Overtopping
(with low-head
hydraulic turbine)

A different way of converting wave energy is to capture the water that is close to the wave crest and introduce it, by over spilling, into a reservoir where it is stored at a level higher than the average free-surface level of the surrounding sea. The potential energy of the stored water is converted into useful energy through more or less conventional low-head hydraulic turbines. The hydrodynamics of overtopping devices is strongly non-linear, and, unlike the cases of oscillating body and OWC wave energy converters, cannot be addressed by linear water wave theory.



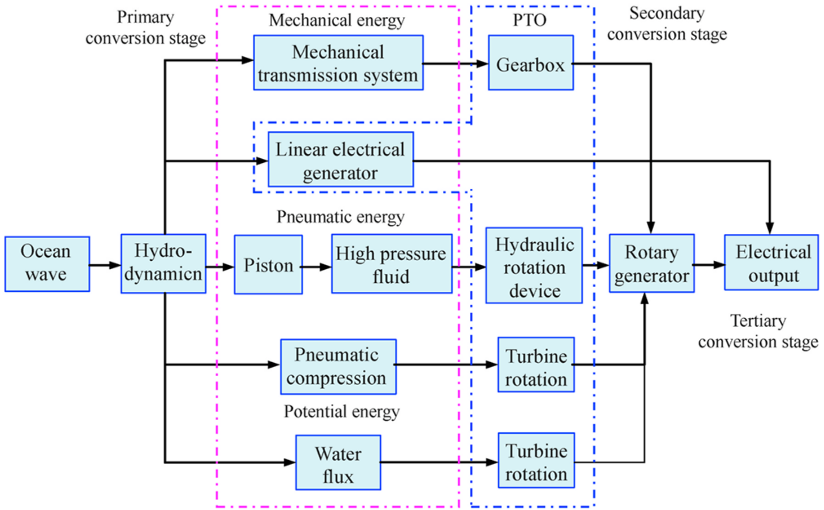
As in conventional mini-hydroelectric low-head plants, axial-flow reaction turbines are used to convert the head (typically 3-4 m at full size) created between the reservoir of an overtopping device and the mean sea level.

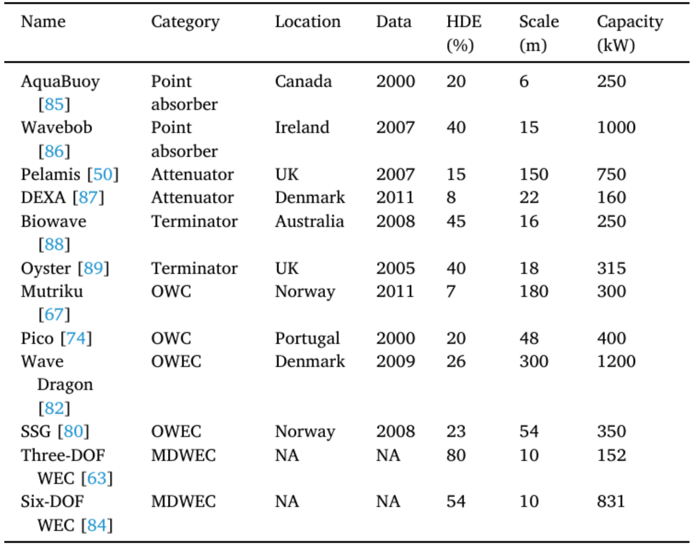
The flow may be controlled by adjustable inlet guide vanes. In some cases the blades of the runner can also be adjusted (Kaplan turbines) which greatly improves efficiency over a wide range of flows; however this can be costly and is not normally employed in the small turbines typical of wave energy applications.

High-head (typically tens to hundreds of metres) impulse turbines (mostly of Pelton type) are adopted in some oscillating body converters.

Falcao et al. 2010

Classification of wave energy converters WECs





Name	Category	Location	Data	HDE (%)	Scale (m)	Capacity (kW)
AquaBuoy [85]	Point absorber	Canada	2000	20	6	250
Wavebob [86]	Point absorber	Ireland	2007	40	15	1000
Pelamis [50]	Attenuator	UK	2007	15	150	750
DEXA [87]	Attenuator	Denmark	2011	8	22	160
Biowave [88]	Terminator	Australia	2008	45	16	250
Oyster [89]	Terminator	UK	2005	40	18	315
Mutriku [67]	OWC	Norway	2011	7	180	300
Pico [74]	OWC	Portugal	2000	20	48	400
Wave Dragon [82]	OWEC	Denmark	2009	26	300	1200
SSG [80]	OWEC	Norway	2008	23	54	350
Three-DOF WEC [63]	MDWEC	NA	NA	80	10	152
Six-DOF WEC [84]	MDWEC	NA	NA	54	10	831

WEC generally includes three parts: an energy capture mechanism, a transmission mechanism and a power generation mechanism. Energy conversion efficiency is the product of the efficiency of each link. Considering the otherness of the existing PTO systems and scales and sizes of different WECs, the energy capture performance index Hydro dynamic Efficiency (HDE) is defined as follows:

$$\begin{cases} HDE = \dfrac{P_d}{P_w D} \\ P_w = \dfrac{1}{32\pi}\rho g^2 H^2 T \end{cases}$$

Where Pd is the mean absorbed power, Pw power per unit of wavefront width, D, ρ, g, H and T express the width of the device, seawater density, gravity, wave surface elevation and wave period, respectively.

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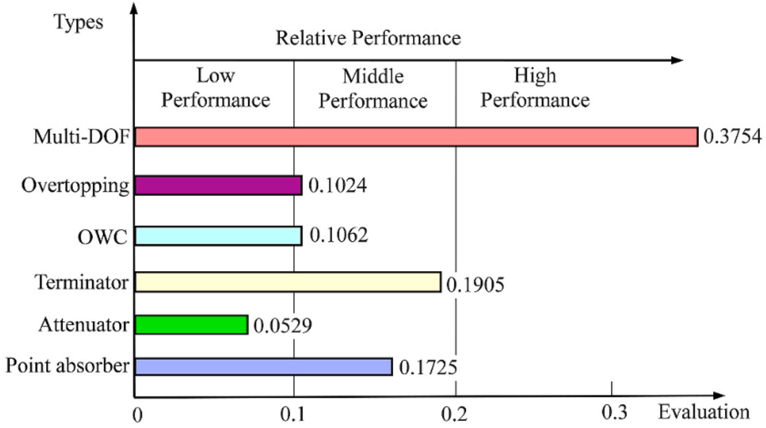
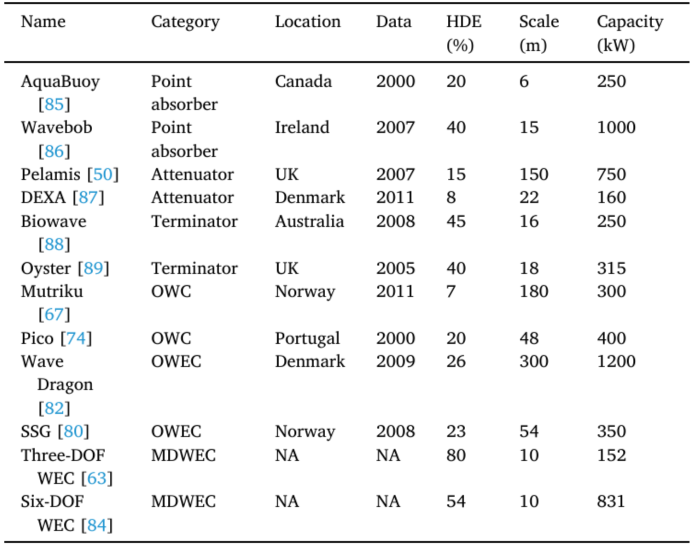
Classification of wave energy converters WECs



Comprehensive performance evaluation of various WECs.



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Based on 5 criteria: HDE, Technology cost economic, Reliability, Environmental friendliness, Adaptability.

Reference paper «Ocean wave energy converters: Technical principle, device realization, and performance evaluation », Renewable and Sustainable Energy Reviews 141, 2021.

CorPower – Oscillating body example

[Wave Energy Technology — How CorPower Ocean's WEC Works | CorPower Ocean]

[Why the Ocean Might Win the Energy Race]

[CorPower Ocean - Wave farms - YouTube]

Operational range (Hs) 0.25 –8m
Installation depth >40m
Device rating 350 kW
Buoy diameter 9m and Height 19m
Weight 100 tonnes

Barriers

Insufficient demonstration of full-scale prototypes

The immediate barrier that is preventing progress is the lack of sufficient demonstration of prototypes in the marine environment to prove technologies work as predicted. Demonstration at full scale or near full-scale is essential to establish the actual cost and energy conversion performance of a device and enable predicted cost and performance data to be validated and evaluated. Such testing is also vital to prove the survivability and the reliability of a device as well as to validate scalability (ie the progression from part-scale to full-scale prototypes). Monitoring and measurement of energy input and output during tests are necessary to validate designs and improve comparability of results. Sea trials are key to reducing the high technical risk associated with this technology and to encourage greater private investment in RD&D. Certain market deployment policies are aimed at trying to motivate developers to perform a minimum amount of testing at this scale.

Cost of grid connecting demonstration systems

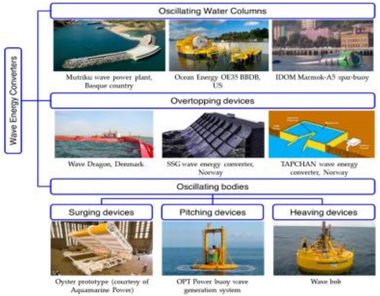
The cost of connecting ocean energy systems to electricity networks impacts on demonstration projects. Typically, ocean energy resources are located offshore, away from population centres and, consequently, some distance from available network connections. Significant transmission infrastructure may be required for pilot systems. An alternative and perhaps more effective way to reduce the cost for single devices is to connect to the existing infrastructure of an offshore wind farm.

Lack of understanding of the potential environmental impacts

Owing to insufficient demonstration of ocean energy technology, there remains a lack of under standing regarding the impacts on the environment. For example, impacts on the environment could include oil leakage from engines, collision between devices and marine mammals, artificial reefs, or noise from power take-off systems. Alternatively, impacts on the technology from the environment might be caused by marine growth (eg algae, shells), seabirds nesting, corrosion or sedimentation flow.

Overview - comments

Which technology to chose?



OWC (Oscillating Water Column)

Pros:
- few mechanical parts in water
- easy integration in ports/dams

Cons:
- average efficiency
- heavily depends on wave frequency

Ideal for:
- rocky coast
- existing infrastructures

Oscillating Bodies

Pros:
- very efficient
- Adaptable

Cons:
- Complex
- difficult maintenance

Ideal for:
- Off-shore
- Energetic waves

Overtopping

Pros:
- more “stable” production
- similar to hydroelectric

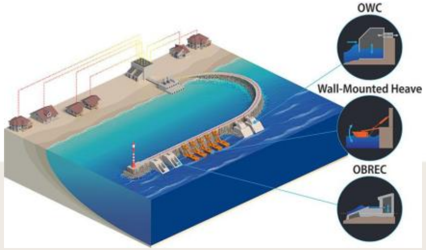
Cons:
- Large structures
- expensive

Ideal for:
- Large and constant waves

Site analysis: wave height (Hs), wave period (T), wave direction, water depth, distance from shore
Device selection or adaptation: each WEC has a natural frequency

- ✓ large companies: design the device first → then look for a compatible site
- ✓ research approach: start from the site → then adapt the device

Ideal site characteristics:
- regular and predictable waves
- high energy (high Hs and T)
- suitable seabed (for anchoring)
- accessibility (cables, maintenance)
- low interference (shipping, fishing)



Overview - comments

1. Cable length and cost
- typical cost: ~0.5–2 million €/km (order of magnitude)

2. Electrical losses
- increase with distance

3. Maintenance
- access requires specialized vessels
- weather conditions can be limiting
- beyond ~10 km operational costs increase significantly

4.Mooring system
- greater depth → more complex anchoring
- longer and more expensive mooring lines

Italy haven't developed many off-shore WECs (most of them in Sardegna), the main problem is that there are few "energetic" waves

The Mediterranean is enclosed sea, thus limited fetch.

So, for example, smaller and less regular waves compared to the Atlantic:
- Atlantic: 20–70 kW/m
- Mediterranean: 2–10 kW/m

Distance	Hs	T	Energy (kW/m)
2 km	~1.2 m	~5.5 s	~4–6 kW/m
8 km	~1.6 m	~6.5 s	~8–12 kW/m

→ the energy roughly doubles but does not increase 5–10 times (as in the coast- to- Atlantic transition)

How much does it cost to go farther offshore?

Subsea cable
2 km → ~1–3 M€
8 km → ~4–12 M€

Mooring and installation
greater depth +30–70% costs
Maintenance (annual)
greater depth +20–50% operational costs

	2 km	8 km
Annual Energy	1×	~2×
Cable costs	1×	2–4×
Maintenance Costs	1×	1.3–1.5×

Fundamentals of wave energy conversion theory

The presence of a power take-off mechanism (PTO) and the requirement of maximizing the extracted energy introduced additional issues. The first theoretical developments addressed the energy extraction from regular (sinusoidal) waves by a floating body oscillating in a single mode (one degree of freedom) with a linear PTO. An additional assumption of the theory was small amplitude waves and motions.

The hydrodynamic forces on the wetted surface of the body were decomposed into excitation forces (due to the incident waves), radiation forces (due to body motion) and hydrostatic forces (connected with the instantaneous position of the floating body with respect to the undisturbed free surface).

These were techniques already known from ship hydrodynamics. This can be illustrated by the simple case of a floating body of mass m oscillating in heave (one degree of freedom).

If the body position is defined by a vertical coordinate x (with x = 0 in calm water), the equation of motion is $(m+A)\ddot{x} = f_d - B\dot{x} - \rho g S x + f_{\mathrm{PTO}}$

fd is (the vertical component of) the excitation force (acting on the assumedly fixed body; fd =0 in calm water),
f_{PT0}(t) is the vertical force due to the PTO mechanism
A is the (hydrodynamic coefficient of) added mass (accounting for the inertia of the water surrounding the body)
B is the radiation damping coefficient (accounting for the damping on the body due to energy transfer to waves radiated away),
S is the cross-sectional area of the body ($-\rho g S x$ is the hydrostatic restoring force)

We assume the PTO force to consist of a linear damper (coefficient C) and a linear spring (stiffness K) and write

$$f_{PTO} = -C\,\dot{x} + Kx$$

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Fundamentals of wave energy conversion theory

$$(m+A)\ddot{x} = f_d - B\dot{x} - \rho g S x + f_{\mathrm{PTO}}$$

We assume the PTO force to consist of a linear damper (coefficient C) and a linear spring (stiffness K) and write

$$f_{PTO} = -C\,\dot{x} + Kx$$

regular waves of amplitude $A(\omega)$ and frequency ω

$$\{x,\ f_d\} = \mathrm{Re}(\{X, F_d\}e^{i\omega t})$$

$$X = \frac{F_d}{-\omega^2(m+A) + i\omega(B+C) + \rho g S + K}$$

The time-averaged absorbed power is $\bar{P} = \overline{f_{PTO}\dot{x}} = C\omega^2|X^2|/2$ which can be written as: $\bar{P} = \frac{1}{8B}|F_d|^2 - \frac{B}{2}\left|U - \frac{F_d}{2B}\right|^2$

Where $U = i\omega X$ is the complex amplitude of the velocity $\dot{x}$. For a given body and given incident regular wave, B and F_d are fixed.

→ Then the absorbed power P depends on X, i.e. on the PTO damping and spring coefficients C and K.

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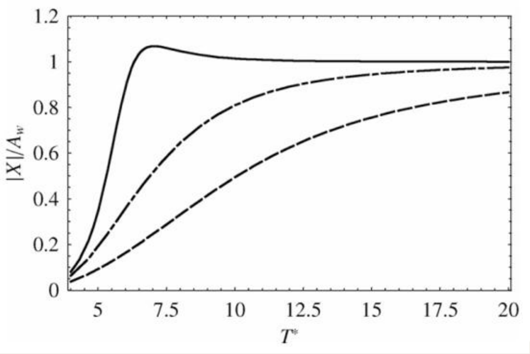
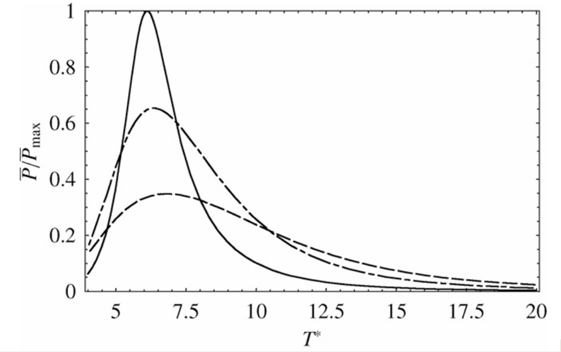
Fundamentals of wave energy conversion theory

It shows that its maximum value, equal to $\bar{P}_{\max} = \frac{1}{8B}|F_d|^2$ which occurs for $U = F_d/2B$, which gives two optimal conditions involving real quantities $\omega = \left(\frac{\rho g S + K}{m + A(\omega)}\right)^{1/2}, \quad C = B(\omega).$

Resonance condition: its right hand side is the frequency of free oscillations of an undamped mechanical oscillator of mass m+A acted upon by a spring of stiffness $\rho g S + K$.

Illustrative performance curves for a floater oscillating in heave, whose submerged part is hemispherical





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Resonance condition: its right hand side is the frequency of free upon by a spring of stiffness $\rho g S + K$.

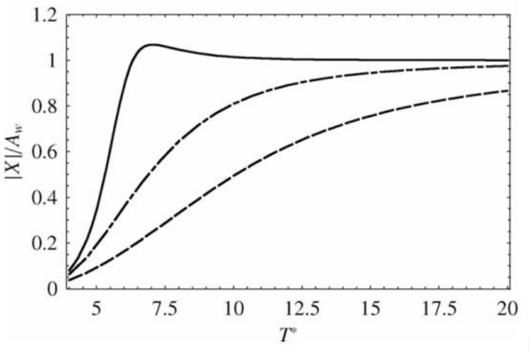
Dimensionless wave period $T^* = 0.5\,(g/a)^{1/2}\,T$
a = sphere radius, $T = 2\pi/\omega$ wave period

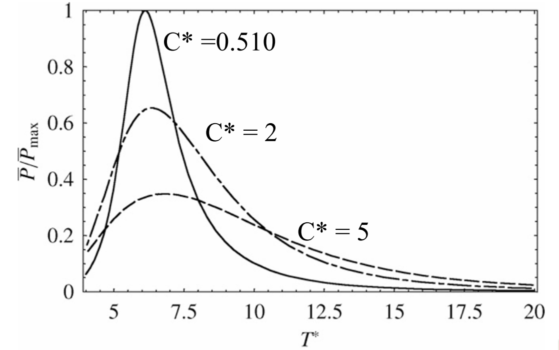
See different values of the dimensionless PTO damping coefficient $C^* = \rho g^{\frac{1}{2}}\, a^{\frac{5}{2}} C$

No spring is assumed to be present, i.e. K = 0.

Optimal conditions to be met for maximum power absorption: the resonance condition yields T* = 6.11, whereas the damping condition gives C* =0.510

Illustrative performance curves for a floater oscillating in heave, whose submerged part is hemispherical





We find the optimum radius a=0.262 T^2
(a in m, wave period T in s).

Taking T = 10 s as a typical value for the northern Atlantic, we obtain **a = 26.2m** for the optimum radius of a hemispherical resonant buoy. The corresponding value for the oscillation amplitude is $|X|\,/A_{\omega} = 0.909$

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Tidal Energy Extraction Systems

More than 1000 years ago, Europeans started using tidal energy to motivate grain mills. The inflow tide is retained in the reservoir, and the outflow tidal motion is used to turn the water wheel to grind grain. This method of generating electricity by falling water and rotating turbines was invented in the 19th century. Early tidal power plants attempted to use a barrage-like approach. However, this did not eventually become the focus of the industry. By the 18th century, there were 76 tidal mills in London alone. There was a time when about 750 tidal plants were operating along the Atlantic coast.

From 1924 to 1977, the US electricity Commission and Nova Scotia lighting and power company, with the US and Canadian governments, conducted respectively four early feasibility research of large tidal power plants in the United States and Canada. All investigations focused on specific geographic locations in the boundary area between Maine and Canada.

In 1966, a vast tidal dam was built in La Rance, France, and is still in operation. It has a power generation capacity of 240 megawatts (MW). Before 2011, it was the most significant tidal dam in the world. In 2011, a 254-megawatt tidal dam was opened in South Korea. In the past twenty years, the industry has turned to in-stream tidal power generation, placing an individual device or a group (or array) of devices in tidal energy. Founded in 2003, the European marine energy center is the world's largest facility under actual ocean conditions to test and demonstrate wave and tidal technologies. The facility has a large-scale prototype grid-connected test site and a small-scale test site for small equipment, which provides convenience for testing more tidal energy equipment than anywhere else in the world.

Tidal Energy Extraction Systems

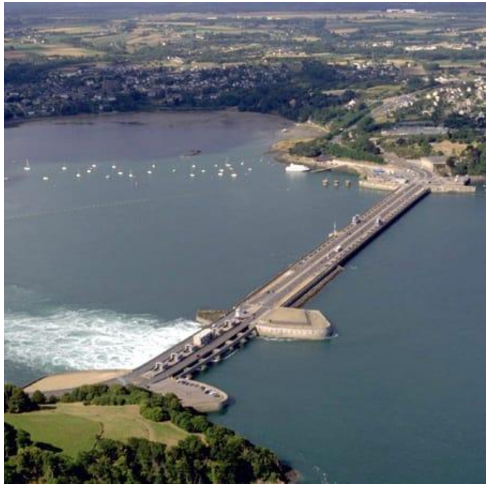
Tidal energy exploits the periodic movement of tides mainly caused by the gravitational interaction between the Moon, the Sun, and the Earth. It is a highly predictable renewable energy source, unlike wind and solar.

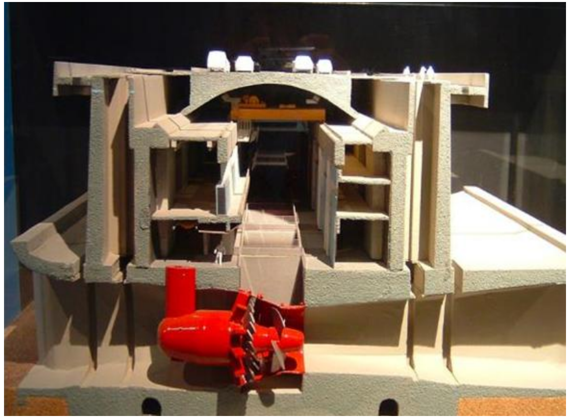
In the 20th century, engineers started developing tidal generators to harness tidal energy and generate electricity in areas of significant tidal range. The first tidal generator was constructed in La Rance, France (November 1966), and Sihwa Lake tidal power station is the largest tidal power Plant. However, tidal energy is still in the early development stage worldwide.

La Rance

The power station has 24 turbines. These reach tota lpeak output at 240 MW, and produce an annual output of approximately 500 GWh (2023: 506 GWh; 491 GWh in 2009, 523 GWh in 2010); thus the average output is approximately 57 MW, and the capacity factor is approximately 24%. Barrage is 750 m long.

500 GWH/AN PRODUITS	30 M€ INVESTIS SUR 2021-2026	25 M€/AN DE RETOMBÉES	+ 40 000 VISITEURS/AN
soit l'équivalent de la consommation de 225 000 habitants. Cela représente 8 % de la production Bretonne grâce à 60 salariés basés sur la Cote d'Émeraude. 67 % de l'électricité consommée en Bretagne est importée d'une autre région. *Source : Bilan RTE 2023*	**pour continuer de produire et de garantir la sûreté.** Des travaux qui mobilisent ≈100 entreprises bretonnes/an pour 1 M€.	**pour le territoire selon la FAUR (Étude de 2016) et 2 M€/an de retombées fiscales.**	**dont 15 % de scolaires.** C'est la 9^{e} entreprise la plus visitée de Bretagne avec une offre entièrement gratuite.

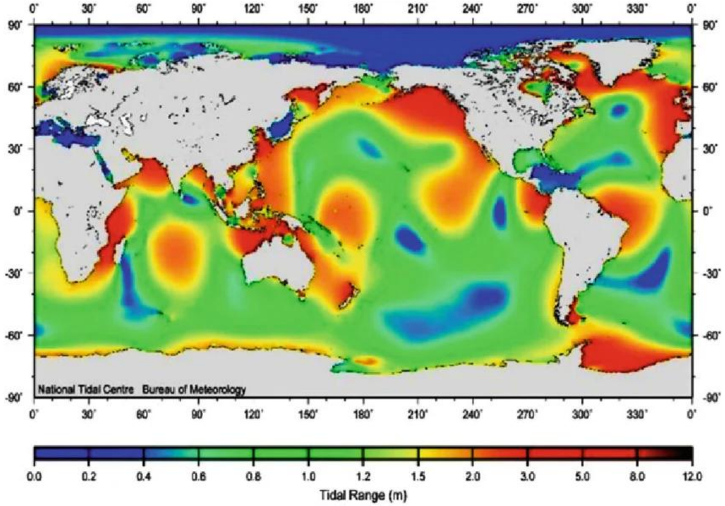




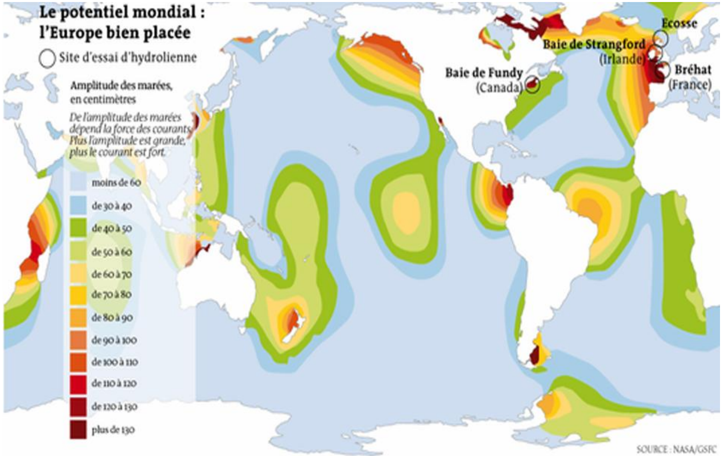
Tidal Energy Extraction Systems

The best sites are natural hydraulic nozzles driven by ocean-scale oscillations. A good tidal site is where:

1) A lot of water moves (thus large tidal forcing)
2) That water is forced through a small area
3) Geometry accelerates the flow



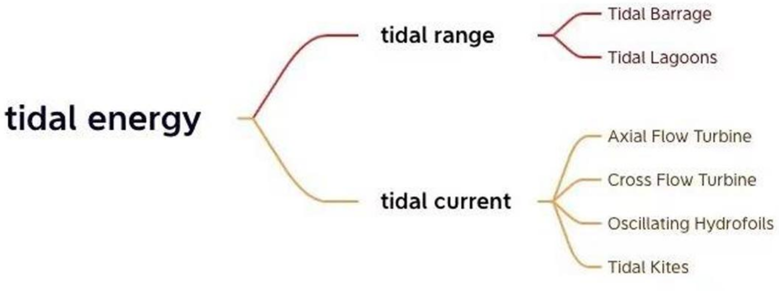
Range of tidal fluctuation for oceans of the world. (Calculated as tidal ranges in meters from principal lunar and solar semidiurnal and diurnal harmonic amplitudes, (M2 + S2 + K1 + O1) from data by National Tidal Centre, Australian Bureau of Meteorology, in Matthews and Matthews (2014).



The worldwide potential of tidal streams is estimated at around 90-120GW and the European potential is estimated at 15GW from which 60% is concentrated in United Kingdom's region.

Tidal Energy Extraction Systems

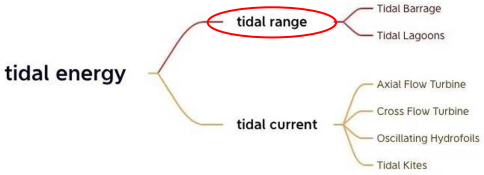
The moon and sun's gravitational pull generates something called the tidal force. The tidal force causes Earth - and its water - to bulge out on the side closest to the moon and the side farthest from the moon, which are the high tides and low tides. There are two kinds of ways to use these tides. The first one is the vertical movement of water (the difference in water level), and humans apply the tidal range to capture this tide. The second is the horizontal movement of water (moving fluid), and tidal current devices are applied to capture this tide.

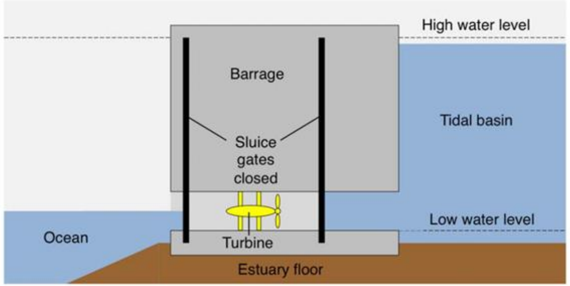


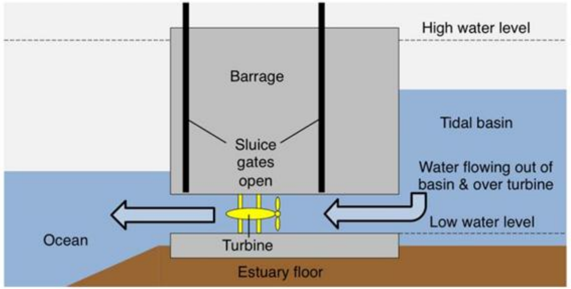
Pros:
Stable and predictable generation
High efficiency
Cons:
Strong environmental impact (coastal ecosystems)
High initial costs

Pros:
Lower visual impact
Scalable (modular systems)
Cons:
Complex maintenance
Harsh marine environment

Tidal Energy Extraction Systems







Tidal range

The tidal range device uses the water level difference between high and low tides to store water in a basin before being released through the turbine, as illustrated in the figure. Moreover, the turbine rotates using the potential energy of the flowing water. The tidal range devices are mainly applied in shallow water areas.

Each tidal range device's potential relates to the difference between high and low head, the amount of water past the impounding structure, and the area of the impounding surface. By considering these factors, a crude estimate of the potential energy available from a tidal range device can be obtained as

$$E_p = \frac{1}{2} A_b \rho g \, H^2$$

Where A_b is the basin surface area, H the hydraulic head.

By considering some large tidal range devices in some countries like UK, Canada, China, Korea, USA, India, we can get an estimate value of total world tidal range resources to be between 386 – 560 TWh/y.

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Tidal Energy Extraction Systems

- tidal energy
  - tidal range
    - Tidal Barrage
    - Tidal Lagoons
  - tidal current
    - Axial Flow Turbine
    - Cross Flow Turbine
    - Oscillating Hydrofoils
    - Tidal Kites

- Barrages block navigation. Locks can be installed, allows some traffic, but it is a slow and costly alternative to free access to the ocean.
- Barrages impede fish migration

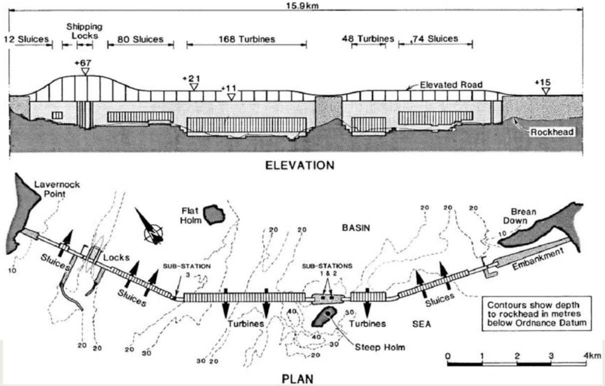
Tidal range

The tidal range device uses the water level difference between high and low tides to store water in a basin before being released through the turbine, as illustrated in the figure. Moreover, the turbine rotates using the potential energy of the flowing water. The tidal range devices are mainly applied in shallow water areas.

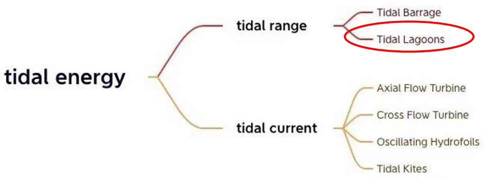
1 - **Tidal barrage**

One essential component of tidal range devices is the tidal barrage, which works by constructing a wall across an estuary or basin. When the tide is rising, it is allowed to go through the sluices to the estuary, where the water level is low. And as the water level in the estuary gets higher, the water keeps flooding through the turbine. Then the sluices in the barrage closed. And when the water outside the barrage is low enough, the sluices are opened, which allows the water in the estuary to ebb back to the sea. The components of a tidal barrage are mainly four big parts, which are a barrage, a turbine, sluices and an embankment.

1) A dam is built across an estuary or bay
2) Water enters during high tide and is retained
3) During low tide, it is released through turbines



Tidal Energy Extraction Systems



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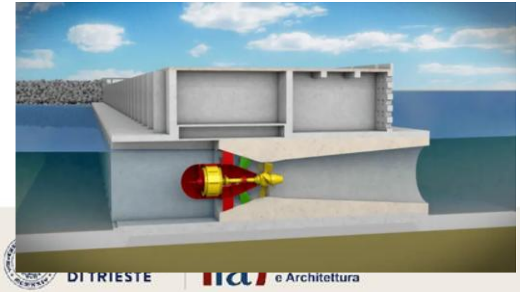
Tidal range

The tidal range device uses the water level difference between high and low tides to store water in a basin before being released through the turbine, as illustrated in the figure. Moreover, the turbine rotates using the potential energy of the flowing water. The tidal range devices are mainly applied in shallow water areas.

2 - **Tidal lagoons**

The working principle of a tidal lagoon is somehow the same as a tidal barrage, but there is a difference in the structures. A lagoon consists of an entirely artificial basin formed like a circle or rectangular with a turbine constructed within the walls. As with barrages, tidal lagoons hold back water behind the structure and then allow it to flow to the lower levels later. Tidal lagoons also use conventional hydroelectric turbines to extract energy from the water



The great project of **Tidal Lagoon Power** will begin with a test in the **Swansea Bay**, Wales. The waters of this bay are known for their high tidal amplitudes, making it an ideal location to test this technology.

This pilot project will include the construction of a 9.5 km long wall, which will surround an artificial lagoon of **11.5 km²**. In this lagoon will be installed **30 turbines**, each with a diameter of **7.35 meters.** The turbines have a bi-directional design that will allow energy to be generated both when the tides are rising and when they are falling, ensuring continuous operation for almost 14 daily hours.

Once completed, this Swansea facility could be the model for five other UK sites to follow, including Cardiff, Newport, Bridgwater, Somerset, West Cumbria and Colwyn Bay in Wales and England.

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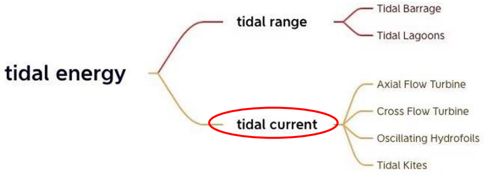
Tidal Energy Extraction Systems



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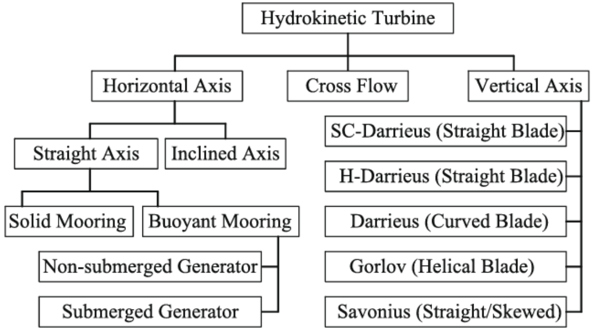
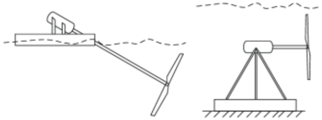
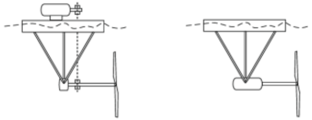


- Hydrokinetic Turbine
  - Horizontal Axis
    - Straight Axis
      - Solid Mooring
      - Buoyant Mooring
    - Inclined Axis
    - Non-submerged Generator
    - Submerged Generator
  - Cross Flow
  - Vertical Axis
    - SC-Darrieus (Straight Blade)
    - H-Darrieus (Straight Blade)
    - Darrieus (Curved Blade)
    - Gorlov (Helical Blade)
    - Savonius (Straight/Skewed)

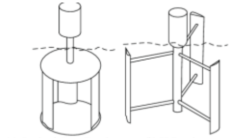


(a) Inclined axis (b) Rigid mooring

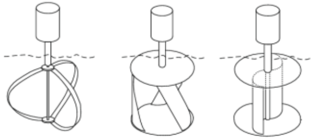


(c) Non-submerged Generator (d) Submerged Generator

Fig. 11. Horizontal axis turbines.



(a) Squirrel Cage Darrieus (b) H-Darrieus

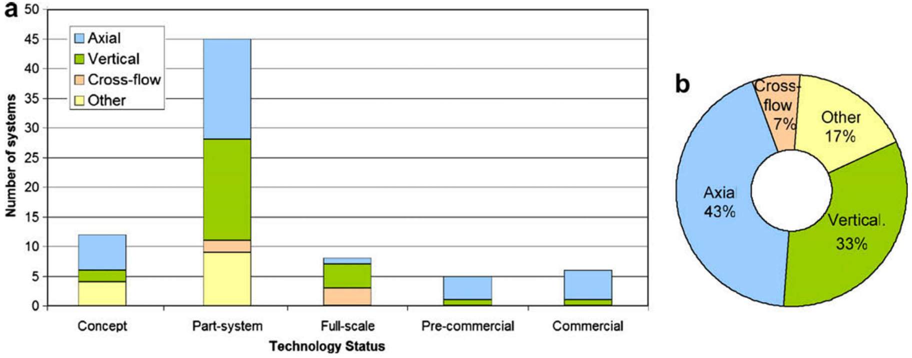


(c) Darrieus (d) Gorlov (e) Savonius

Fig. 12. Vertical axis turbines.

Tidal current

Tidal current devices utilize only a portion of the energy from the tidal stream with a rotor placed into the flow. Tidal current technology use devices to convert kinetic energy into mechanical energy and then to electrical energy, which is somehow similar to wind energy devices. But considering the differences between water and air, such as the density and the flow speed, the tidal current devices have to be designed to survive higher structural load and allow both ebb and flood directions. Tidal turbines can be broadly classified according to their design as either axial flow or cross flow.



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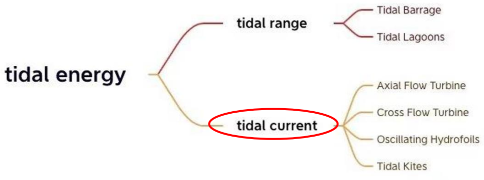
Tidal Energy Extraction Systems



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Tidal stream technologies act much like underwater wind turbines, generating power from the kinetic energy of fast-flowing tidal currents. The generators are sunk 20-30 meters, and can be situated anywhere that possesses a strong tidal flow.

Because water is about 800 times denser than air tidal stream turbines must be built much sturdier than their terrestrial counterparts, though they can also spin much more slowly, around 7-11 rotations per minute. Shrunken diameters help to reduce the structural strain. The advantage of greater density of water is that relatively large amounts of power can be produced with relatively small rotor diameters.
For example: rotors with a diameter of 10-15 meters can generate as much as 700 kW of power, whereas a 600 kW wind turbine requires a rotor diameter of 45 meters.

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The power that a turbine can generate from a free fluid flow can be illustrated as

$$P = \frac{1}{2}\,\rho A\, C_p U^3 \eta_g$$

Where A is the device swept area, C_p is Turbine power coefficient (dimensionless), U is free-stream flow speed.

Betz limit $C_p \sim\ 0.59$ – maximum value, it's a function of blade tip speed ratio $\lambda = \omega R/U$

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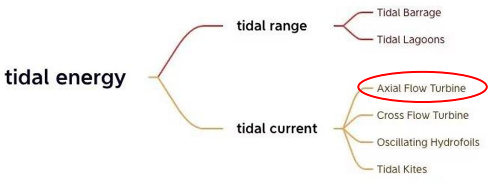
Tidal Energy Extraction Systems



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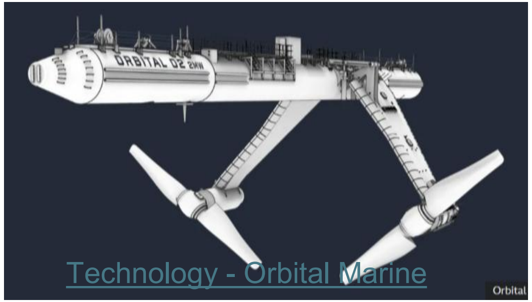

Technology - Orbital Marine

1 – Axial Flow Turbine

Tidal current devices utilize only a portion of the energy from the tidal stream with a rotor.

Tipical efficiency $C_p \approx$ 0.4-0.5

→Require yaw system or bidirectional blades (to face flow)
→ Mature technology (similar to wind turbines)

→ Sensitive to flow direction changes
→ More complex installation (alignment needed)
→ Performance drops in turbulent flows

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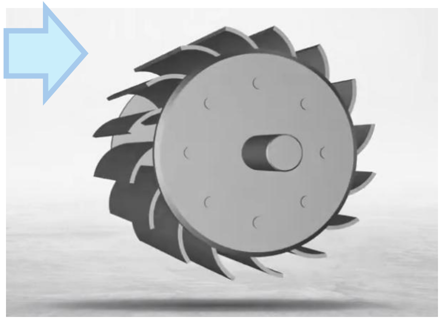
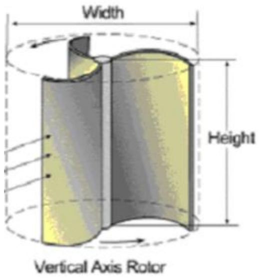
How velocity is estimated in practice?
Usually measured using **ADCP (Acoustic Doppler Current Profiler)**
ADCPs use piezoelectric oscillators to transmit sound of a known frequency. This sound is scattered by suspended particles in the water, and some is reflected back to the piezoelectric oscillators. The oscillators sense the frequency of that backscattered sound, and the difference between the frequency of the transmitted sound and the backscattered sound is the Doppler shift. By measuring the Doppler shift of backscattered sound, one can determine the speed of the object that scattered that signal.

Typical cycle:
Flood tide: up to **3-4 m/s**

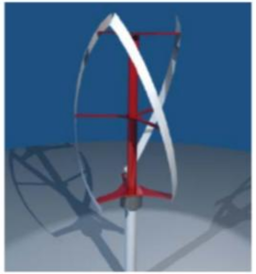
2 – Cross Flow Turbine

Vertical axis turbines may be appealing for two reasons: (1) They have an easier adaption to periodic flows; and (2) Less problems with vibrations.
Savonius® turbines are very easy to build and have few stresses on the primary axes. However, the torque is not smooth.
Gorlov® turbines are very promising, if flow remains perpendicular to the axis, regardless of the flow direction, turbine rotates always in the same direction, this makes this turbines the most efficient solution in present of flow direction variation. They can self-start with flow speeds lower than 1 m/s, and low fluctuations in torque are present in the vertical axis. Due to complex geometry, large-scale production and low power devices may not be cost effective.



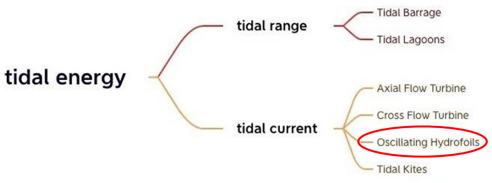


Savonius®



Gorlov®

Tidal Energy Extraction Systems



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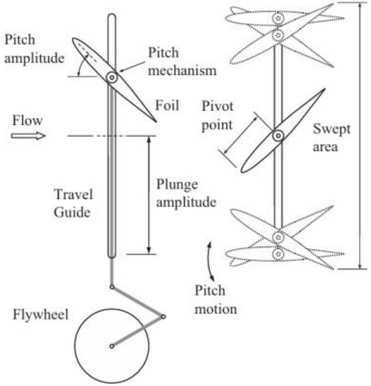
1) A hydrofoil (wing) is placed in a tidal current
2) It oscillates (heaves up/down + pitches)
3) Lift forces generate a periodic motion
4) That motion drives a hydraulic or electric generator



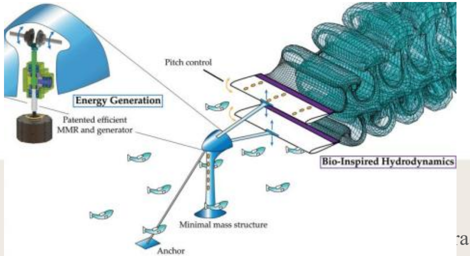
3 – Oscillating hydrofoils

An oscillating hydrofoil consists of a large hydrofoil wing attached to a long lever arm that is allowed to move up and down. Due to its wing-like shape, as the tidal energy current flows over the hydrofoil wing, it generates a vertical lift which causes the attached lever to move upwards. At the peak of the movement, the hydrofoil's angle of attack relative to the approaching tidal currents changes, so that now the lift is being generated on the underside of the hydrofoil wing. This reverses the direction of motion, forcing the wing downwards until moving water over the wing causes it to reverse direction, and the up-down movement continues once again. Thus, the total swept area for a tidal energy device like an oscillating hydrofoil wing will be its vertical up-down distance by its wingspan.

The efficiency of power generation is usually measured as the ratio of the time-average power output $\overline{P}$ to the power available in the flow through the frontal area swept by the foil (the so-called "Betz efficiency", in line with rotary turbine literature

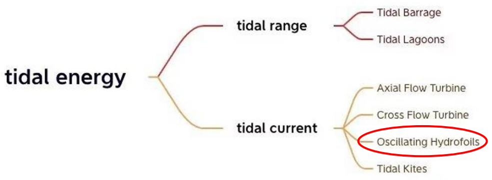
$$\eta = \frac{\overline{P}}{P_a} = \frac{\overline{P}}{\frac{1}{2}\rho U_\infty^3 sd} = \overline{C}_P \frac{c}{d}$$

Where s is foil span (m) and d is total vertical distance swept by the foil leading or trailing edge, whichever is greater (m)



Leading Edge Oscillating Hydrokinetic Turbine v1

Tidal Energy Extraction Systems



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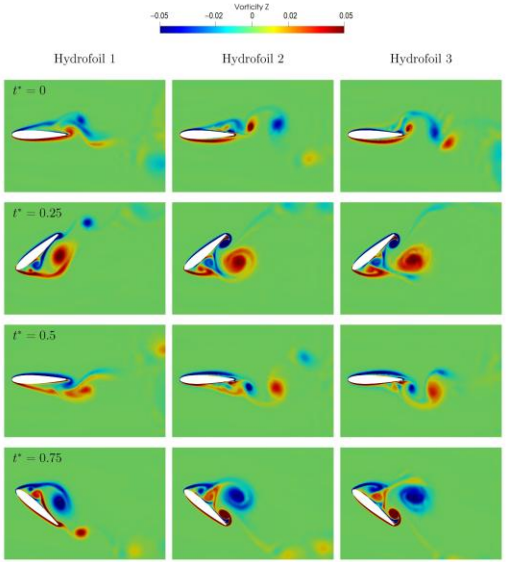

3 – Oscillating hydrofoils

The entire foil moves at the same speed, such that the proportion of the foil surface working at maximum power extraction is greater than for a rotary design. For this reason the foil speed may be kept relatively low regardless of turbine size. This is in contrast to rotary designs, where tip speeds increase proportionally with turbine radius, creating hazards to wildlife and leading to large stresses in the blade structure. Flapping foil turbines are thus expected to have diminished impact on wildlife in comparison with existing turbines.

The foil may be mounted horizontally (with a vertical plunging motion) allowing installation in shallower water by extending the foil horizon tally to the desired size. Thus flapping foil designs may be more easily scaled up than rotary turbines.

For rotary turbines, efficiency decreases as rotors are scaled down due to increasing viscous effects at lower Reynolds numbers. In contrast the efficiency gain due to Leading Edge Vortex (LEV) creation that occurs at low speeds also accrues to flapping foil systems when the Reynolds number is reduced by decreasing the size of the foil.

The untwisted hydrofoils in the oscillating concept have a much simpler geometry and are easier to produce than usual rotor blades, reducing design complexity and manufacturing costs. Recent works suggest that a flat plate may even be preferable to a foil section by promoting LEV formation, reducing manufacturing costs even further

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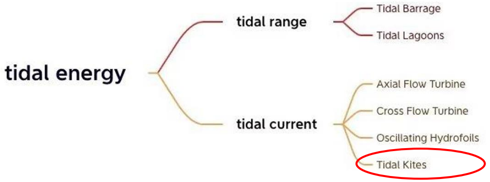
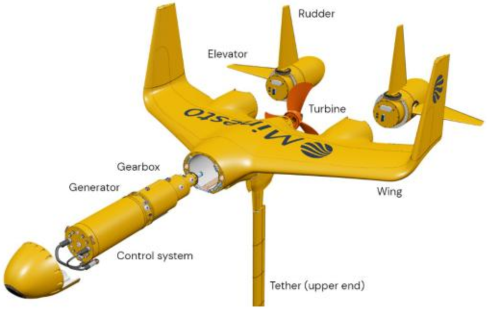
Tidal Energy Extraction Systems



4 – Tidal kites

The advantage of these types of tidal power technologies is their cost-effectiveness, ease of maintenance, relatively low environmental impact, and versatility, as they can be installed in almost any sea or river.

→ Bing Video



Our technology

Powerful, lightweight and modular power plants.

With an outstanding power-to-weight ratio, our kite systems can operate cost-effectively, enabling affordable energy from the ocean.

Rated power of	100 kW – 1.2 MW
Weight	2.7–28 tonnes
Wing span	4.9–12 m

Minesto | Our technology

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Overview - comments

There are only a limited number of places around the world where the tidal range is great enough to justify a barrage. The world's greatest tidal range is found in Canada's Bay of Fundy, where it is over 15 meters. Quebec's Ungava Bay and numerous estuaries around the Pacific Northwest feature ideal tidal ranges as well. Around the world sites on the coasts of Argentina, Australia, India, South Korea, Mexico, the US and Russia offer the best potential sites for tidal barrage plants.

Developers of tidal turbines are seeking out locations that possess tidal streams - areas of quickly flowing water caused by the motion of the tides. Typically, tidal streams are found where underwater valleys force currents to constrict and speed up. These are generally more common and located nearer economic centres where the power would be useful.

Major tidal currents occur in the Bay of Fundy, the Gulfs of Saint Lawrence and Mexico, the Amazon and Rio de la Plata river estuaries, and straits like the Straits of Magellan, Gibraltar, Sicily, the Skagerrak-Kattegat separating Denmark and Sweden, and the Bosporus in Turkey. In the Far East, useful currents are found near Taiwan, Korea, and the Kurile Islands north of Japan.

How much power could this all add up to? There are considerable quantities of untapped tidal energy in waters all around the world and it is difficult to precisely calculate just how much power could be derived from it. One estimate by the International Renewable Energy Agency puts global potential resources at 3 TW. A study by the European Innovation Partnerships for Water, a think tank, picked the 27 most promising locations for tidal barrages in the world and pegged their total capacity at 152,000 MW. Tidal lagoons and Dynamic Tidal Power plants could theoretically multiply that number several times over.

Overview - comments

Large tidal barrages present three main problems for skittish investors: they have large up-front capital costs, long construction times and produce relatively limited quantities of power. This is somewhat balanced out by operational lives of 100 years. Once over that initial capital building cost hump, tidal barrages become attractive investments. Studies peg maintenance and operations over the barrage's century long lifespan at less than 0.5% of initial capital costs. Despite having been around for decades, tidal barrage technology is not well developed. There are only four real examples to draw economic conclusions from, not enough to have any clear idea of just how expensive any proposed barrage will end up being.

Tidal stream technologies are essentially a decade old, and have only begun making great strides in the past five years. As yet the price is very high but it is almost certain dramatic price drops will accrue over time. Furthermore any scale of tidal stream turbines can be built as opposed to one giant project for barrages, giving developers much greater flexibility. Farms don't have to be built in one go, like tidal barrages, but gradually expanded over time.

→ Tidal Power - Energy British Columbia