UNIVERSITÀ DI TRENTO

DEPARTMENT OF

INDUSTRIAL ENGINEERING

Renewable Energy Conversion Systems

Lecture 13

Prof. Elisabetta Tedeschi

MSc Degree in Mechatronic Engineering,

Academic Year 2024-2025

Lecture 13: Outline

Main topic:

Ocean Wave Energy Conversion Systems

Wave energy: **why?** — Resource amount

Wave energy: **when?** — Ocean energy roadmap

Wave energy: **where?** — Geographical availability of the resource

Wave energy: **what?** — Origin of wave energy

Wave energy: **how?** — Exploitation mechanisms (concepts and basics of control)

Conclusions

Introduction to wave energy

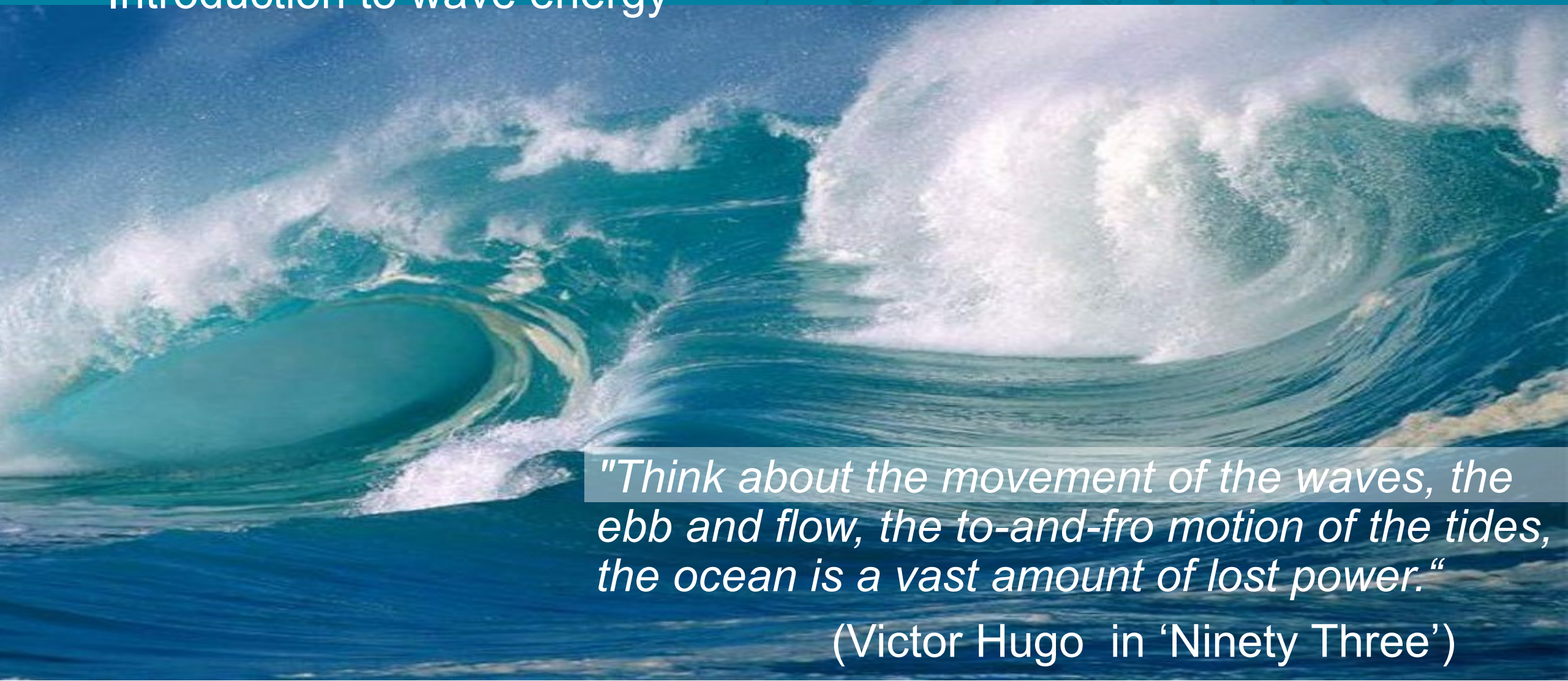
The sea is part of our lives

Introduction to wave energy

Challenging…

…With alternating fortunes…

Introduction to wave energy



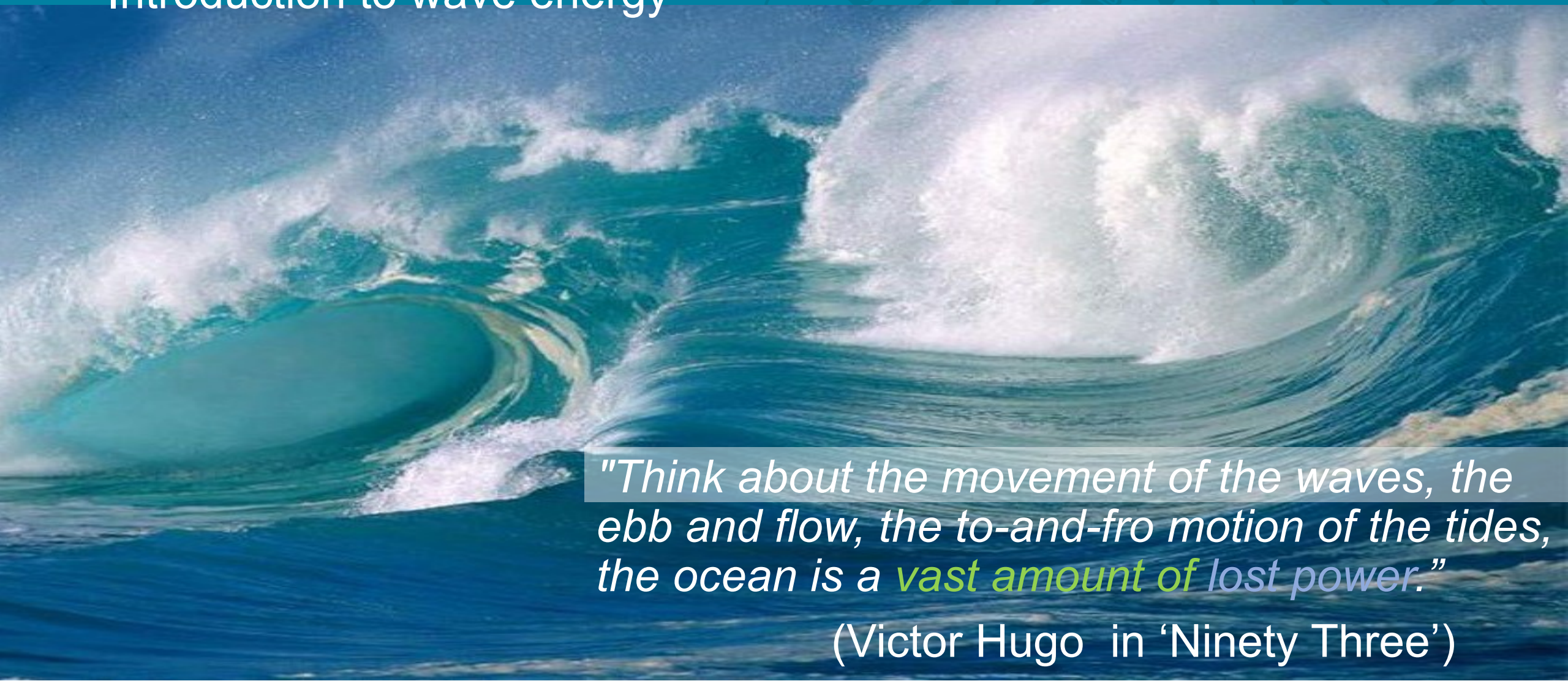
"Think about the movement of the waves, the ebb and flow, the to-and-fro motion of the tides, the ocean is a vast amount of lost power."

(Victor Hugo in 'Ninety Three')

Introduction to wave energy

Why?

Introduction to wave energy



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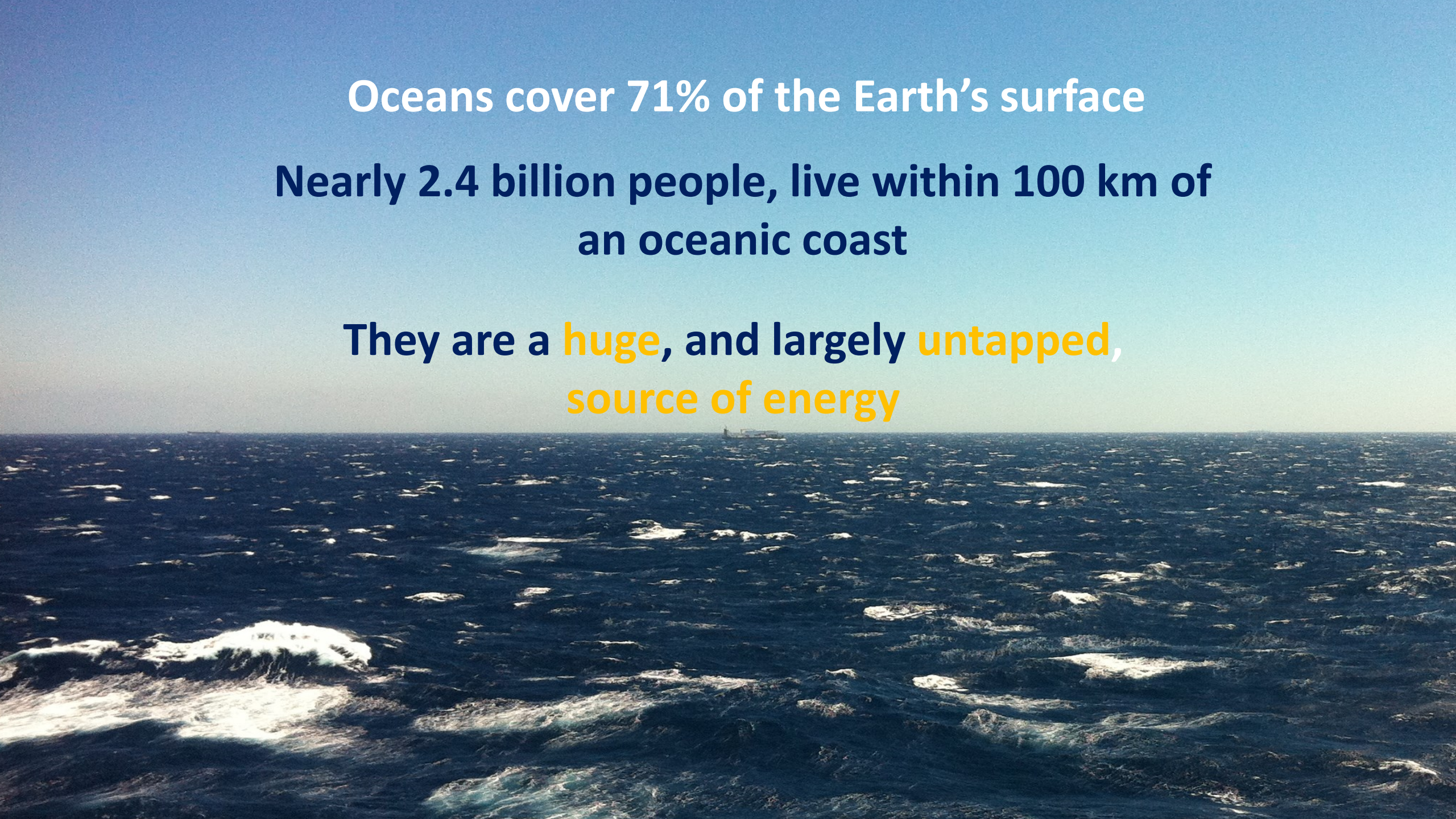

Oceans cover 71% of the Earth’s surface
Nearly 2.4 billion people, live within 100 km of an oceanic coast
They are a huge, and largely untapped, source of energy

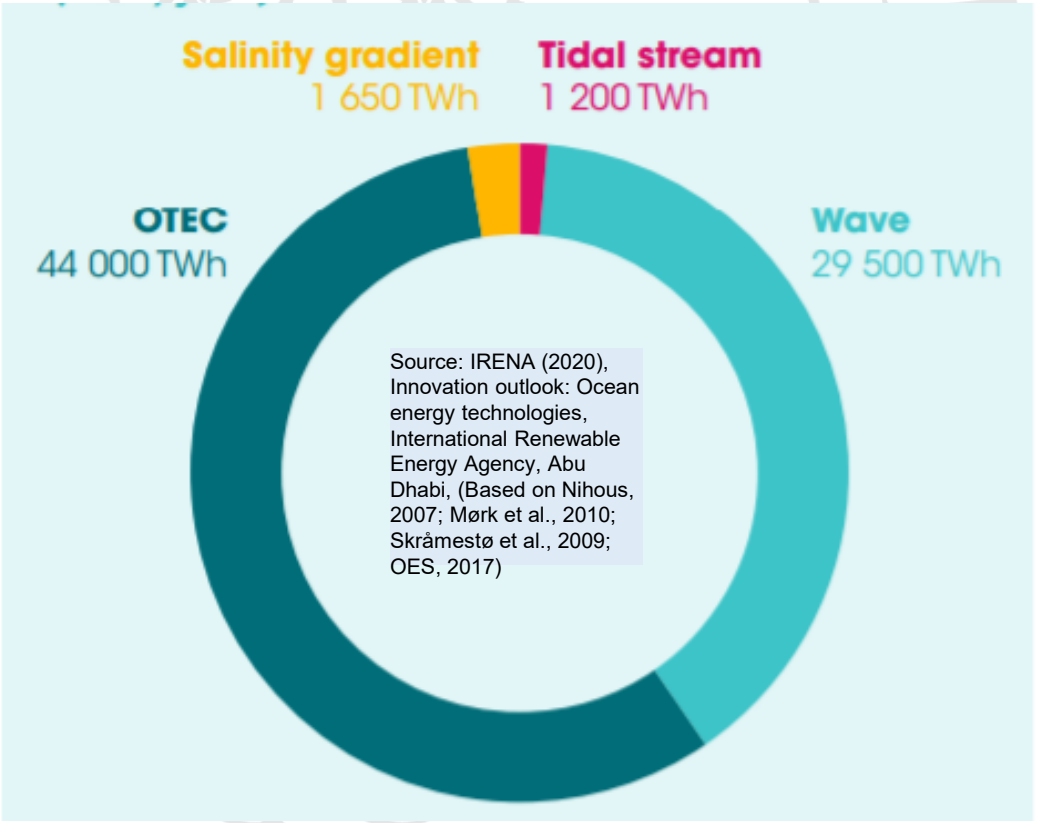
Introduction to wave energy

Offshore renewable energy portfolio

It includes many different ways of extracting energy from the sea:

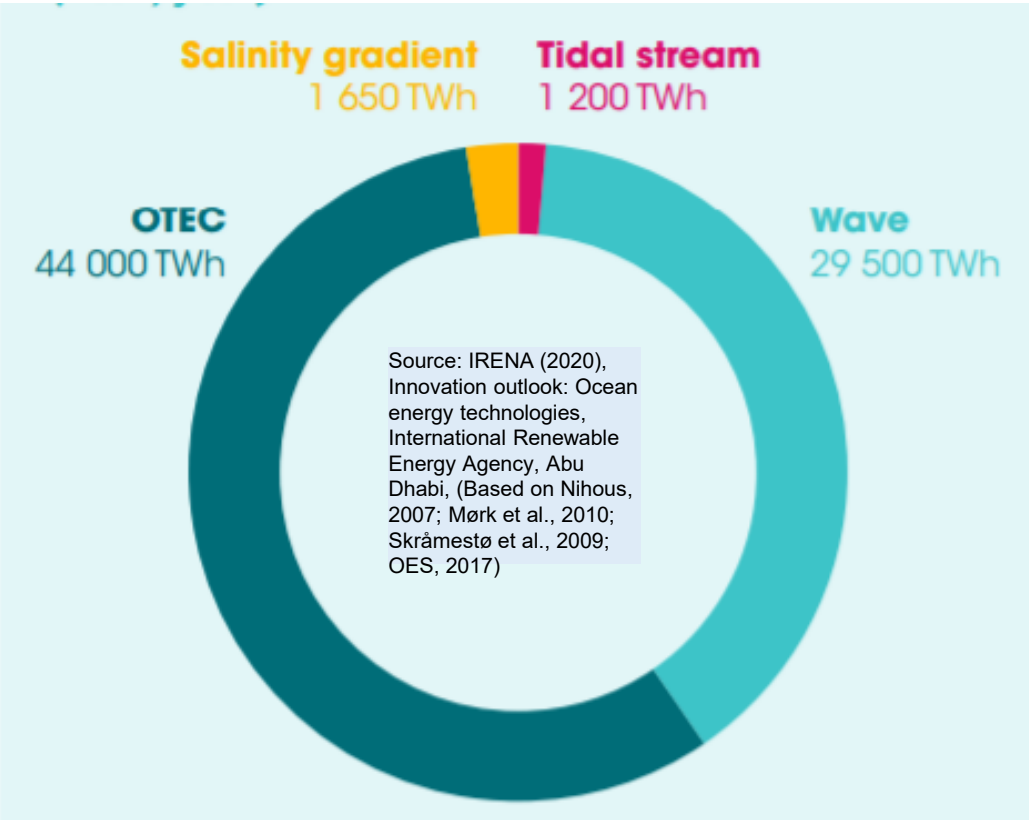
- **Tidal energy: (range and currents): exploits the 12h periodic tides due to moon gravity**
- **Salinity gradient: pressure differential between salt water and fresh water**
- **Ocean thermal: temperature differential between deep water and surface water**
- **Wave Energy: surface and subsurface motion of the waves**

Theoretical resource potential

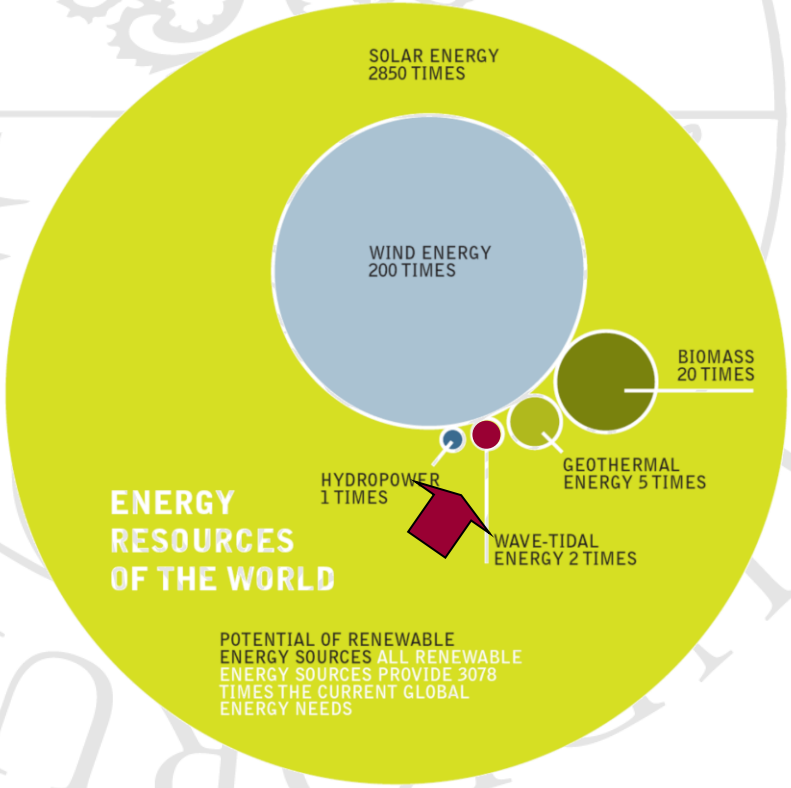


Introduction to wave energy

Ocean energy perspectives



Source: IRENA (2020), Innovation outlook: Ocean energy technologies, International Renewable Energy Agency, Abu Dhabi, (Based on Nihous, 2007; Mørk et al., 2010; Skråmestø et al., 2009; OES, 2017)



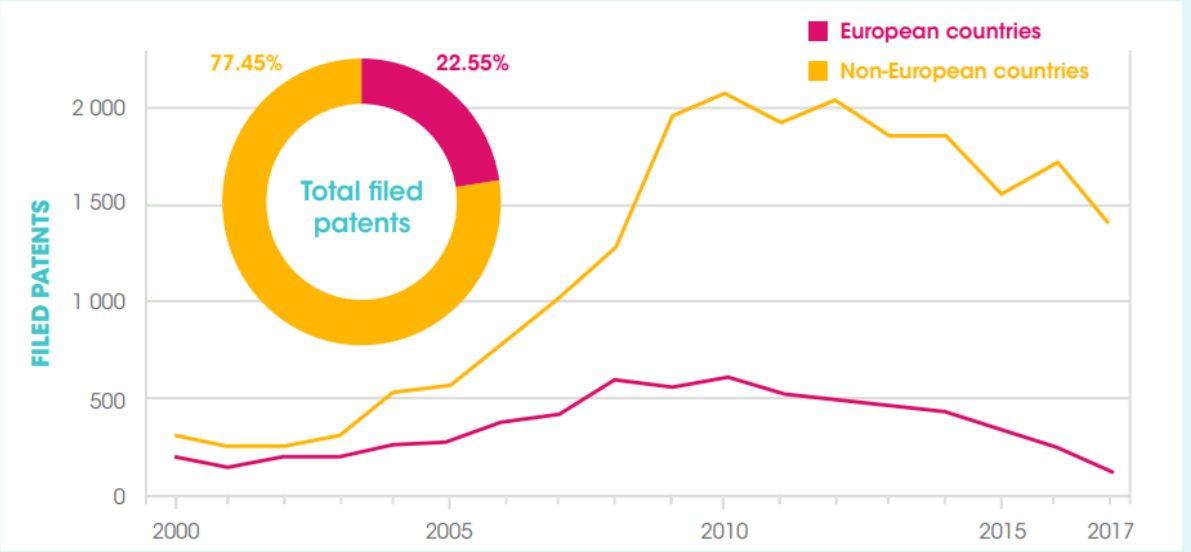
Introduction to wave energy

When?

Brief history of wave energy

- **First patent** filed in **1799**
- **Intense research** in wave energy in the **1970s, many devices** proposed
- More than 1000 patents followed
- Lack of interest at the **end of the oil crisis**
- Slow development till **2000**
- **New interest** due to the European quest for renewable energy production
- Contribution to the goals set by the **Paris Agreement**

Figure 7: Number of ocean energy patents filed (2000-2017)



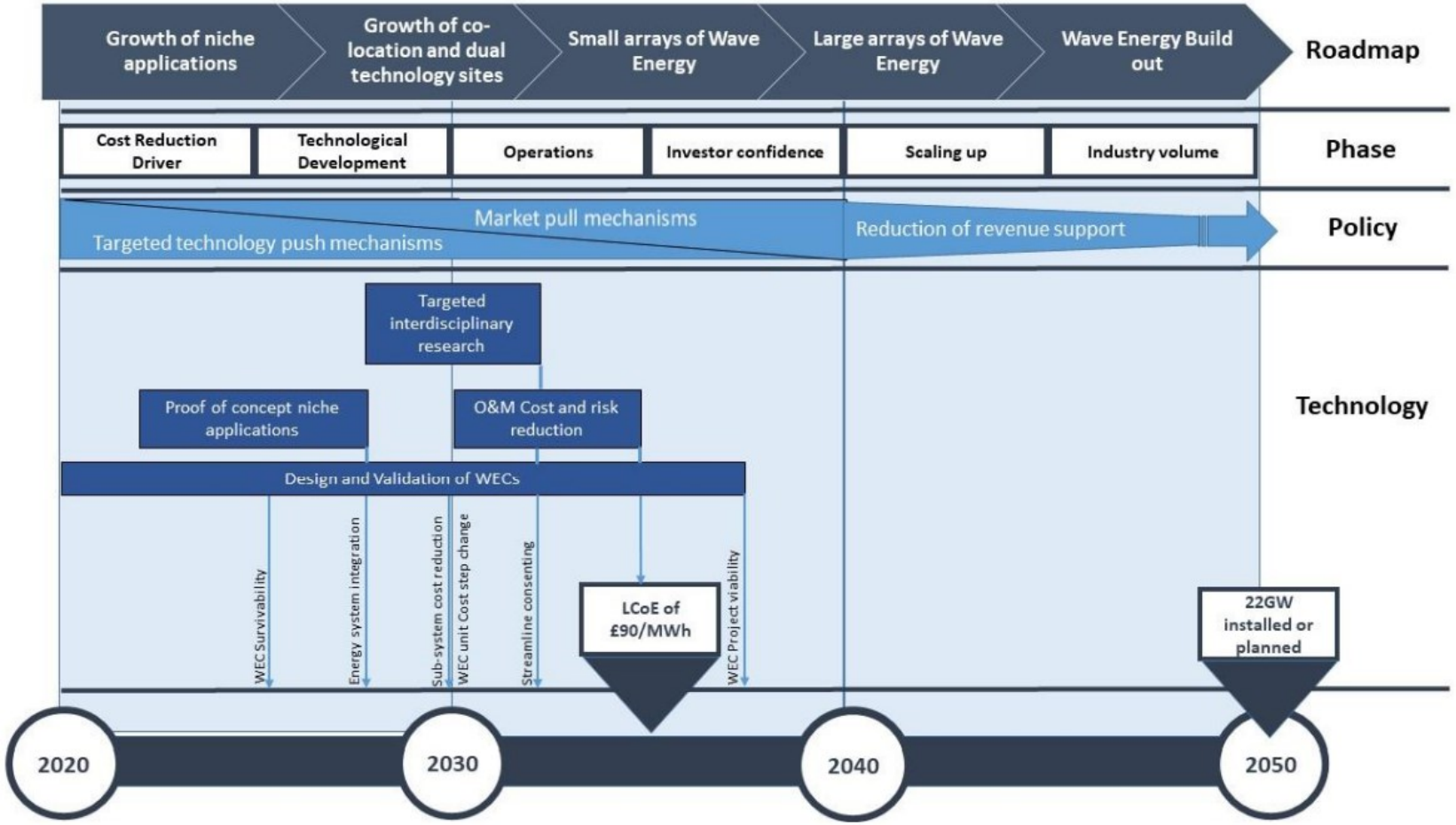
Source: *IRENA, 2020b*

Ocean energy roadmap

	1991*	2010**	Today	2030	2050
Average power capacity of offshore wind turbine	0,45 MW	3MW	7,8MW	↗	↗
EU offshore wind energy capacity	5MW	3GW	12GW	≥60GW	300GW
Ocean energy capacity (e.g. wave, tidal)		3,8MW	13MW	≥1GW	40GW

Source: European Commission, Offshore Renewable Energy Strategy, 19/11/2020

Wave energy (UK) roadmap



Source: Supergen «Wave Energy Roadmap»

2020-2025

Alternative technology, novel Wave Energy Converters (WECs) Survivability and reliability. Innovative materials. Power Take-Offs (PTOs) and control systems

2025-2030

Mooring and connection systems. Foundation design and installation for bottom fixed devices Demonstration of WECs in real sea conditions.

2030-2038

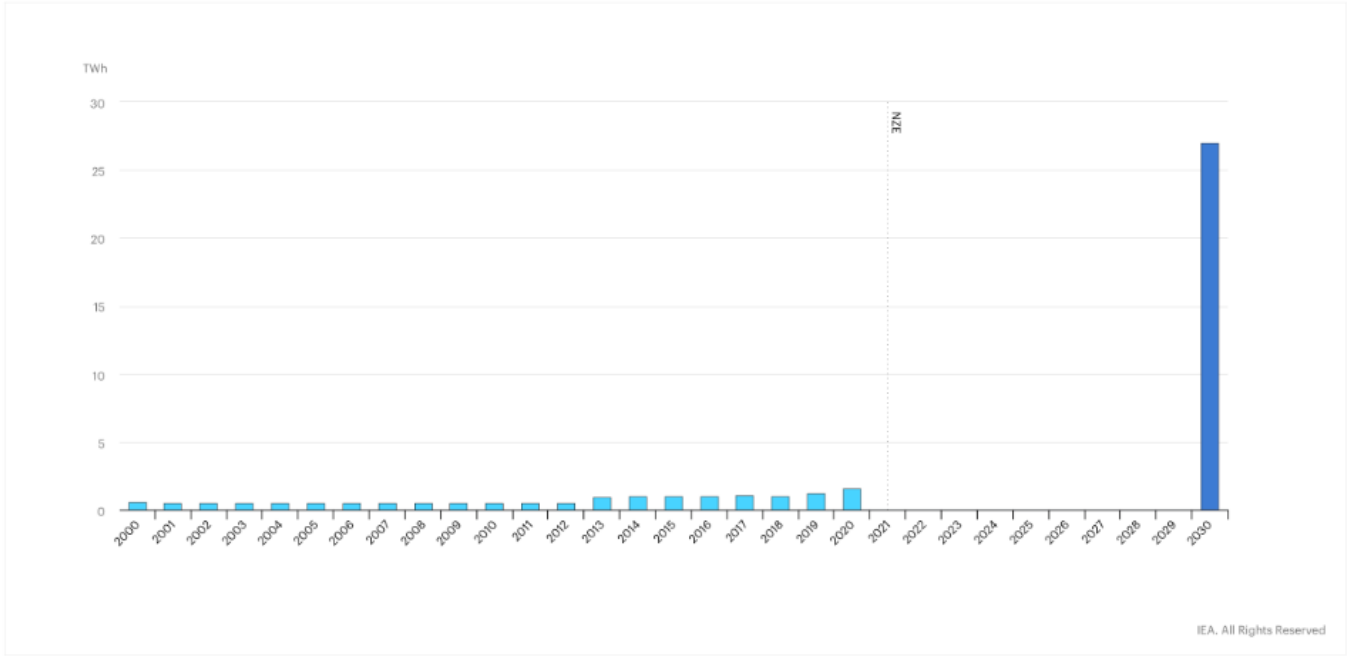
Demonstration of pilot WEC farm in real sea conditions

Ocean energy outlook

Ocean power generation in the Net Zero Scenario, 2000-2030

Last updated 2 Nov 2021

Download chart ↓ Cite Share



Appears in
Ocean Power

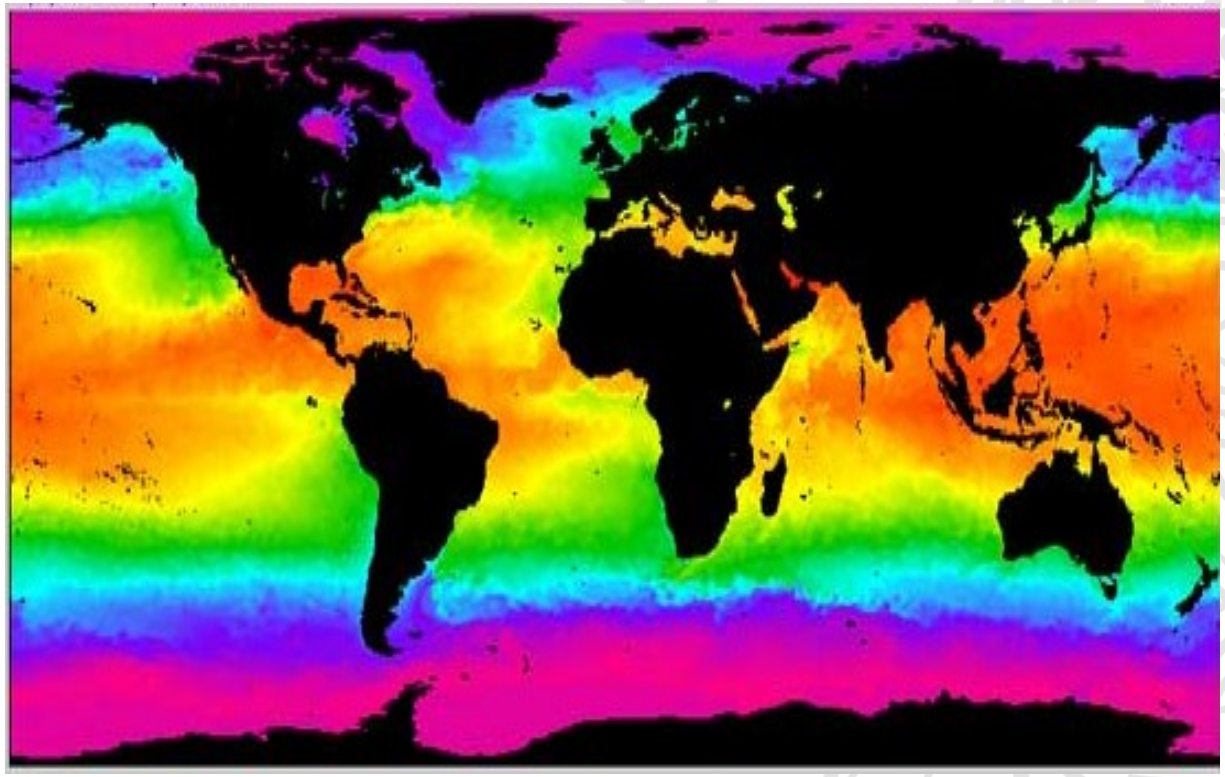
Notes
NZE = Net Zero Emissions by 2050 Scenario.

Source: International Energy Agency (IEA)

Ocean power generation needs to grow 33% a year to achieve net zero by 2050

Introduction to wave energy

Where?



Availability of the resource

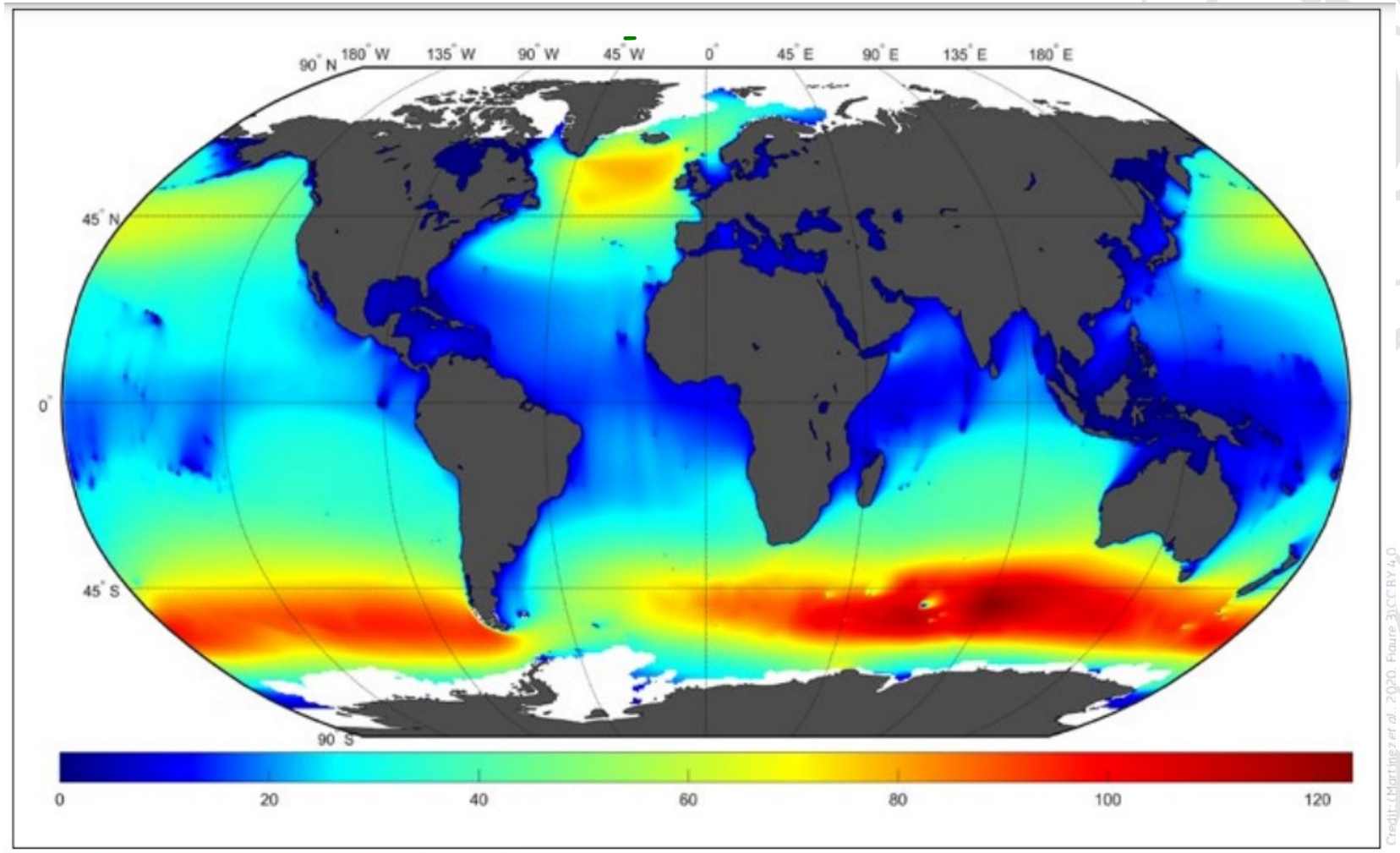


Figure 2.2 Global mean value of wave power, P (kW/m).

Highest wave energy transport at latitudes between 40° and 60°

Higher waves on the west coasts

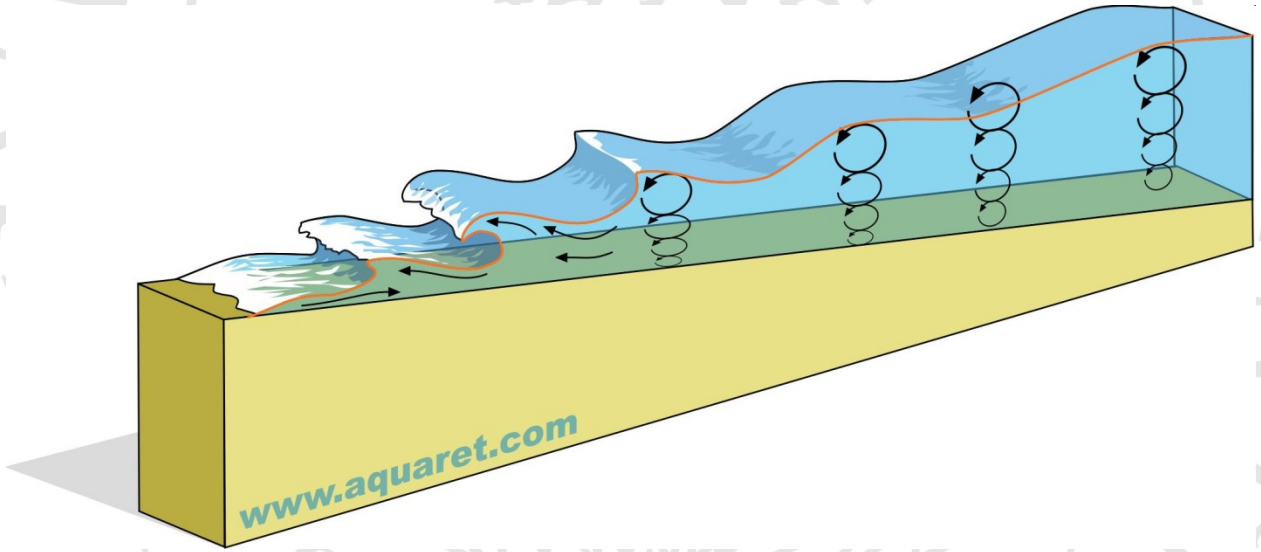
Europe as the most favored continent for wave energy exploitation

High potential also in America and Oceania

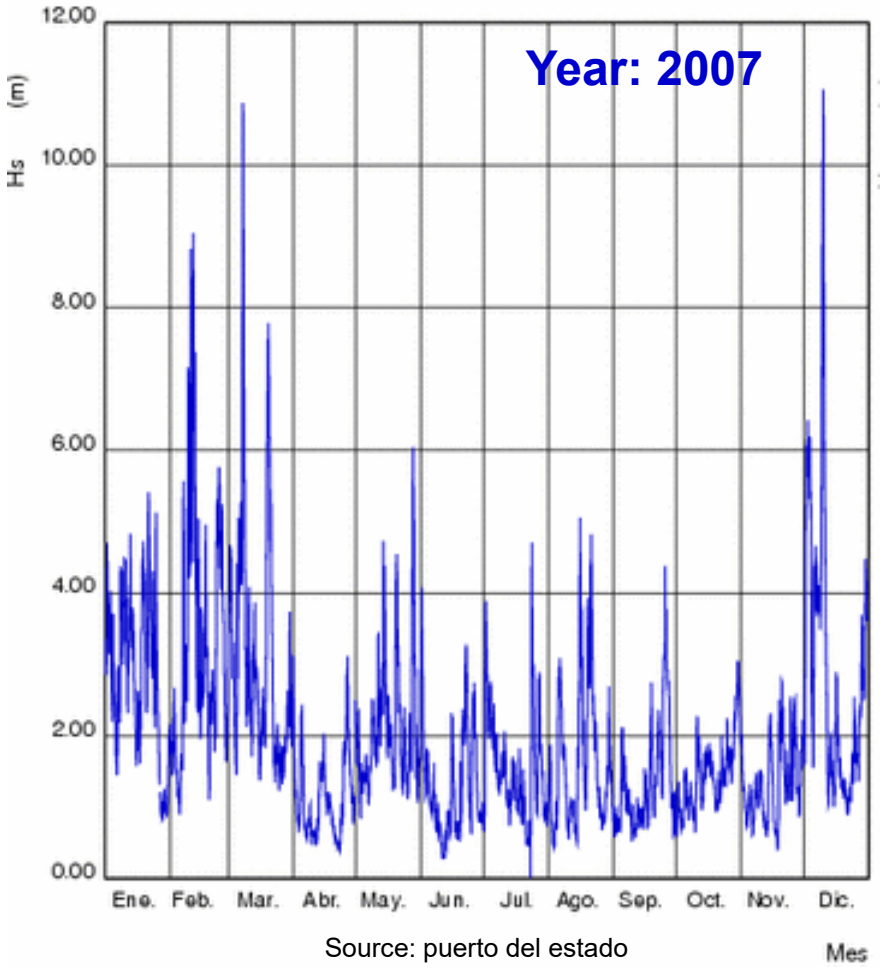
Wave propagation

Waves travel a lot without loosing energy in deep waters

They rapidly loose their energy close to shore due to interaction with seabed



Variability of the resource



Source: puerto del estado

Waves show a seasonal variability, being more energetic during winter

Such variability can be of a factor two or more

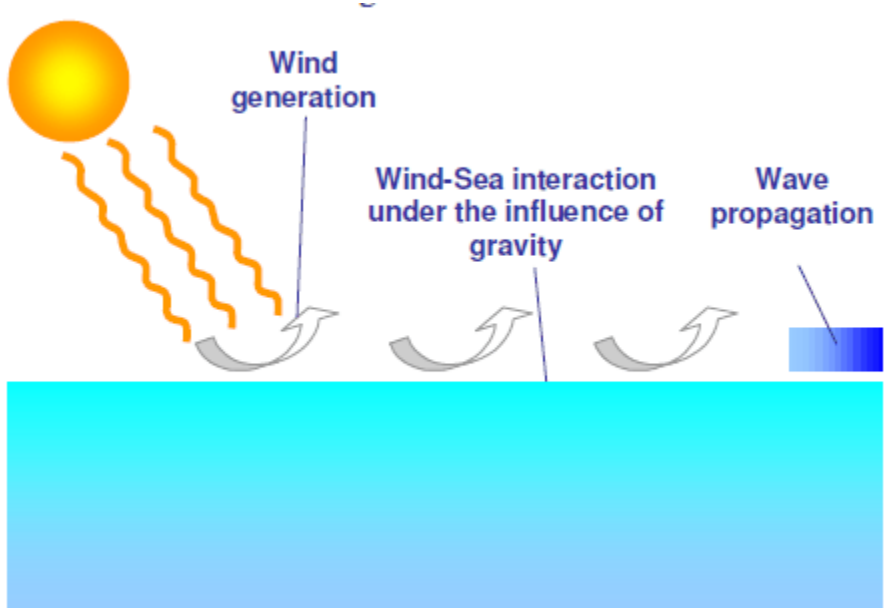
Data recorded from an offshore buoy located close to Bilbao, Spain

Introduction to wave energy

What?

Origin of the energy

Waves are created by winds and act as a concentrated storage of wind energy below the sea surface



Actually, waves are a concentrated form of solar energy

Comparison with other renewables

Just below the sea level, wave energy flow is typically 5 times denser than the wind energy flow 20 m above the sea surface

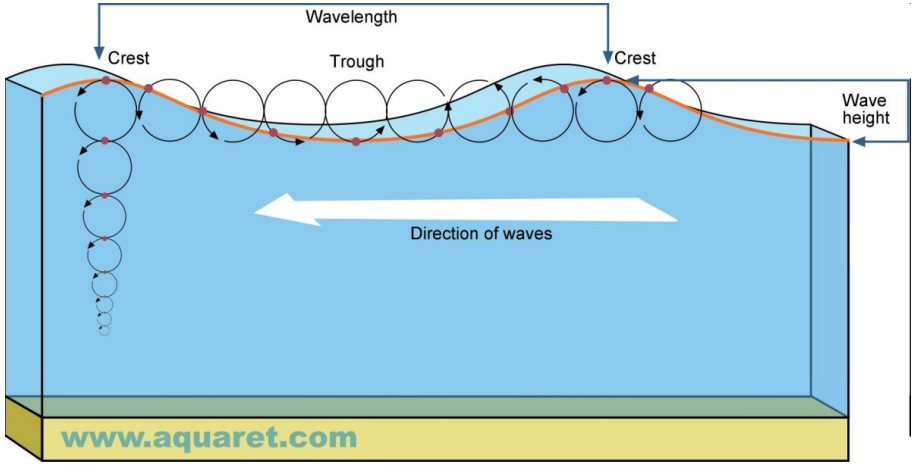
Just below the sea level, wave energy flow is typically 20-30 times denser than the solar energy flow

Comparison with other renewables

ENERGY TYPE	CAPACITY FACTOR
	(The average absorbed power (or electricity) divided by the maximum power (or electricity) that a device can produce)
Offshore wind	0.3-0.6
Wave energy	0.25-0.32
Tidal current	0.5-0.7
Floating solar	0.1-0.3
Thermal gradient	0.9-0.95
Salinity gradient	0.8-0.84

Source: EMB “European offshore renewable energy (2023)

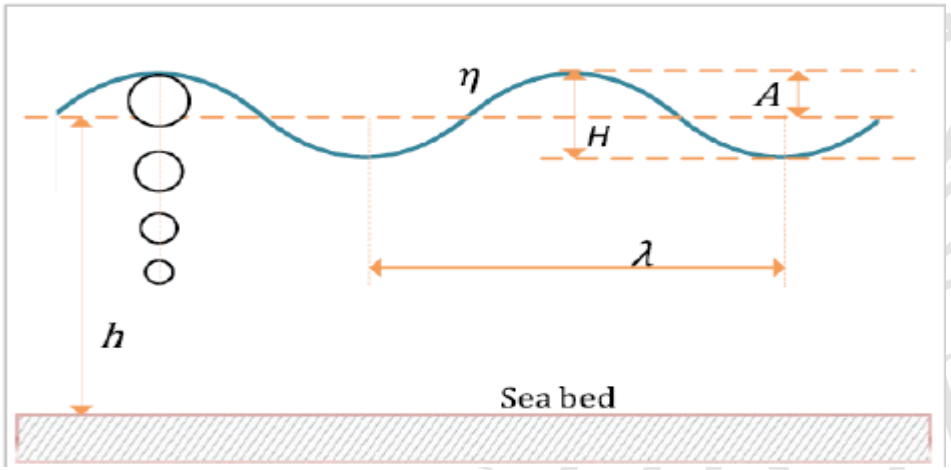
Origin of the energy



Due to wind action, water particles move in small circles

Most of the energy is concentrated just below the sea surface

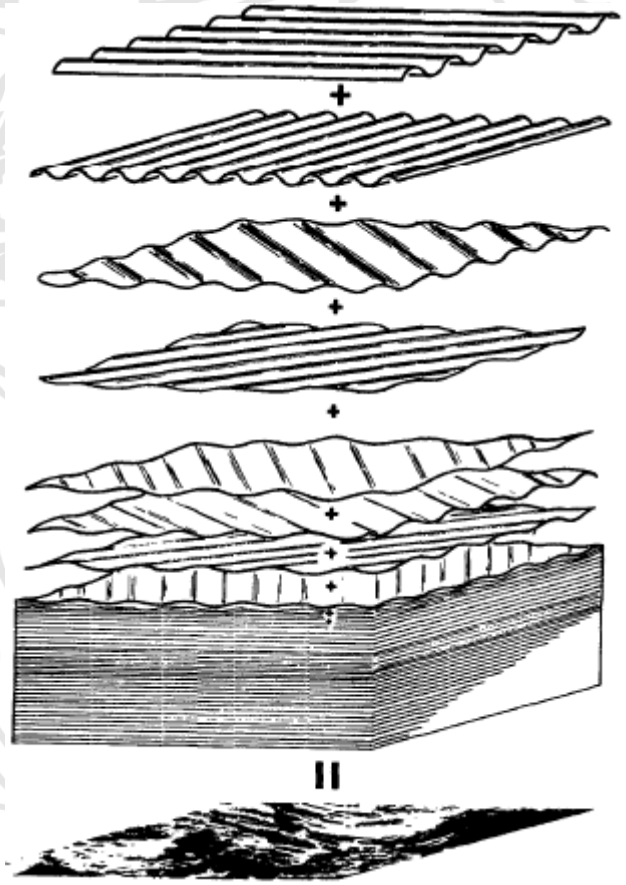
Sinusoidal (i.e. regular wave) approximation for sea waves is often used in the first instance



λ = wavelenght
A = wave amplitude
H = wave height
h= water depth
η =wave elevation

Nature of irregular waves

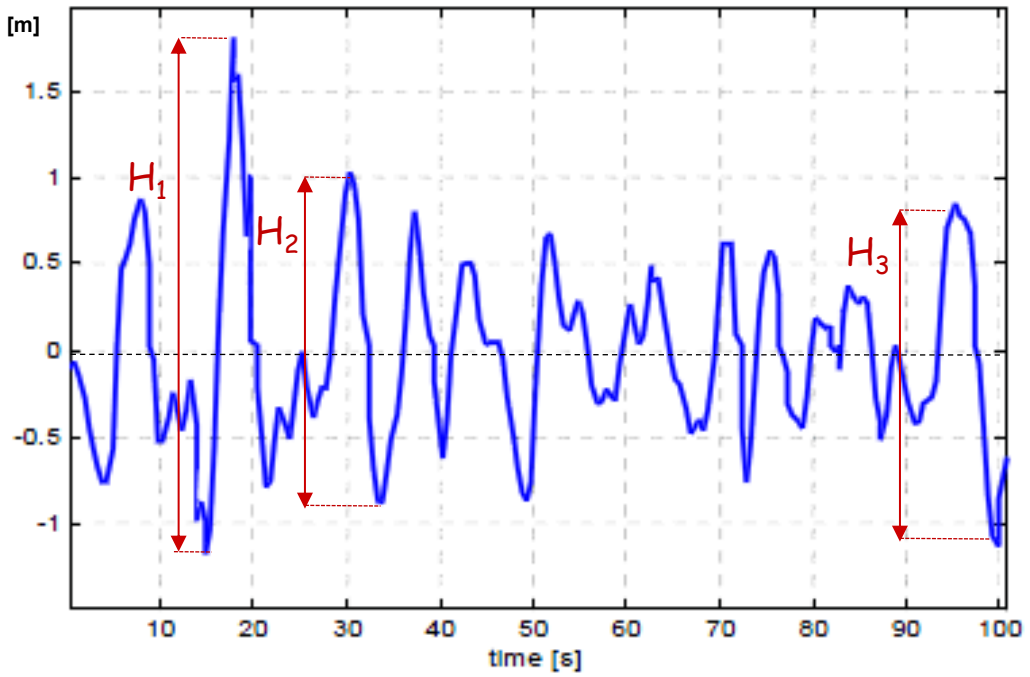
Intuitive description of an irregular sea:
"A collection of a great number of simple regular waves of different lengths, all of small height and all mixed together with no apparent relation to each other except that they are all there and are travelling in the same direction"



After Willard J. Pierson ***et al.,*** with permission of the **US.** Naval Hydrographic **Office**

Significant wave height

Wave profile: example recorded in the North Atlantic

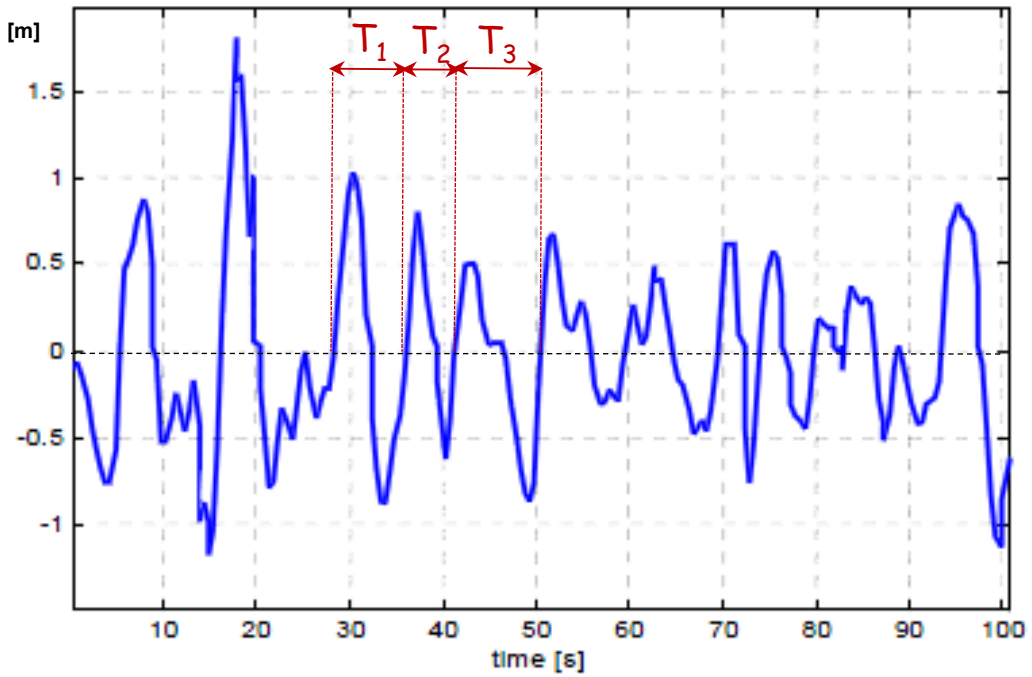


Significant wave height is the average of the highest one third of the individual trough-to-crest heights H_i (i=1,2,3,…), and is denoted by $H_{1/3}$ or often H_s

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

Average zero up-crossing time

Wave profile: example recorded in the North Atlantic



The individual *zero up-cross time* T_i (*i*=1,2,3...) is the time interval between two consecutive instants where the wave elevation crosses the zero level in the upward direction. An average of these over a certain time provides a useful measure of the real-sea wave period.

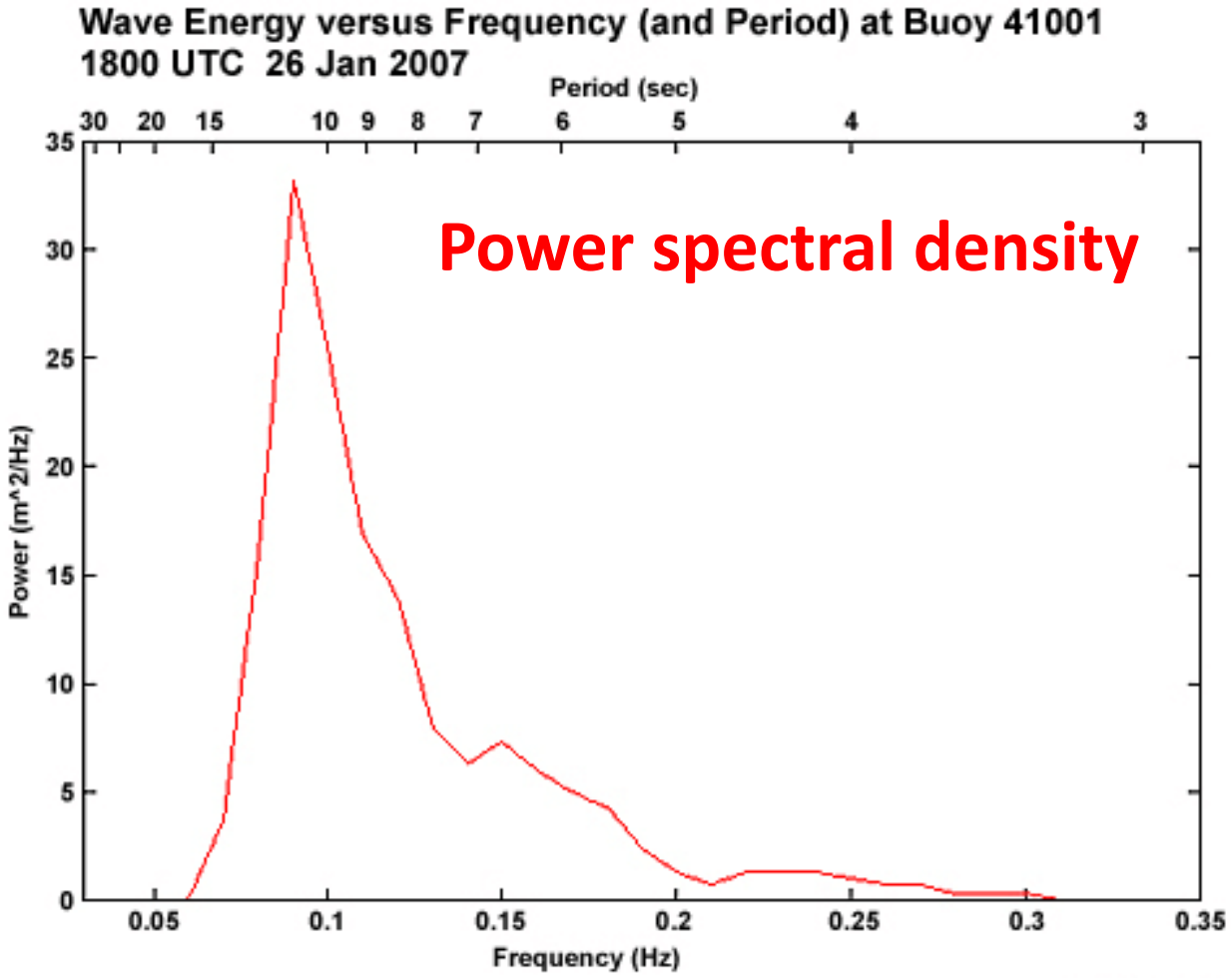
$$T_z = \frac{T_1 + T_2 + \ldots + T_N}{N}$$

Energy spectrum

- The intensity of the sea is characterized by its total energy, and we can show the individual contribution made by each of its component waves
- With each component waves of different height and frequency, we can show how the total energy of the sea is distributed according to the frequencies of the various wave components
- Such distribution is the energy spectrum of the sea, or simply, sea spectrum

(J.H. Michels, Sea Spectra Revisited)

Energy spectrum



From real sea measurements, the sea spectrum can be derived

Bretschneider Spectrum

$$S_f(f) = 0.08\, H_s^2\, T_z^{-4} f^{-5} \exp\left(-\frac{0.318}{T_z^4} f^{-4}\right)$$

Pierson-Moskowitz spectrum

$$S_f(f) = 5\ 10^{-4} f^{-5} \exp\left(-\frac{2\ 10^{-3}}{H_s^2} f^4\right)$$

Wave power per meter length

- **The wave power of linear regular (sinusoidal) waves per unit length of wave front in deep water is:**

$$P_{\sin} = \frac{\rho g^2 H^2 T}{32\pi} \quad \text{[W/m]}$$

- **The wave power of linear irregular waves per unit length of wave front in deep water is:**

$$P_{irr} = \frac{\rho g^2 H_s^2 T_e}{64\pi} \quad \text{[W/m]}$$

$T_e \approx [1.15 - 1.25] T_z$

depending on sea spectrum

Wave resource characterization at a specific site

Significant wave height, Hs (m) \ Te (s)	<5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5
14.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
13.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
13.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.00
12.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
11.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
11.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.00
10.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.00	0.02	0.02	0.00	0.00	0.00
9.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.01	0.01	0.02	0.04	0.00	0.01	0.00
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7.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.05	0.05	0.02	0.00	0.01	0.02	0.02	0.00	0.00
7.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.04	0.09	0.09	0.06	0.02	0.01	0.01	0.03	0.00	0.00	0.00
6.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.04	0.09	0.13	0.11	0.09	0.01	0.02	0.02	0.01	0.00	0.00	0.00	0.00
6.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.07	0.14	0.14	0.12	0.03	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00
5.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.07	0.14	0.24	0.21	0.14	0.11	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.11	0.28	0.34	0.35	0.31	0.22	0.14	0.05	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.5	0.00	0.00	0.00	0.00	0.00	0.01	0.08	0.12	0.52	0.60	0.72	0.47	0.27	0.20	0.12	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.0	0.00	0.00	0.00	0.00	0.00	0.04	0.16	0.50	0.83	0.95	0.86	0.55	0.52	0.37	0.10	0.03	0.00	0.05	0.01	0.01	0.00	0.00	0.00	0.00
3.5	0.00	0.00	0.00	0.00	0.07	0.11	0.52	0.89	1.49	2.06	1.57	1.05	0.68	0.51	0.34	0.10	0.08	0.05	0.00	0.00	0.00	0.00	0.00	0.00
3.0	0.00	0.00	0.00	0.09	0.21	0.74	1.15	2.14	2.61	2.58	1.58	1.14	0.90	0.56	0.39	0.26	0.09	0.10	0.02	0.01	0.00	0.00	0.00	0.01
2.5	0.00	0.01	0.02	0.17	0.57	1.71	2.03	2.15	2.42	1.87	1.53	1.18	0.68	0.36	0.21	0.14	0.15	0.13	0.09	0.03	0.02	0.02	0.02	0.02
2.0	0.00	0.11	0.67	1.08	1.74	1.93	2.81	3.43	3.71	2.68	1.79	1.15	0.49	0.20	0.17	0.10	0.03	0.02	0.00	0.01	0.02	0.00	0.01	0.01
1.5	0.02	0.46	1.34	0.92	1.50	2.18	2.38	3.12	2.25	2.27	1.74	1.02	0.55	0.20	0.03	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.0	0.09	0.14	0.55	0.30	0.71	0.95	0.79	0.49	0.33	0.40	0.14	0.06	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

At a specific site, the wave resource is often characterized by the % occurrence of each different couple of wave height/wave period and represented through a scatter diagramme

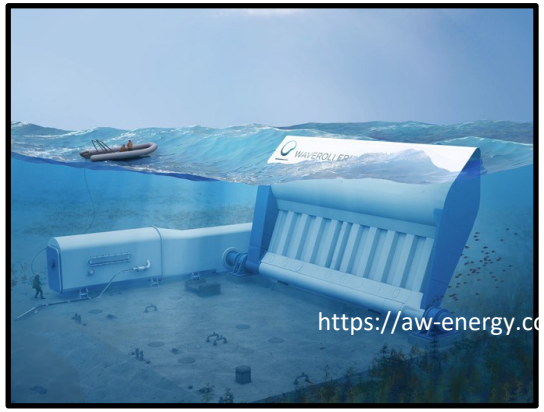
Source: AMETS scatter diagram (2010)

Introduction to wave energy

How?

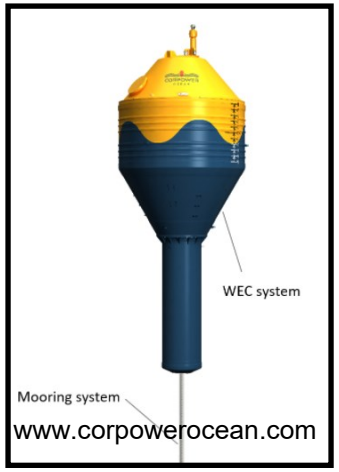
Introduction to wave energy

WAVEROLLER



WELLO-PENGUIN

CORPOWER



High concept diversification

Frequent need of tailor-made solutions

MARMOK

Classification of devices

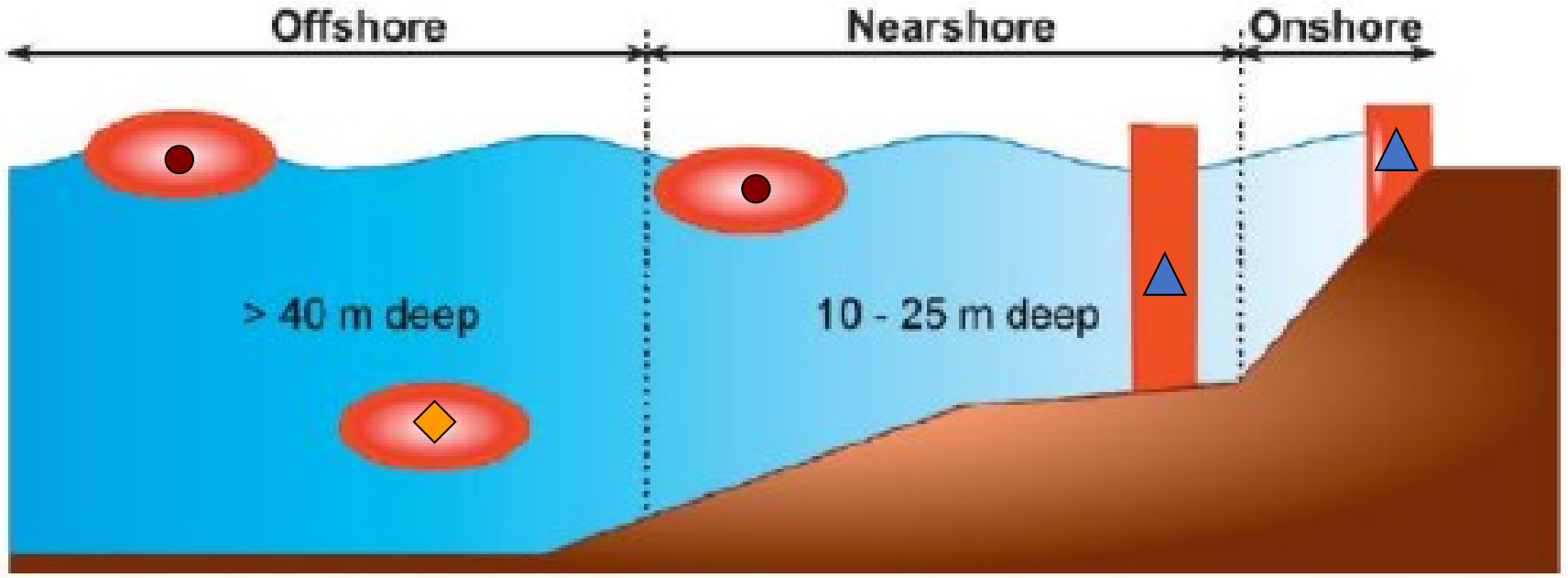
- Location

- Depth of installation

- Size and orientation

- Primary conversion mechanism

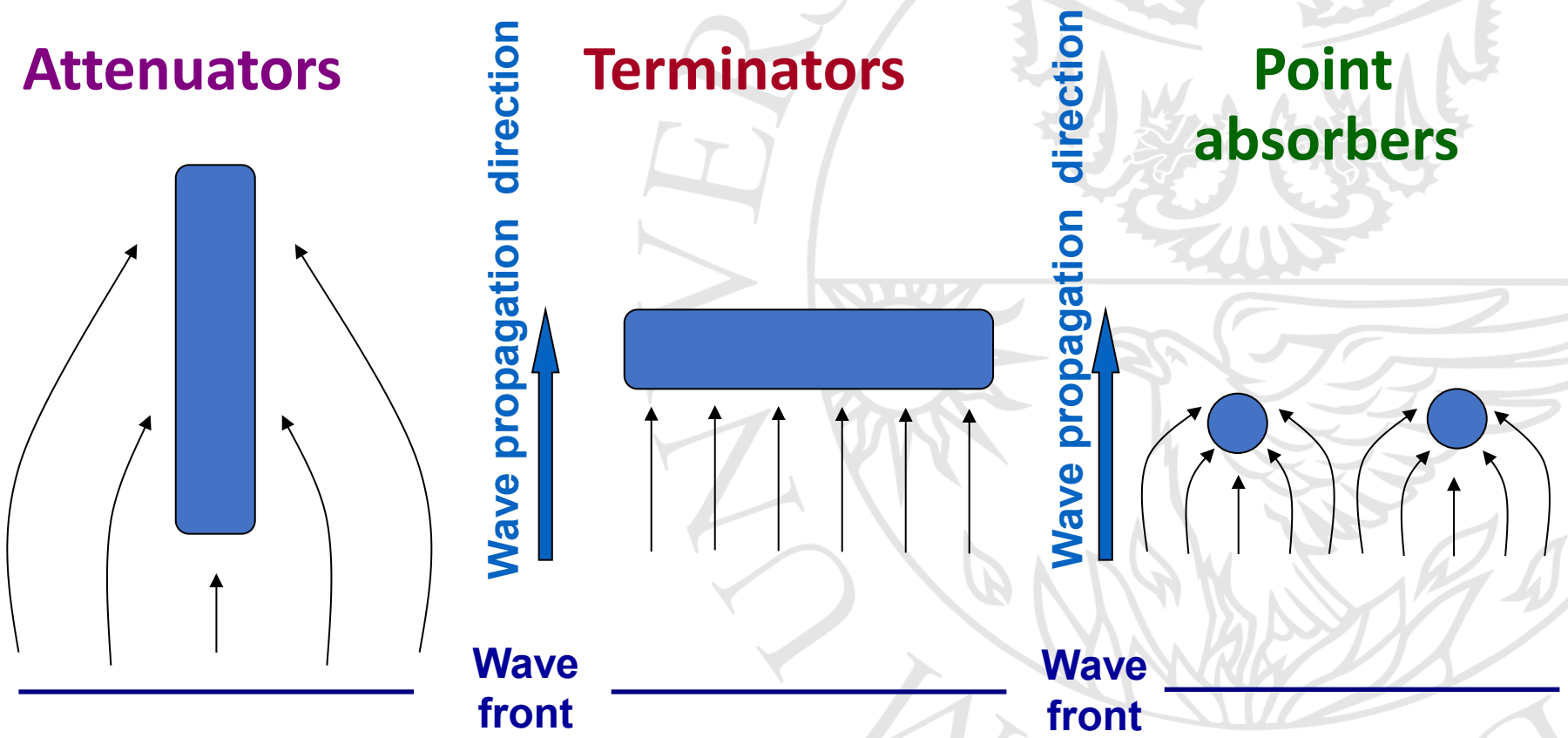
Location and depth of installation



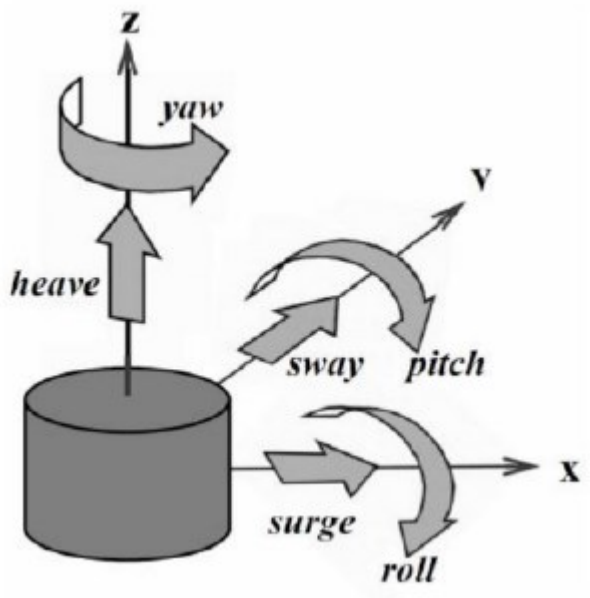
- Floating
- Submerged
- Bottom standing

Source:: Titah-Benbouzid and Mohamed Benbouzid, 2014

Size and orientation



Motion of a rigid body subject to waves



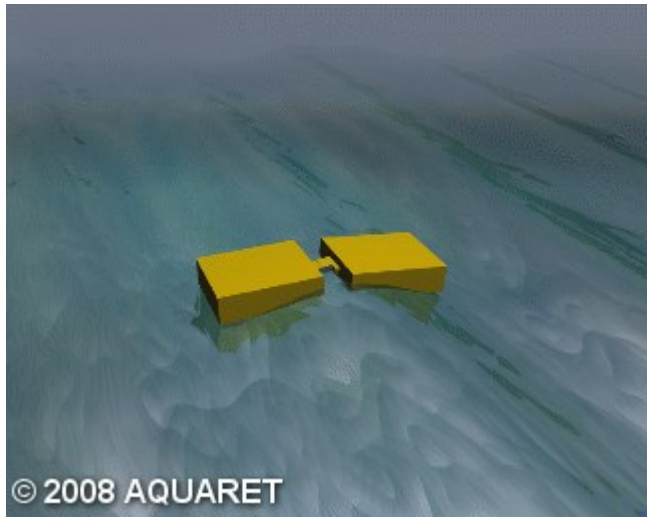
Source: W. Sheng (2010)

Translational degrees of motion:
SURGE – Forward and backward moving along the longitudinal horizontal axis.
SWAY – Left and right motion along the lateral horizontal axis.
HEAVE – Up and down motion along the vertical axis is.

Rotational degrees of motion:
ROLL – Rotating motion about the longitudinal horizontal axis.
PITCH – Rotating motion about the lateral horizontal axis.
YAW – Rotating motion about the vertical axis.

Working principle

Attenuator

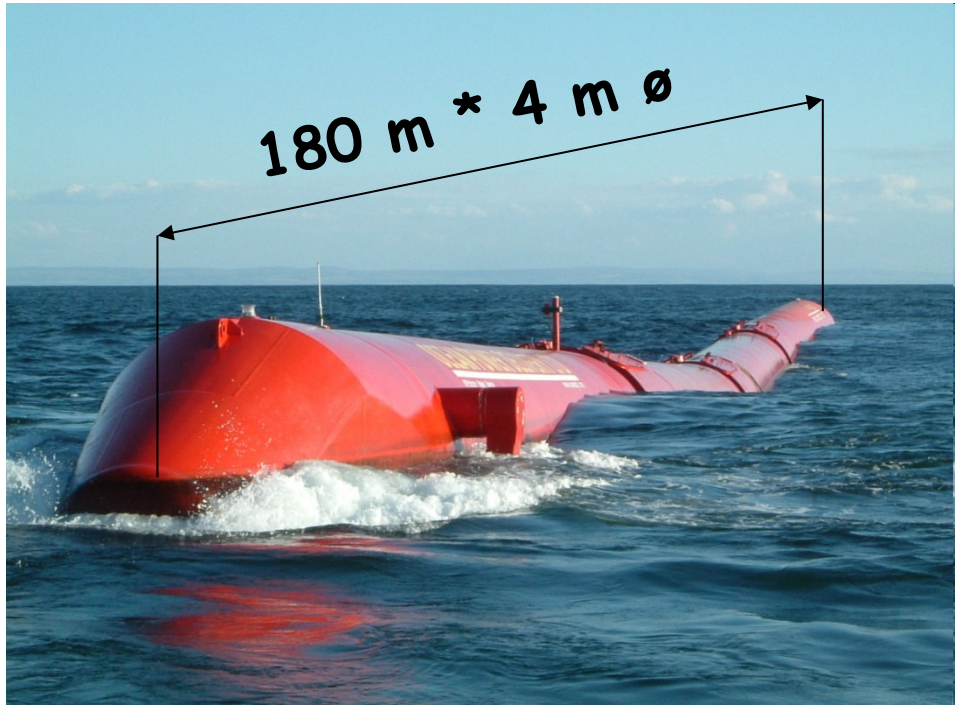


An attenuator Wave Energy Converter (WEC) is a line absorber operating parallel to the wave propagation direction. The device is usually not physically fixed in place. This device captures energy from the relative motion of the two arms as the wave passes them.

Source: EMEC website

Example

Attenuator

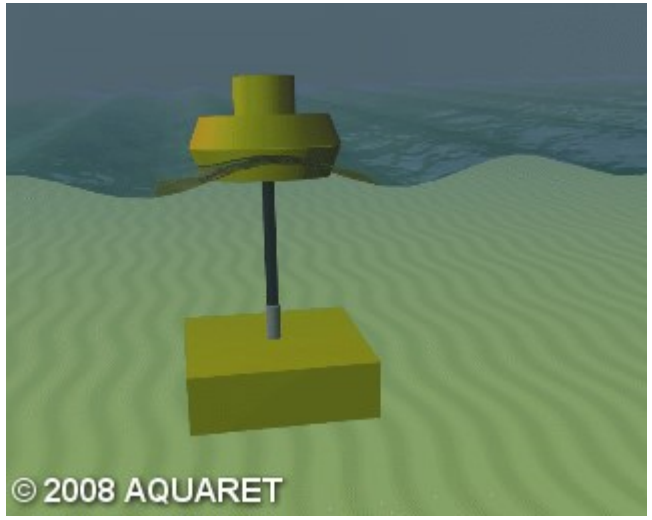


Source: www.pelamiswave.com

- PELAMIS was the first attenuator to be deployed offshore and grid-connected (2004)
- 5 modules for 750 kW
- 180 m lo and 4 m in diameter
- Annual p duction around 25-40% of full rated pov r
- Hydraulic ms
- High pressure fluid
- Smoothing accumulators
- Hydraulic motors + electrical generators

Working principle

Point Absorber

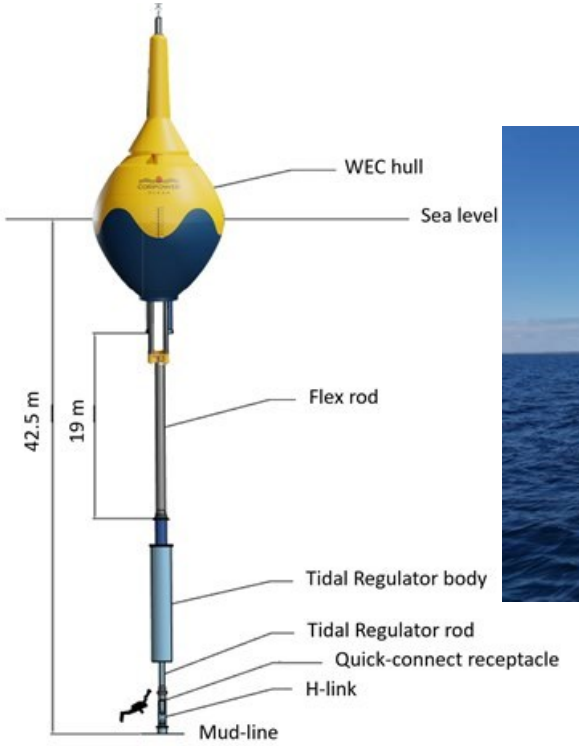


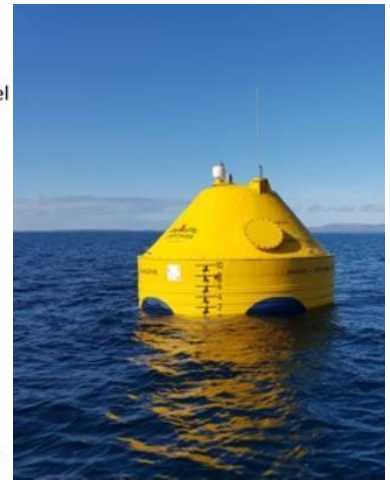
A point absorber is a device with small dimensions compared to the incident wavelength and because of that, wave direction is irrelevant for the system.
Point absorbers are most often used in offshore locations, and they mainly utilize heave motion for wave energy extraction

Source: EMEC website

Working principle

Point Absorber



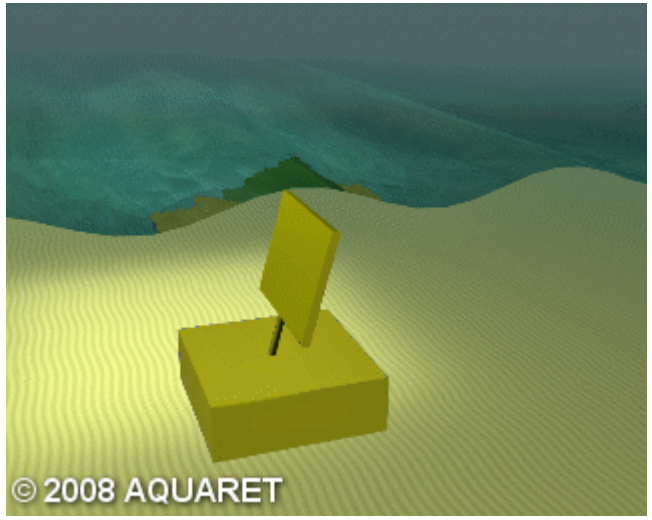


Source: www.corpowerocean.com

- CORPOWER point absorber concept
- 300 kW power rating of the buoy
- 9 m diameter, 18 m high buoy
- Exploitation of waves between 0.5 m and 8 m
- Capacity factor between 40% and 60%
- Suitable for offshore installations, including array deployment

Working principle

Oscillating Water Surge Converter

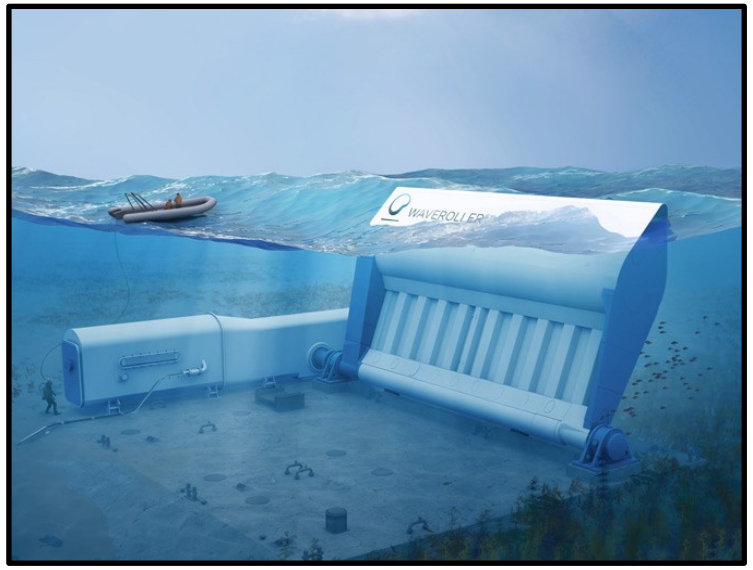


An oscillating water surge converter (OWSC) is positioned perpendicular to the wave direction and extracts energy from wave surges, exploiting the horizontal particle velocity of the waves. The arm oscillates as a pendulum around a pivot axis in response to the movement of water in the waves.

Source: EMEC website

Example

Oscillating Water Surge Converter

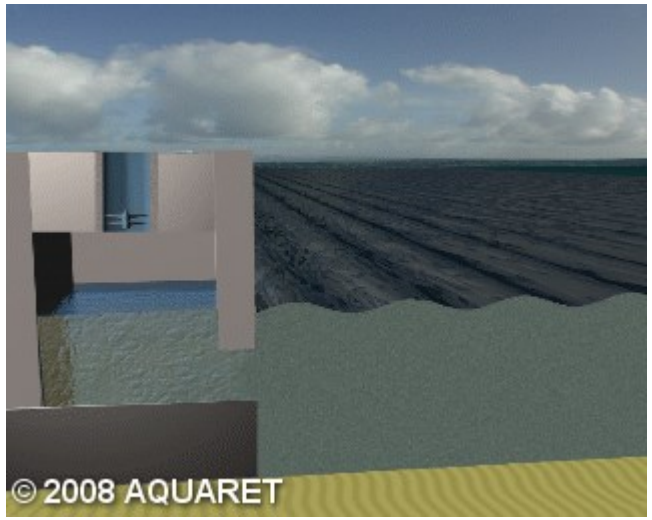


- WAVEROLLER is a buoyant, hinged flap (OWSC)
- Deployed in near shore areas (8-20 m water depth)
- A single WaveRoller unit (one panel and Power Take Off system combination) is rated at between 350kW and 1000kW
- Capacity factor between 25% and 50%

Source: https://aw-energy.com

Working principle

Oscillating Water Column



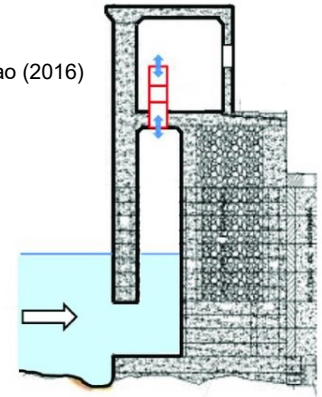
An oscillating water column (OWC) consists of a semi-submerged and hollow structure with an underwater opening that allows water to enter and leave the device.
The structure encloses an air column on top of a water column. Water is forced into a chamber as soon as waves move towards the device and the trapped air, compressed and decompressed, drives the air turbine. So OWCs use the different wave-induced water level to force air to flow through an air turbine to extract energy

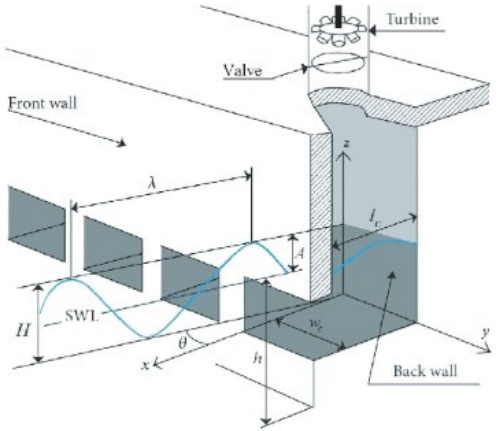
Source: EMEC website

Example

Oscillating Water Column

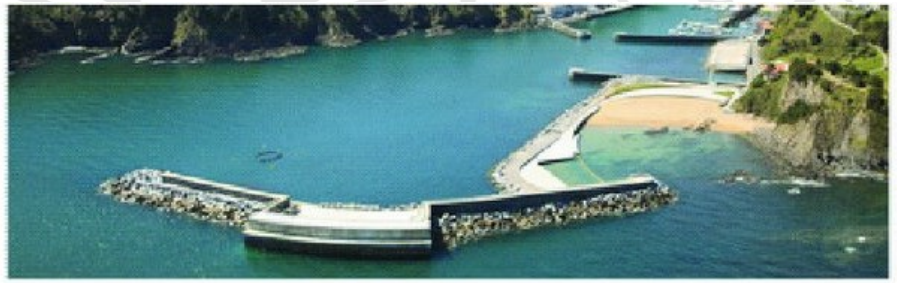
Source:
A. Falcao (2016)





Source: Fares M'zoughi (2019)

- NEREIDA power plant in Mutriku
- 16 OWC integrated in the breakwater
- Total installed capacity: 296 kW
- Each OWC has a Wells turbine
- Each Wells turbine drives an 18.5 kW Doubly Fed Induction Generator (DFIG)



Source: Fares M'zoughi (2019)

Working principle

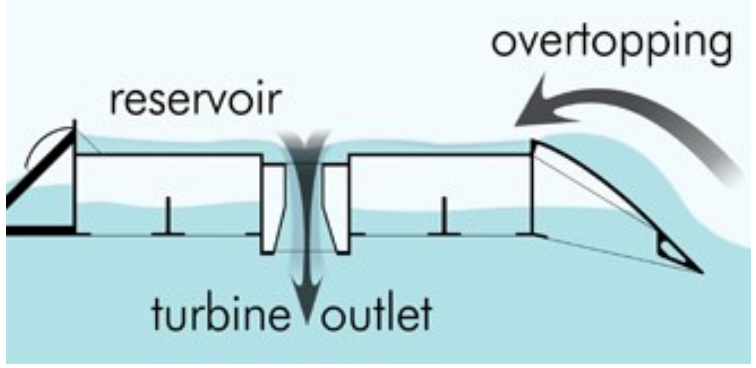
Overtopping device

An overtopping device is a partially submerged terminator with a reservoir above the sea level for capturing sea waves. A ramp allows the incident waves to pass over the structure and then to return to the ocean falling through low-head water turbines to generate electricity

Source: EMEC website

Working principle

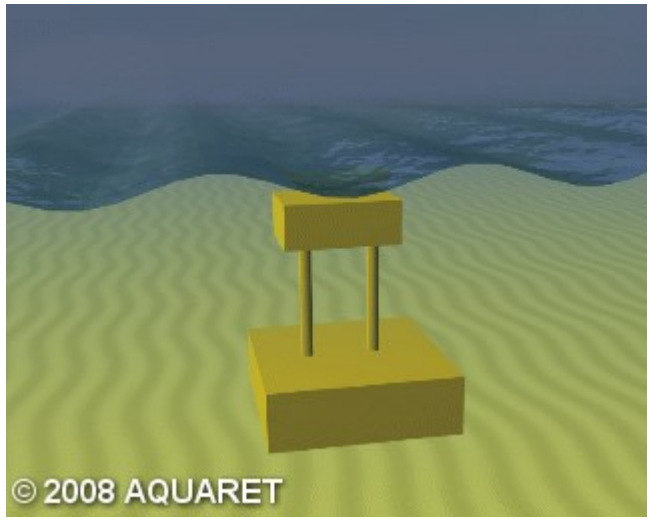
Overtopping device



- WAVEDRAGON overtopping device
- Floating, slack moored with curved ramp and wave deflector
- Reservoir above the sea level
- Kaplan turbines + PM generators
- Total width and length: 390 m * 220 m (for a 4MW device)
- Tested in small scale (20 kW) between 2003-2005 and 2006-2011

Working principle

Submerged pressure differential

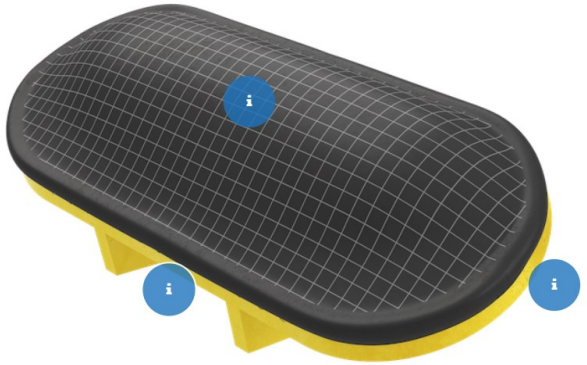


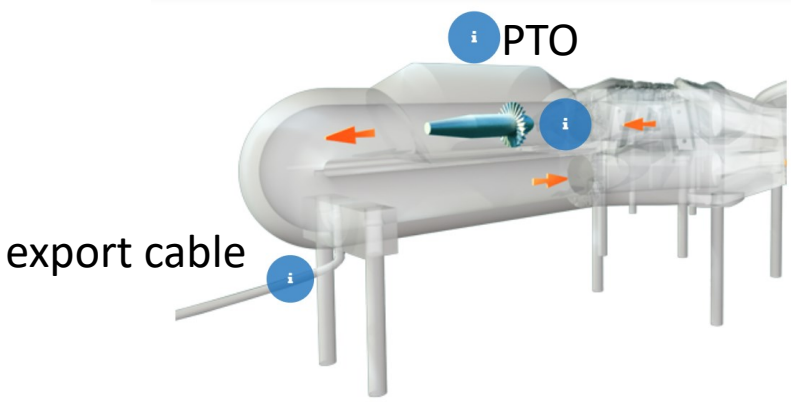
A submerged pressure differential device exploits the sea level rise and fall above the device, due to sea waves, which induces a pressure differential in the device. The alternating pressure pumps fluid through a system to generate electricity. It's typically installed near shore.

Source: EMEC website

Working principle

Submerged pressure diff.





- BOMBORA mWave
- Concave cells covered by air-inflated rubber membranes
- High speed unidirectional turbine + PM generators
- Full scale (1.25 MW) demo tested in 2020
- Modular for scalability and coupling with other renewables

Wave energy conversion chain

Waves

Primary en. conversion: from waves to pressurized air, water or hydraulic oil

Secondary en. conversion: from the fluid to a turbine or motor converting it into mechanical energy

Tertiary en. conversion: from mechanical into electrical by electric generator

Electricity

Can be merged for «direct-drive» solutions

Wave energy conversion chain

Waves

First conversion stage:
from waves to mechanical energy (Direct-drive solution)

Second conversion stage:
from mechanical into electrical by electric generator

Electricity

Power Take-Off systems for Wave Energy Converters

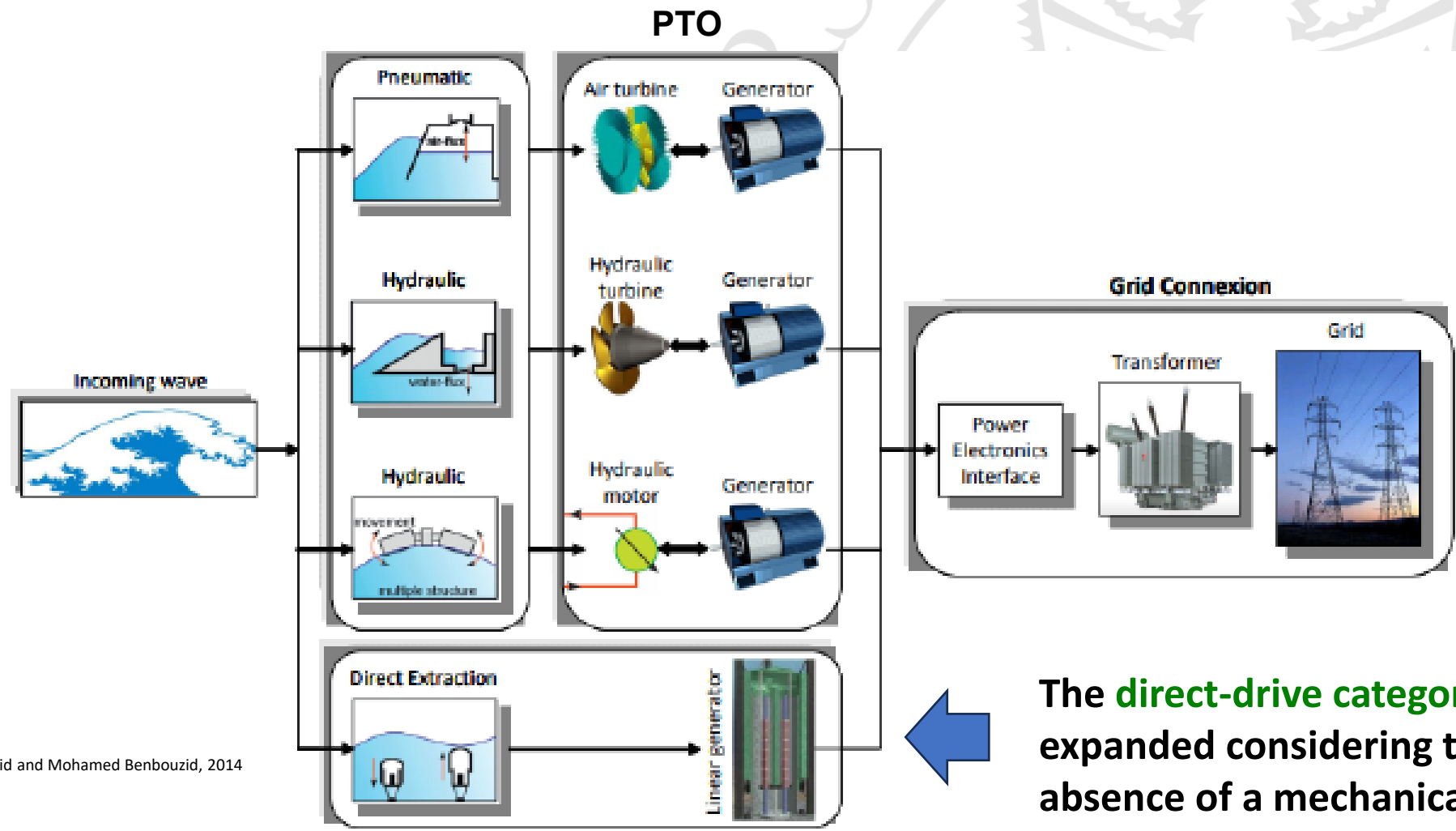
The Power Take-Off (PTO) system of a wave energy converter is the mechanism with which the absorbed energy by the primary converter is transformed into useable electricity

High PTO concept diversification and frequent need of tailor-made solutions characterize the wave energy industry

"The limited amount of electricity generated by wave energy converters suggests that designs still need to be optimized; and that conversion technologies, in particular reliable Power Take Offs (PTO) need still to be validated"

Magagna, D., Ocean Energy Technology Development Report 2018, EUR 29907 EN, European Commission, Luxembourg, 2019, ISBN 978-92-76-12428-3, doi:10.2760/158132, JRC118296

Power Take-Off systems for Wave Energy Converters

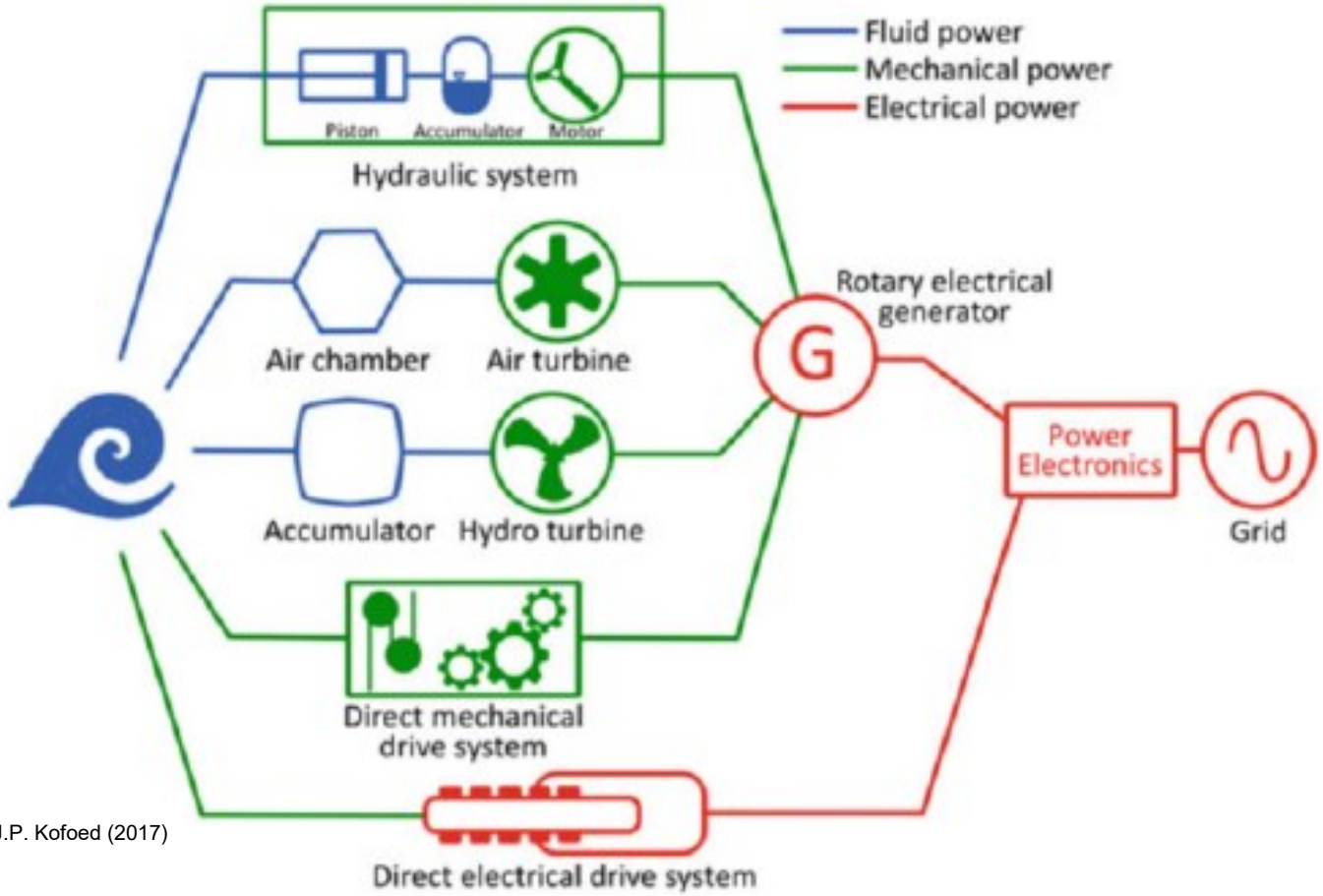


Source:: Titah-Benbouzid and Mohamed Benbouzid, 2014

The direct-drive category can be further expanded considering the presence/ absence of a mechanical transmission

Power Take-Off systems for Wave Energy Converters

PTO

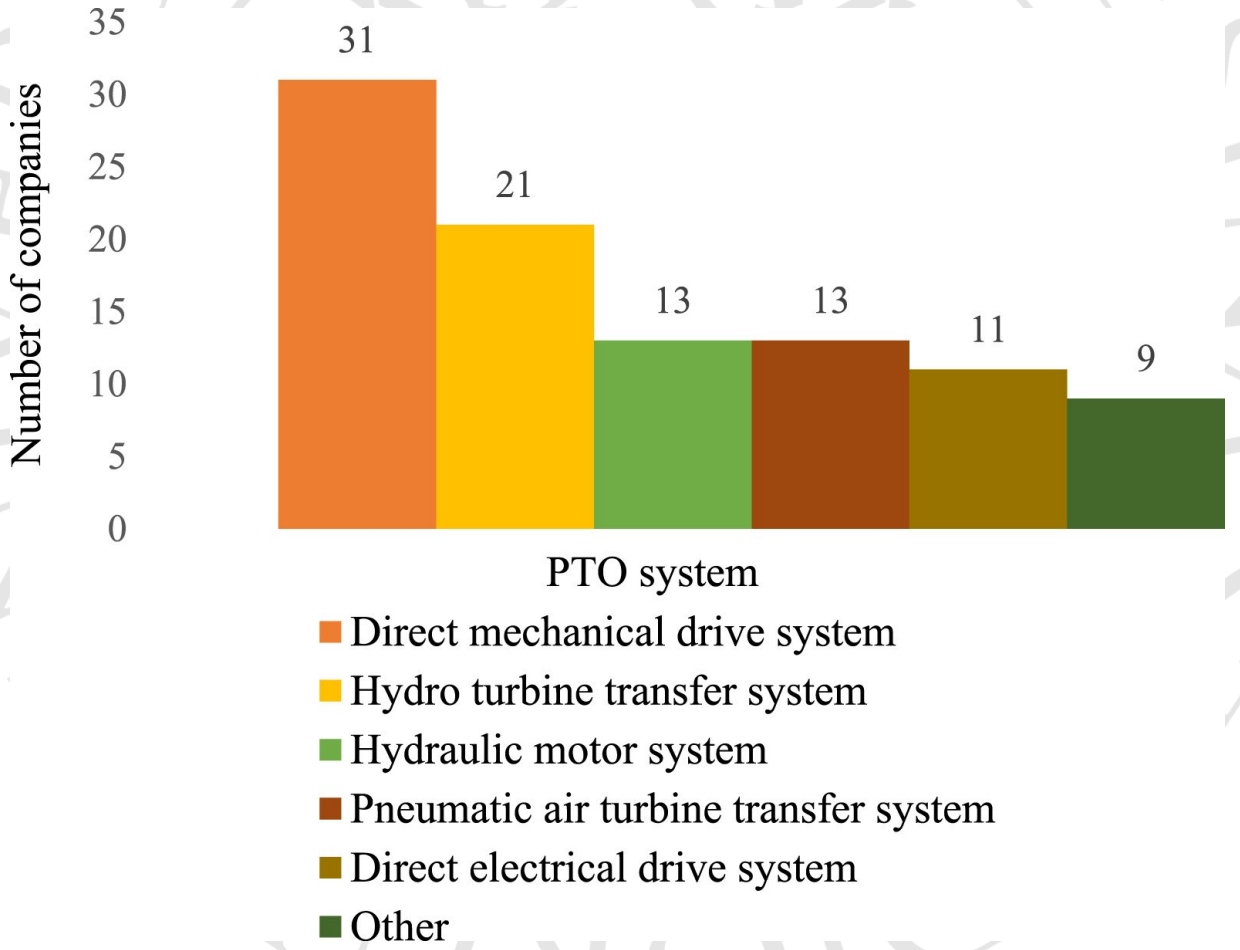


Source: A Pecher, J.P. Kofoed (2017)

Market share

WEC developers based on PTO system

The largest number of WEC developers are from Europe (63%) and North America (25%)



Source: Ahamed et al. (2020)

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Dipartimento di Ingegneria Industriale

Control of Wave Energy Converters

Basis of wave energy capture mechanism

Wave energy absorption is based on an apparent paradox:

"To absorb a wave means to generate a wave"

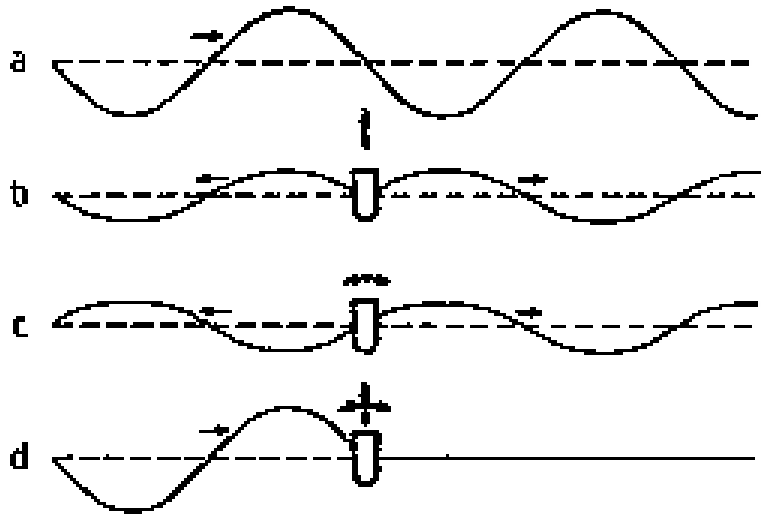
or in other words:

"To destroy a wave is to create a wave"

Control of wave energy converters

Wave energy exploitation is based on a destructive interference between sea waves and buoy oscillation

Active control of the buoy movement is needed to maximize power extraction from the sea

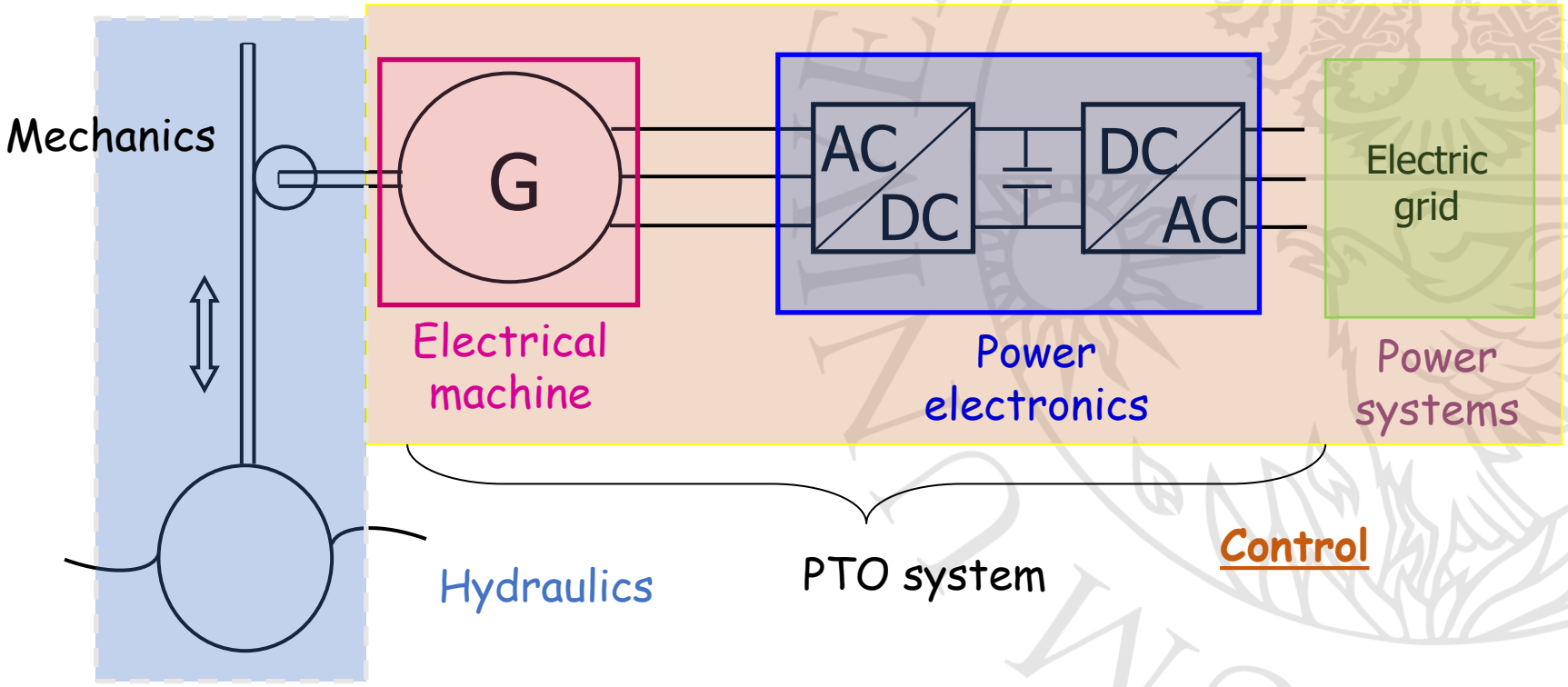


Source: Falnes (2000)

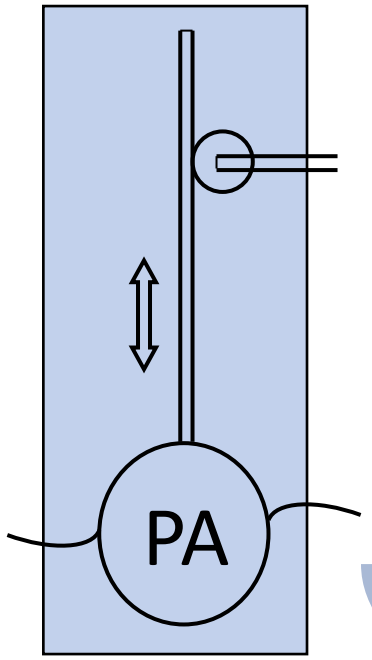
The first goal of WEC control is to maximize such extraction

Multidisciplinary approach to wave energy

Reference system for control discussion



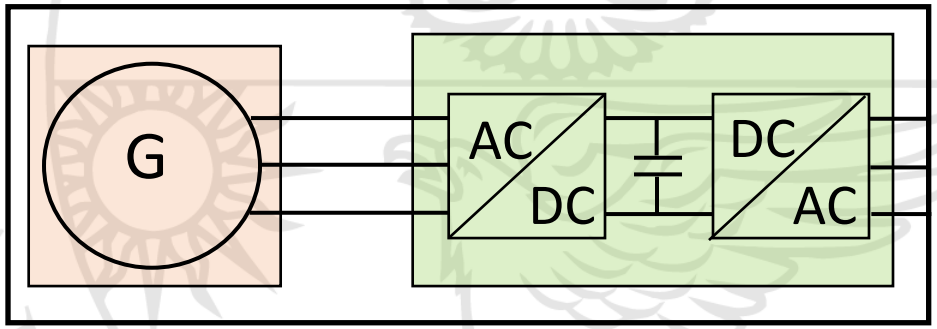
Control of wave energy converters



WEC control goal: Set F_L

WEC control is the bridge between the hydrodynamic domain and the electrical domain

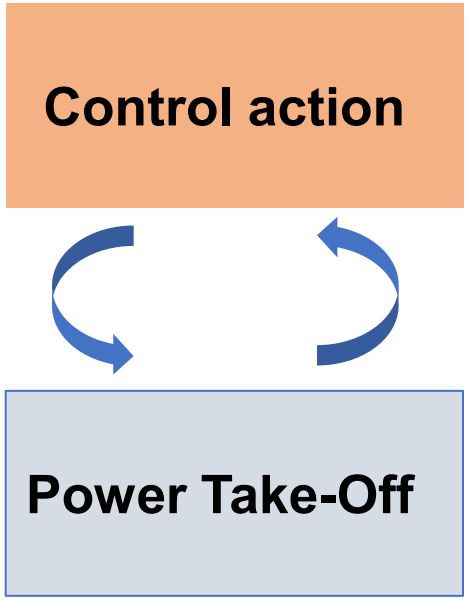
POWER TAKE-OFF



Interaction of subsystems through control is the basis of power conversion, delivery and conditioning

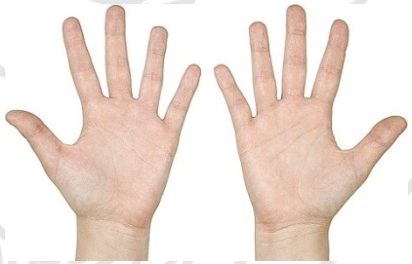
Control of wave energy converters

The PTO is the component that actuates of the control action



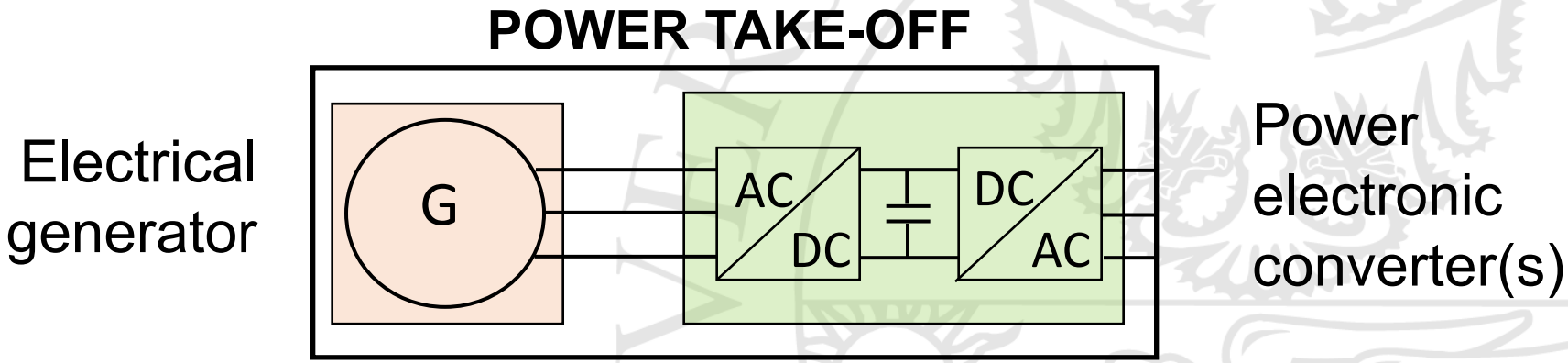
How we want the system to behave and what reference signals we consequently need to generate

How we practically apply the (control) reference signals in the real system



There is a strong, mutual interaction between control strategies and the Power Take-Off system

The Power Take-Off (PTO) system



To transform the mechanical energy extracted from the buoy into electrical energy

power conversion **->** **Electrical machine**

Control and inject electrical power into the local power system respecting the conditions imposed by utilities

power conditioning **->** **Power electronics interface**

Electrical machine selection

Permanent magnet linear generator

Asynchronous generator

Typical requirements:
- low speed
- high torque/force

Electri

"+/0/-" is favorable/neutral/less advantageous.

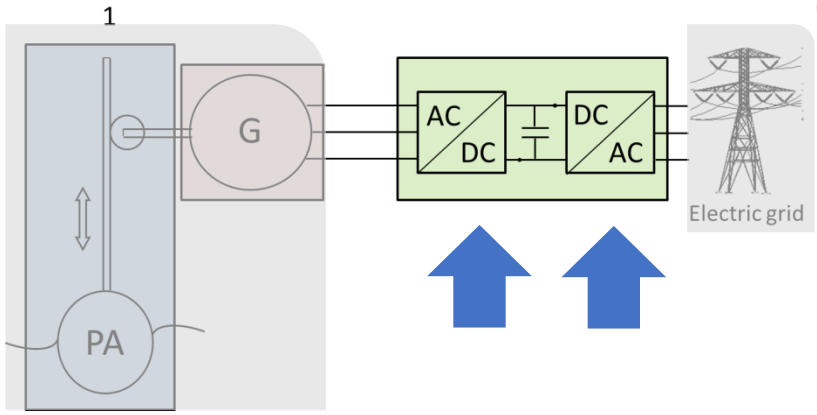
Solution	kg	η	Robust-ness	Conver-ter size	Cost
Induction	+	0,90	+	0	+
Linear PM	-	0,93	-	0	-
Rotating PM	-	0,95	0	+	0

Source: H. Lendenmann *et al*

Control of wave energy converters

Control of wave energy converters (WECs) has a twofold function:

- **"WEC side" control**
- **"Grid side" control**



Improve the power absorption from the waves

Control the quality of the power delivered to the electric grid

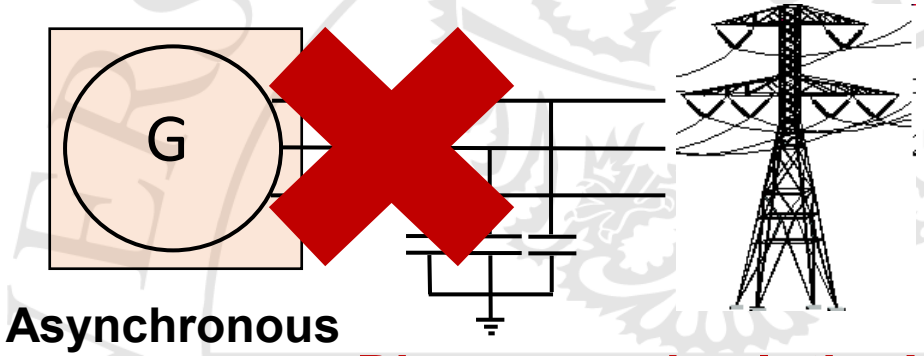
Power electronics is crucial in both of them

- **The power electronic interface is used to properly control the electrical generator**
- **It is also used to regulate the power injection into the local power system**

Power electronics selection

Direct connection to the grid

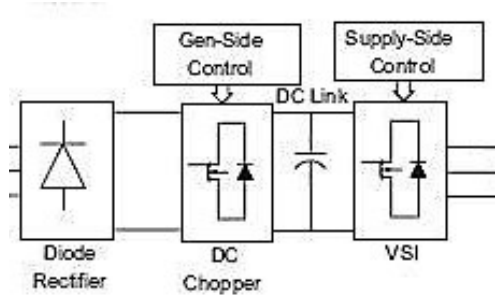
No power electronics interface

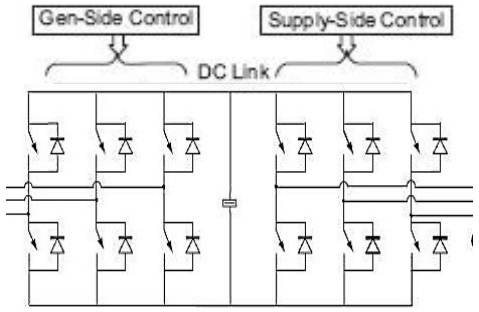


Asynchronous machine

Discouraged solution!

Similar to Type 1 & Type 2 wind turbines





Power electronics

Diode rectifier + DC/DC converter + inverter

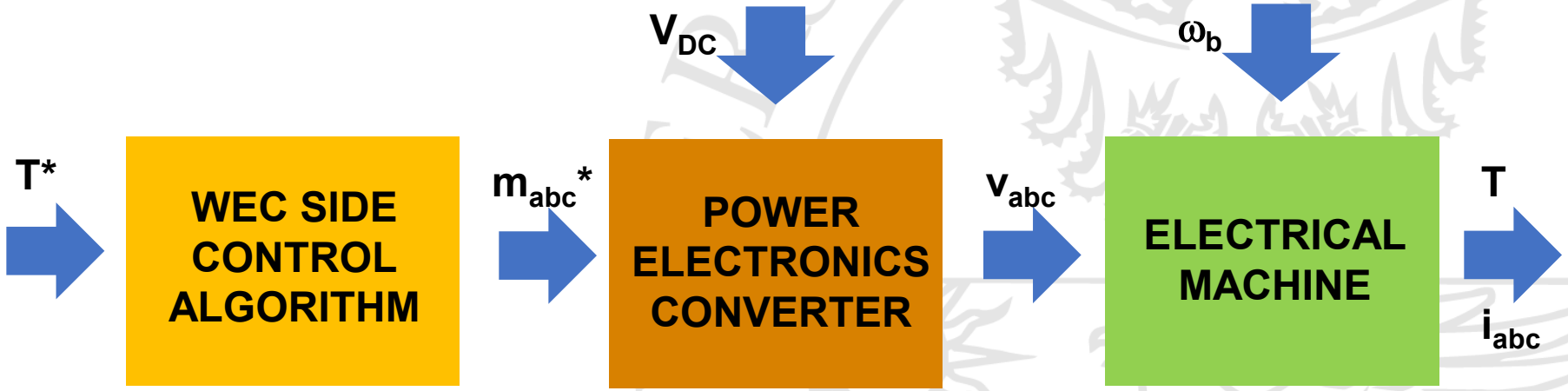
Controlled rectifier + inverter = Back-to-back converter

Selection of one or the other topology affects the degree of controllability of the system

Similar to Type 4 wind turbines

Low level control of a WEC generator

The control force F_L is turned into a torque signal, T,
In the case of rotating machines



Similar to low level control of a wind turbine

T*, T = Torque reference, actual torque of the electrical machine

m_{abc}*= Switching signals for the power electronics converter (v_{abc}*=V_{DC}*m_{abc}*)

V_{DC}= Voltage of the DC link

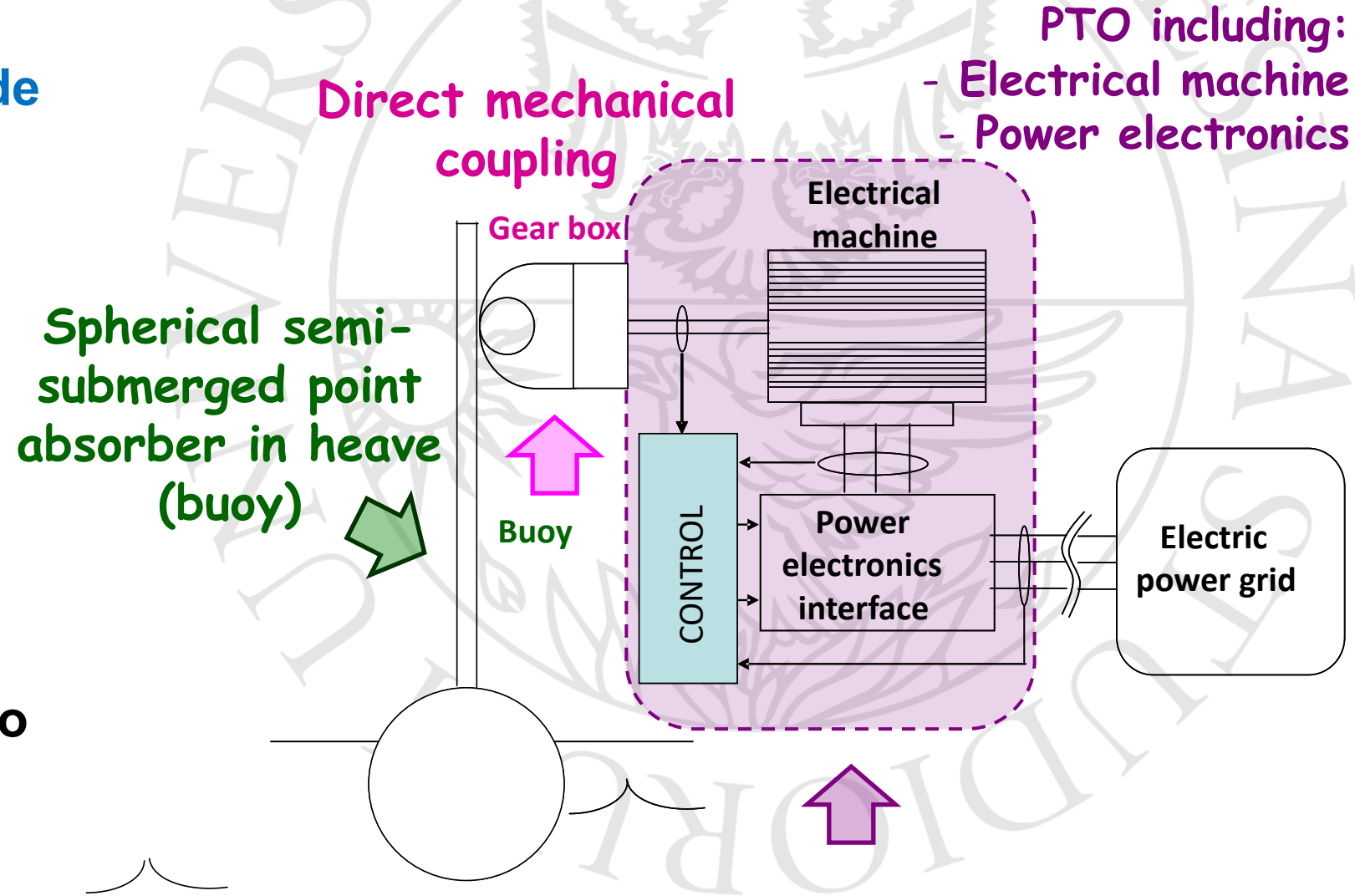
V_{abc}= Voltages at the terminals of the electrical machine

ω_b = Electric rotating speed of the electrical machine

i_{abc}= Currents at the terminals of the electrical machine

High level control of a WEC generator

- A key point is how to provide the torque (or equivalently, force) reference to the low-level controller to optimize the power extraction from the ocean waves
- Such task is accomplished by the high-level controller, whose operation can be better explained with reference to a simple (point absorber) system, subject to regular (sinusoidal) waves

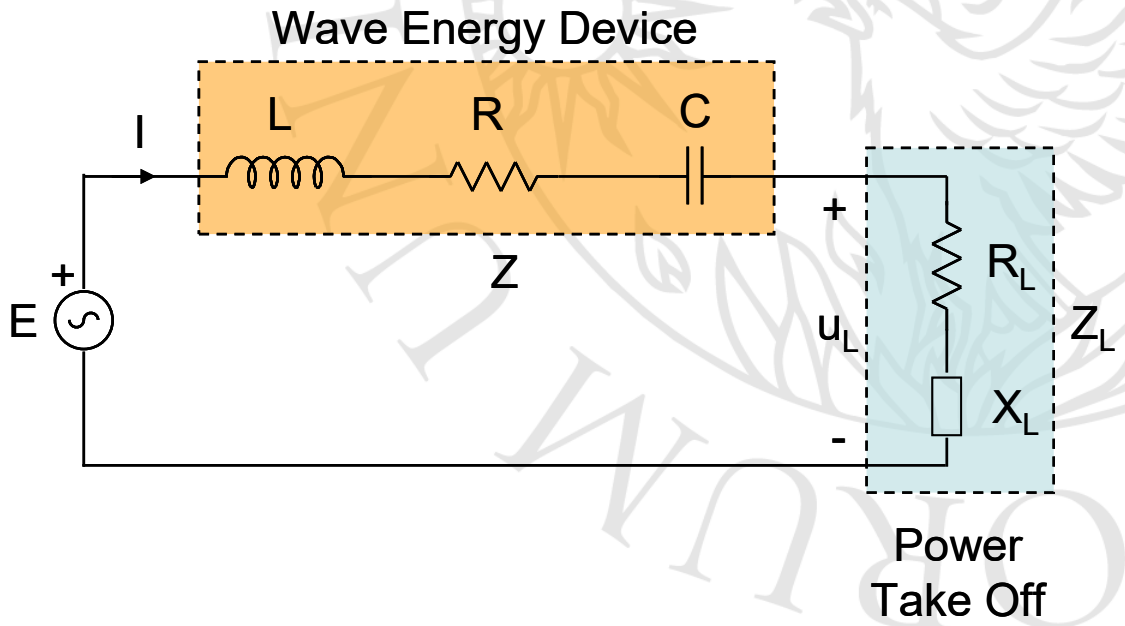


Modeling of a point absorber WEC – frequency domain

Assumption of sinusoidal (i.e. regular) waves, of angular freq. ω

Equation describing the buoy hydrodynamic model (mass-spring-damper system):

$$-\omega^2 (M + a(\omega))\hat{X} + j\omega B(\omega)\hat{X} + K\hat{X} = \hat{F}_E + \hat{F}_L$$



F_E = Excitation force
F_L = Control Force
M = Mass of the device
a = "Added mass"
B = Mechanical damping
K= Hydrostatic stiffness
X= position of the buoy

The «hat» sign indicates phasors

Modeling of a point absorber WEC – time domain

Cummins equation to deal with irregular waves:

x(t) is the buoy position

$$(M + a_\infty)\ddot{x}(t) + \int_{-\infty}^{t} K_{rad}(t-\tau)\dot{x}(\tau)d\tau + Kx(t) = F_E(t) + F_L(t)$$

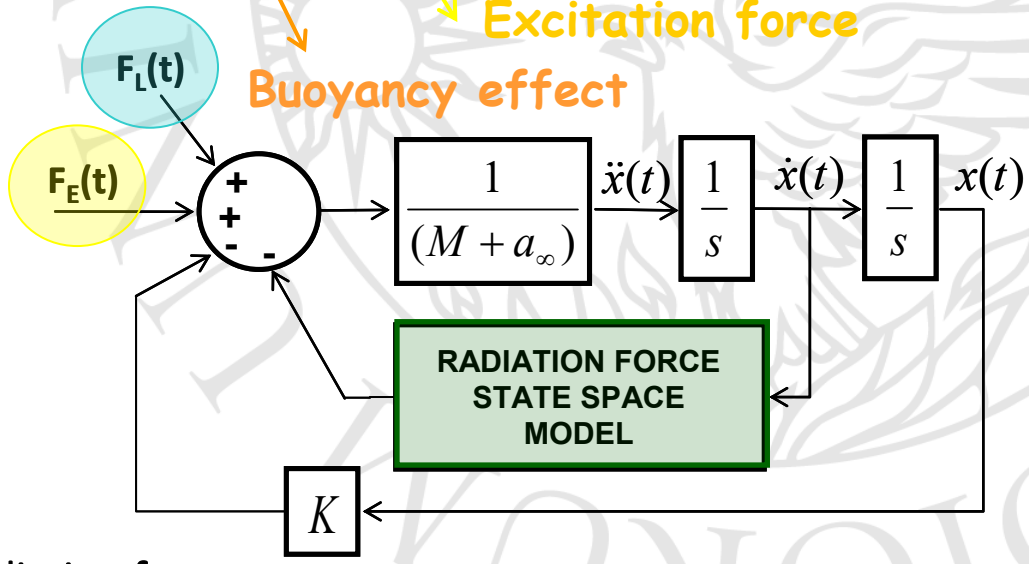
PTO control force

Excitation force

Buoyancy effect

Mass of the system + added mass for: ω->∞

Radiation force: convolution integral



Availability of hydrodynamic coefficients

↓

[...]

↓

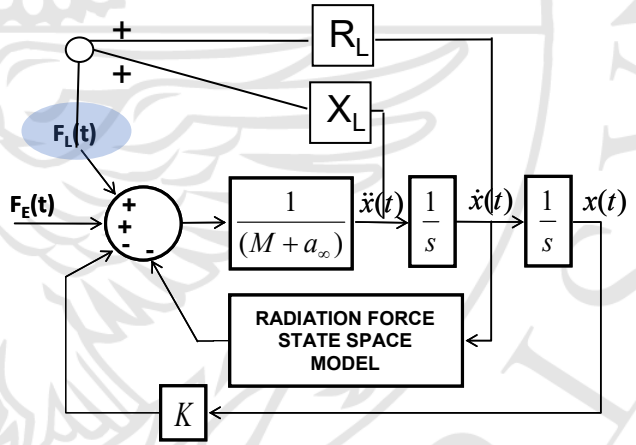
State space representation of the radiation force

High level control of a WEC generator

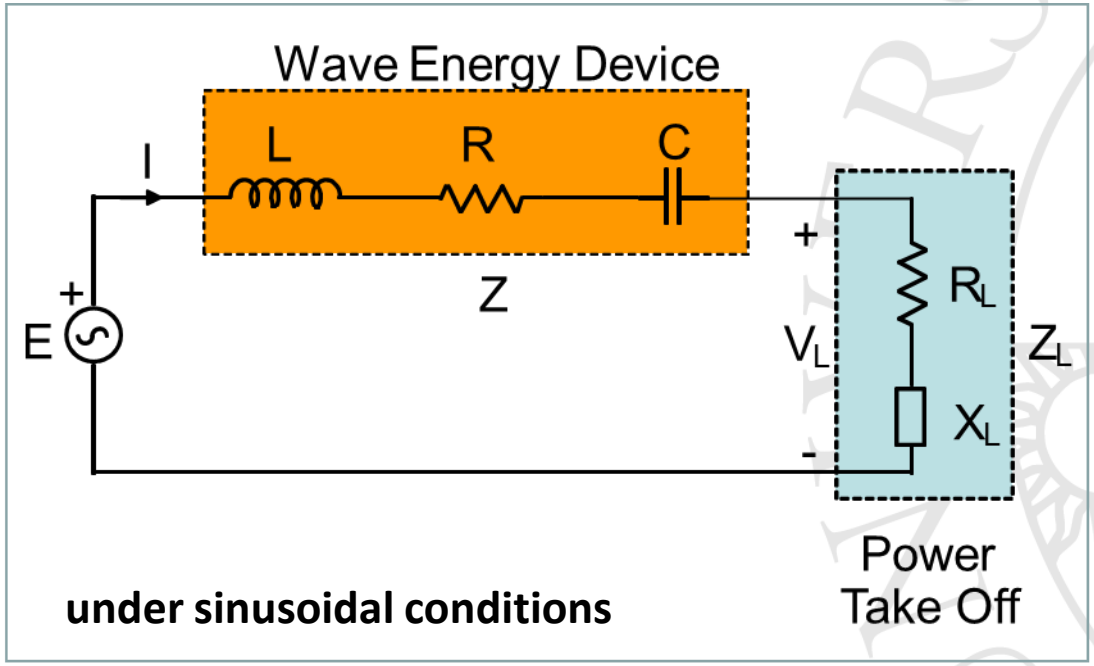
Most widespread control techniques are the linear ones, whose effect is well-established under sinusoidal conditions

Passive loading: force applied by to Power Take Off (PTO) is proportional to the buoy velocity

Optimum (complex-conjugate/reactive) control: force applied by the PTO has a component proportional to the buoy velocity and another to the buoy acceleration



High level control of a WEC generator



Mechanical-Electrical equivalence

Mechanical domain		Electrical domain	
Quantity	Symbol	Quantity	Symbol
Excitation force	F_E	Source voltage	e
Buoy velocity	u	Current	i
Buoy position	x	Charge	q
WEC total mass	$M+a$	Inductance	L
Spring constant	K	Capacitance^{-1}	C^{-1}
Total buoy damping	B	Resistance	R
PTO force	F_L	Load voltage	v_L
PTO damping	B_L	Load resistance	R_L
PTO spring constant/PTO added mass	K_L/ω *or* ωM_L	Load reactance	X_L

The control problem corresponds to the suitable tuning of "load" parameters: R_L and X_L

Optimum control: $R_L = R \qquad X_L = \omega L_L - \frac{1}{\omega C_L} = -(\omega L - \frac{1}{\omega C})$

$$F_L = -R_L\,\dot{x}(t) - L_L\,\ddot{x}(t) - \frac{1}{C_L}x(t)$$

Passive loading: $R_L = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2} \qquad X_L = 0$

$$F_L = -R_L\,\dot{x}(t)$$

High level control of a WEC generator

The choice of the high-level control strategy has implications on the equipment required, in particular:

- **Optimum control produces a bidirectional power flow, between the point absorber and the grid, hence it requires a reversible electrical machine and (current-) bidirectional power electronic converters**
- **Passive loading produces a unidirectional power flow, so an electrical generator with unidirectional power electronics would be potentially sufficient, but it is suboptimal in terms of wave energy harvesting**

High level control of a WEC generator

Under sinusoidal conditions (i.e., regular waves) it is possible to exactly define control parameters for the maximization of the average extracted power…

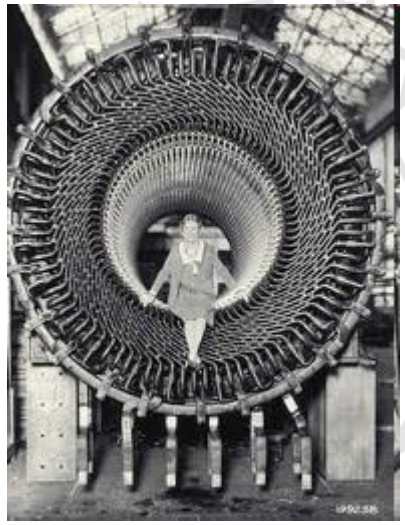
…Under irregular waves this is not trivial…

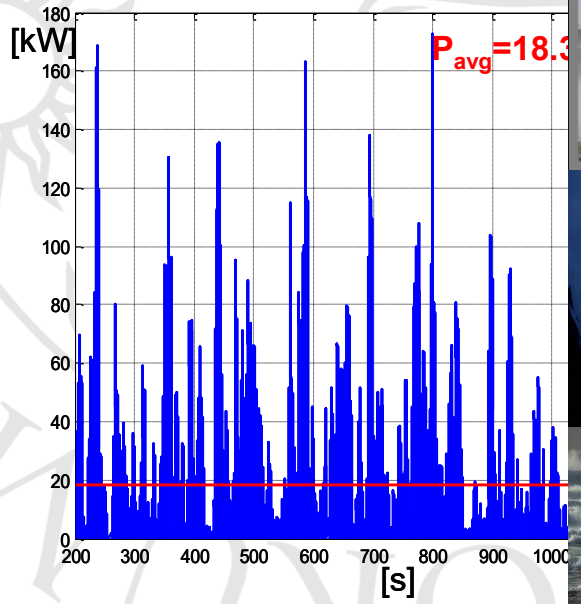
…And in real seas this is even more difficult!

High level control of a WEC generator

Main problems for control implementation:

- **Very intermittent operation**
- **High peak to average extracted power**
- **Oversized PTO required**





Conclusions

- **Wave energy has enormous potential that is still mostly unexploited**
- **High concept diversification (primary converter, PTO, etc.) has hampered the development of the wave energy industry**
- **The PTO system is still recognized as a critical component in the power conversion chain**
- **Control is critical to achieve high energy harvesting in compliance with equipment physical limits**

Lecture 13: Reference material

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