Wave Energy: A Brief Introduction

From: waves4power.com

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GOTHENBURG, 1 OCTOBER 2020

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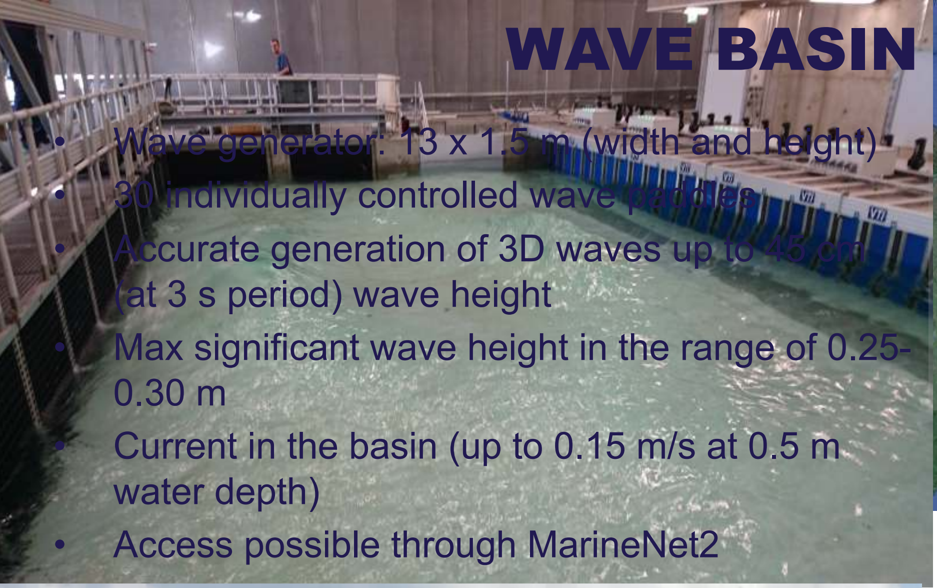
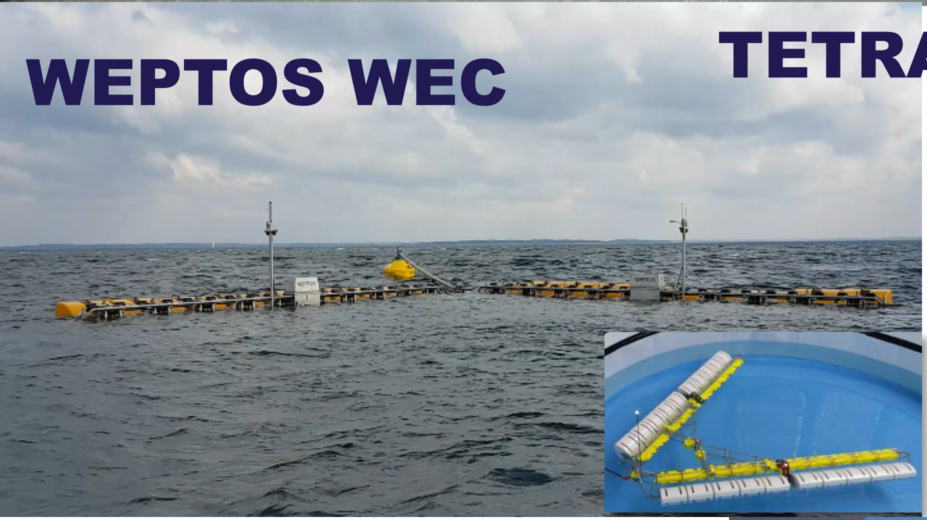
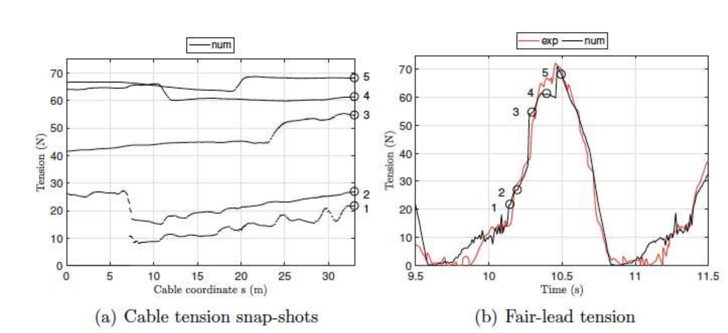
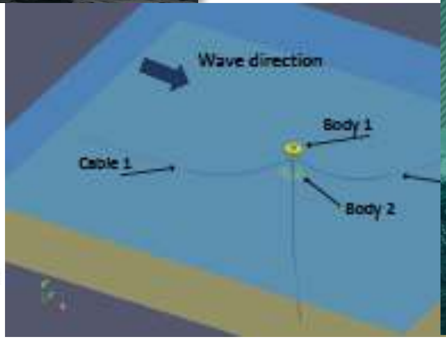


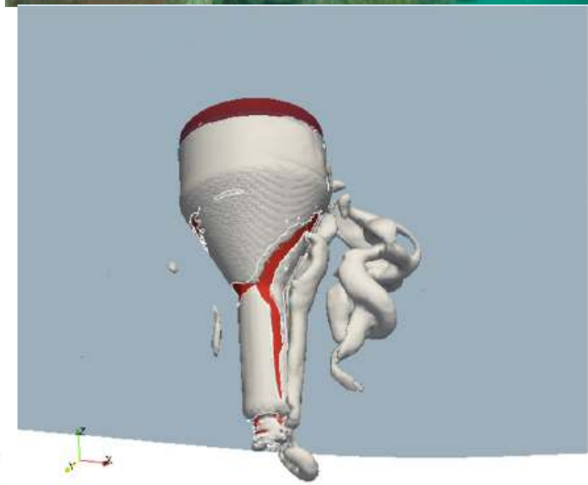




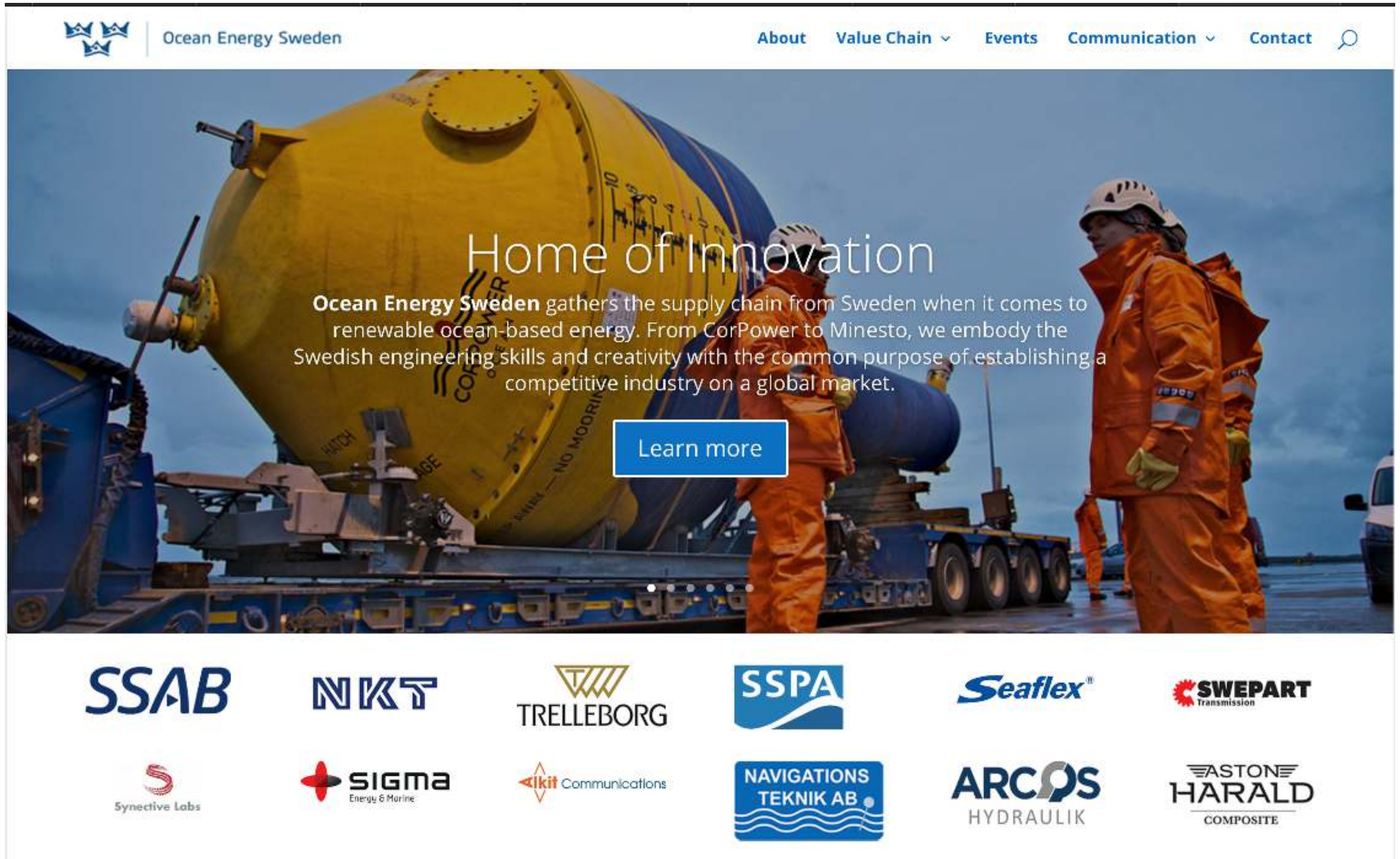
(a) Cable tension snap-shots

(b) Fair-lead tension





Ocean Energy Sweden



OCEAN HARVESTING

Ocean Harvesting Technologies AB develops the novel InfinityWEC, using a flywheel based kinetic energy recovery system to provide advanced force control and constant power output.

Learn more

WAVES4POWER

Waves4Power is a Swedish company that develops and sells wave energy systems. Waves4Power's concept is to focus on profitable electricity production with a system that is survivable and easily serviceable.

Learn more

MINESTO

Develops a new concept for tidal power plants called Deep Green. The power plant is applicable in areas where no other known technology can operate cost effectively due to its unique ability to operate in low velocities.

Learn more

SEABASED

Seabased wave energy plants are complete systems, which has been verified through the grid connection in 2015 of the Sotenäs Wave Power Plant and subsequent generation of power to the Nordic Electricity Grid.

Learn more

CORPOWER OCEAN

CorPower Ocean AB has developed a compact high-efficiency Wave Energy Converter. Thanks to patented control technology, the buoys operate in resonance over a wide range of waves frequencies.

Learn more

jabeEnergy

Develops jabePower Rig which is based on a hydrokinetic Run on River rig-technic (RoR). It is a vertical and mobile turbine, requires no fixed construction or dam facilities, focused on OFF-GRID or totally "unplugged" areas.

Learn more

NoviOcean

Is developing the world's largest and strongest wave power unit. The estimated output is up to 10MW per unit, as well as being very light in relation to output. It has an unusual simple and strong PTO, which also facilitates latching.

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BLEKINGE TEKNISKA HÖGSKOLA BTH
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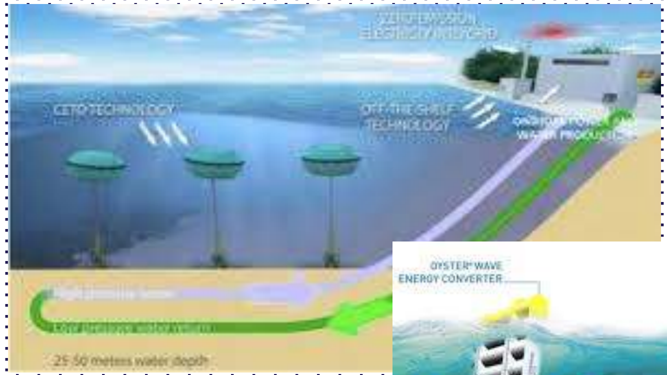
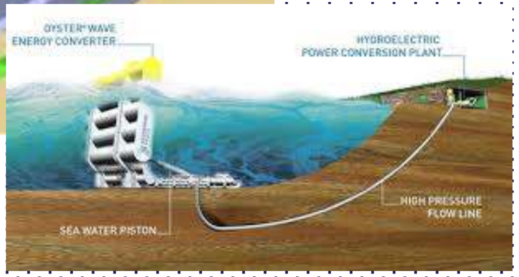
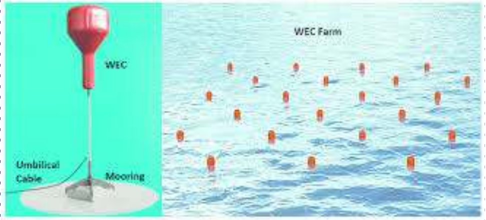
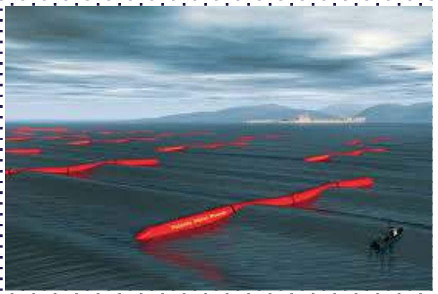
OUTLINE

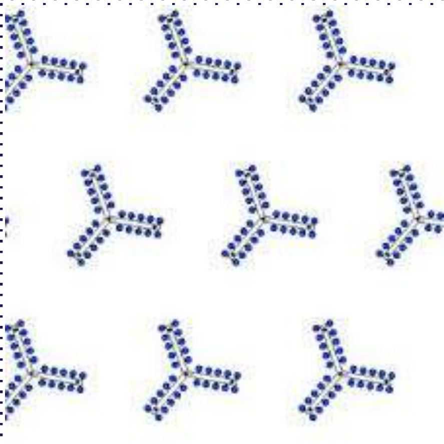
- Overview of wave energy – principles
- The resource – background on waves
- BREAK
- Buoy motion
- Power and control











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MARINE ENERGY

Marine energy is diverse (OES definition)

Tidal/ocean currents

GE Oceande 1.4MW
From: www.gerenewableenergy.com

Wave energy

Wave Dragon sea trial at Nissum Breding
Photo: Wave Dragon AS

Salinity power

Statkraft Osmotic Power Station (Tofte, Oslo Fjord, Norway)
(From: OES - An international vision for ocean energy)

Tidal range

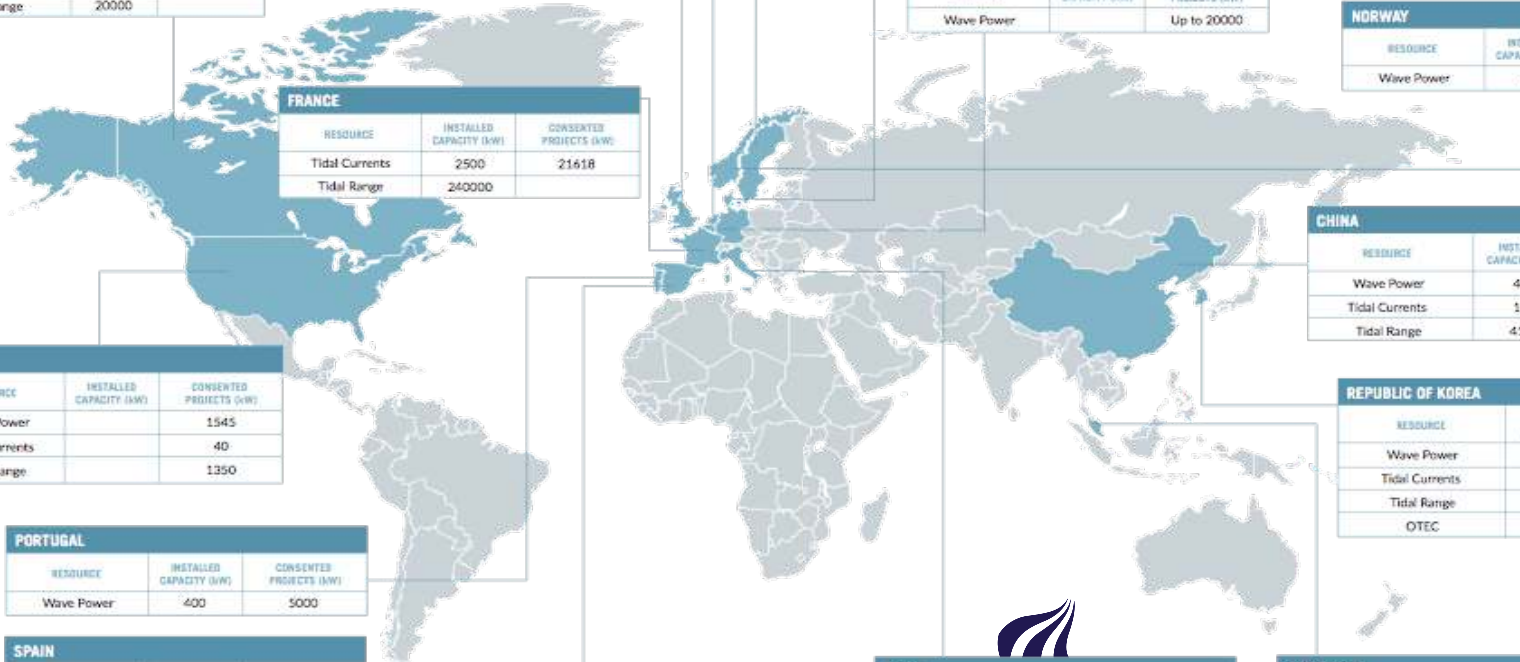
Sihwa Lake Tidal Power Station, Korea
(From: OES - An international vision for ocean energy)

Ocean thermal energy

Onshore OTEC in Hawaii
From: www.makai.com

EU goals of 2050 : 100 GW marine energy in EU
Compare to 2015 wind: 161 GW in EU
Current status (2015) : 0.5 GW marine energy worldwide out of which 12 MW is not tidal range…

WORLDWIDE OCEAN POWER INSTALLED CAPACITY



NETHERLANDS

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Tidal Currents	1300	1600-2200
Salinity Gradient	50	100000

SWEDEN

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	200	10400-10600
Tidal Currents	8	

DENMARK

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		50

UK

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	960	40000
Tidal Currents	2100	96000

CANADA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	9	
Tidal Currents		20450
Tidal Range	20000	

BELGIUM

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		Up to 20000

NORWAY

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	200	

FRANCE

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Tidal Currents	2500	21618
Tidal Range	240000	

CHINA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	450	2760
Tidal Currents	170	4800
Tidal Range	4100	200

USA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		1545
River Currents		40
Tidal Range		1350

REPUBLIC OF KOREA

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	500	500
Tidal Currents	1000	1000
Tidal Range	254000	254000
OTEC	220	220

PORTUGAL

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	400	5000

SPAIN

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	296	

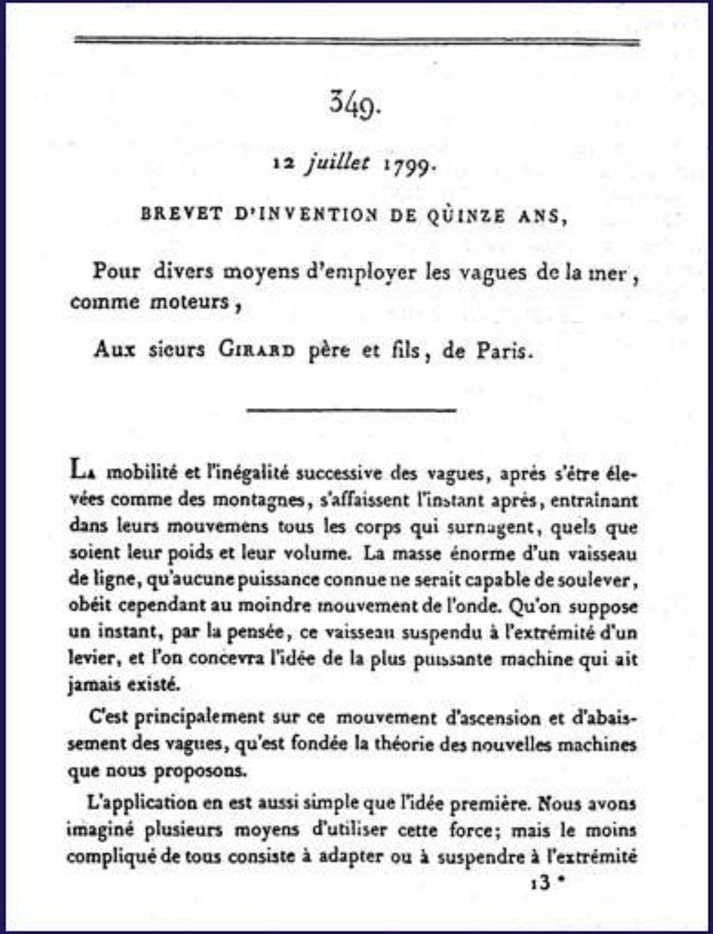
ITALY

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power		99

SINGAPORE

RESOURCE	INSTALLED CAPACITY (kW)	CONSENTED PROJECTS (kW)
Wave Power	16	
Tidal Currents		50
Tidal Range	5	

WAVE ENERGY IS AN OLD IDEA...



349.

12 *juillet* 1799.

BREVET D'INVENTION DE QÛINZE ANS,

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

Aux sieurs GIRARD père et fils, de Paris.

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

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

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

13 *

SALTERS DUCK

Wave power

S. H. Salter

Bionics Research Laboratory, University of Edinburgh, Edinburgh EH1 2QL, UK

Solar energy is one form of income on which we can afford to live. Here is another proposal: the use of power from the waves at sea.

THE amount of power in a wave train can be estimated by calculating the change of potential energy as the water in a wave above sea level falls into the trough in front of the wave (Fig. 1). If the sea water has a density ρ, and the width of the wave front is W, then the mass of water in the half sinusoud above sea

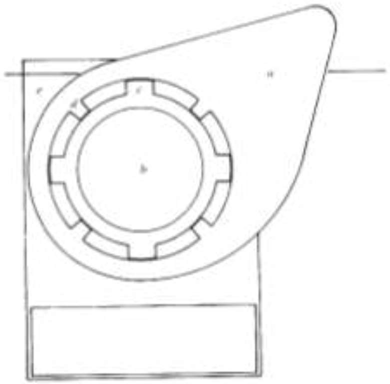
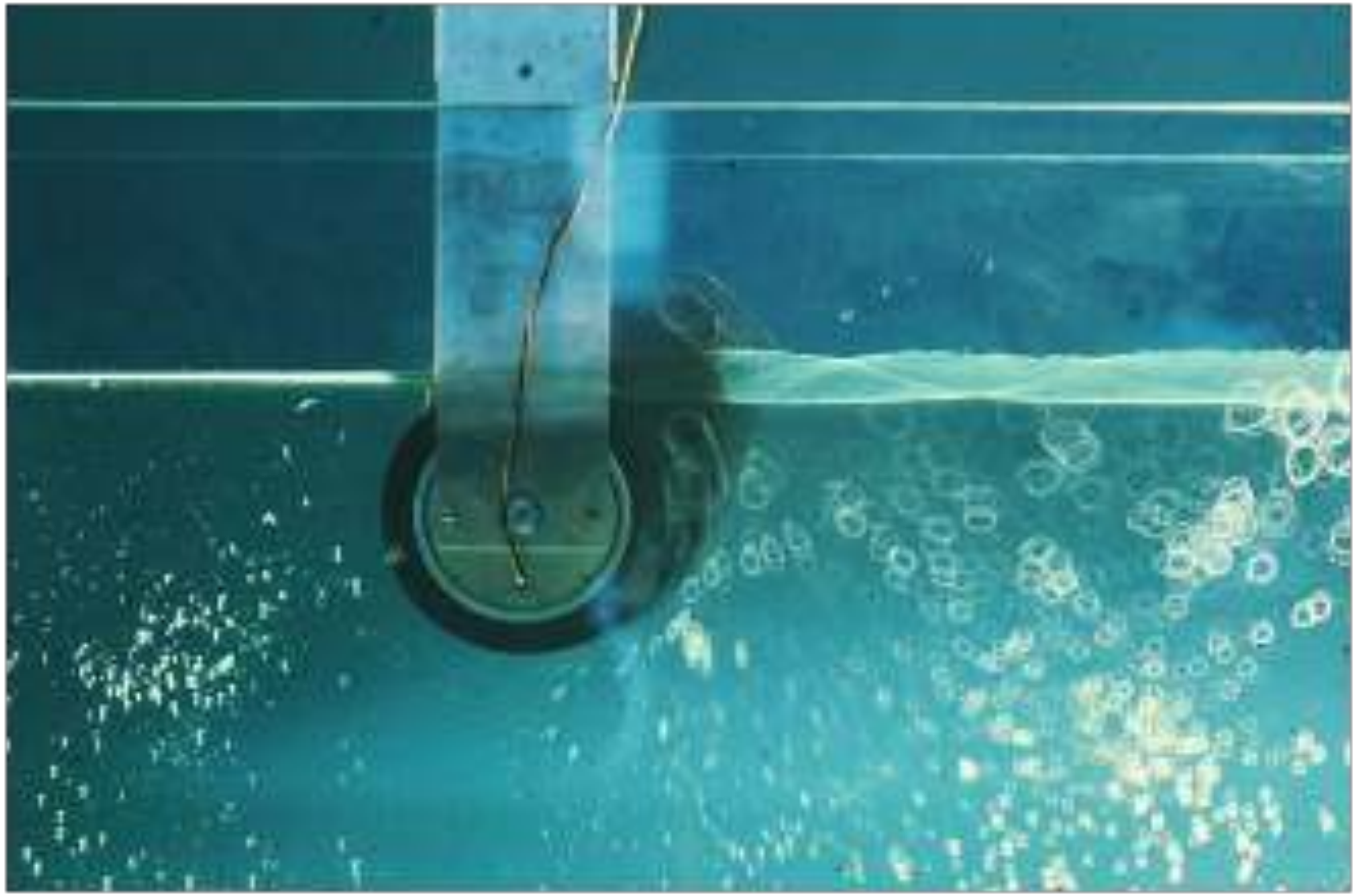


Fig. 5 A vertical section through vane and spline pump. *a*, vane; *b*, a hollow cylindrical member; *c*, paraxial ridges; *d*, inward facing ridges on the vane; *e*, vertical fin between this vane and the next. For the North Atlantic the diameter of the cylindrical portion will be between 10 and 20 m.



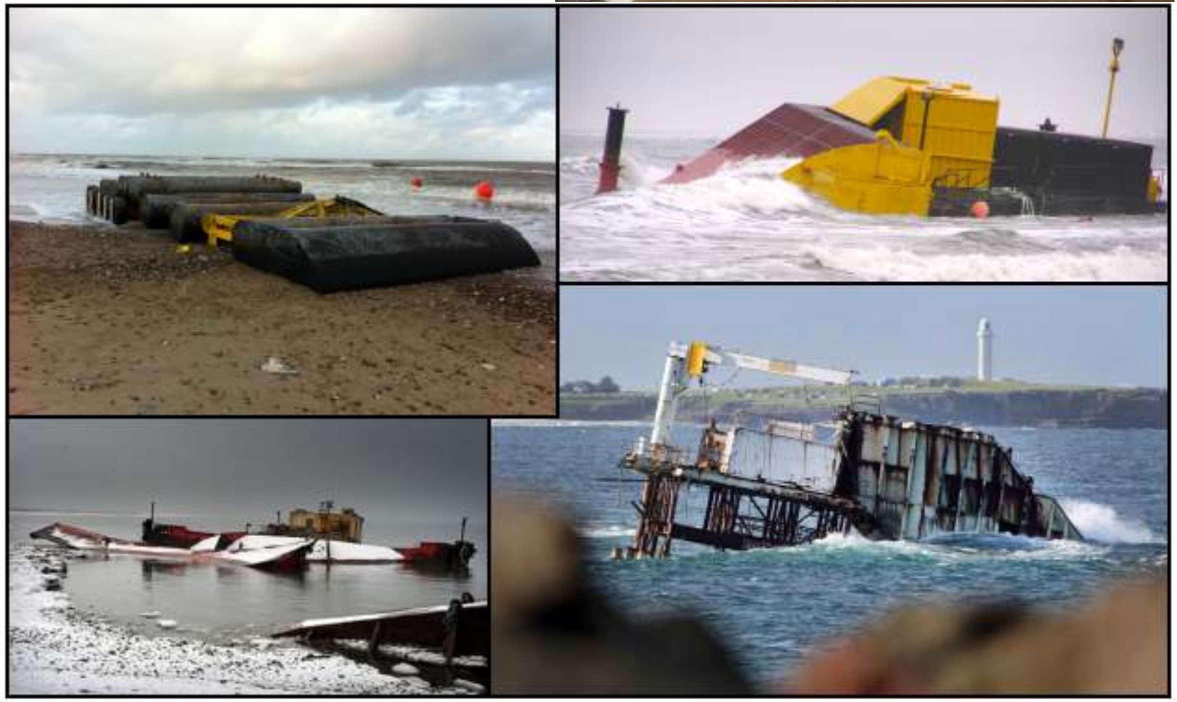
WHY NOT COMMERCIAL?

COSTLY

LCOE is high but a few tech companies are on the SET plan track

Energy source	LCoE [€/kWh]	Reference
Coal (Germany)	0.06 – 0.10	[4]
Onshore wind (Germany)	0.04 – 0.08	[4]
Offshore wind (Germany)	0.08 – 0.14	[4]
Solar photovoltaic (Germany)	0.04 – 0.12	[4]
Wave estimate (UK)	0.17	[5]

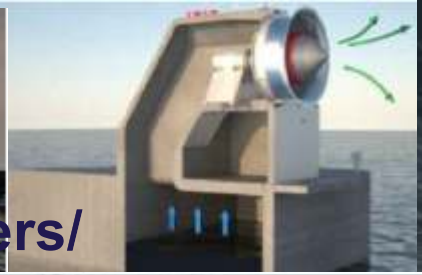
- **REPETED FAILURES**

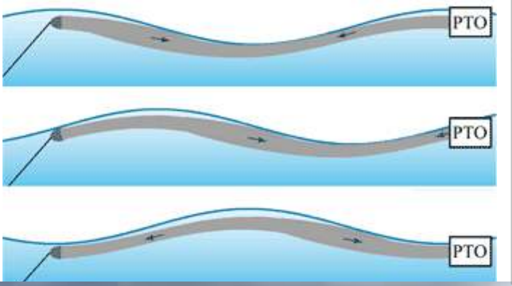


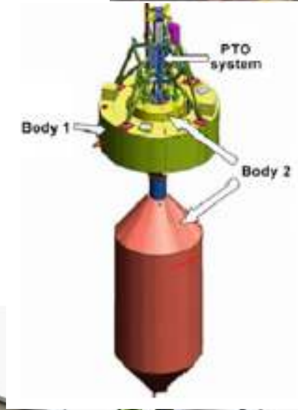
DISPERSED DESIGNS

Bjerg Thomsen 2017

Over 200 concepts world wide (EMEC)
http://www.emec.org.uk/marine-energy/wave-developers/
1000s of patents filed





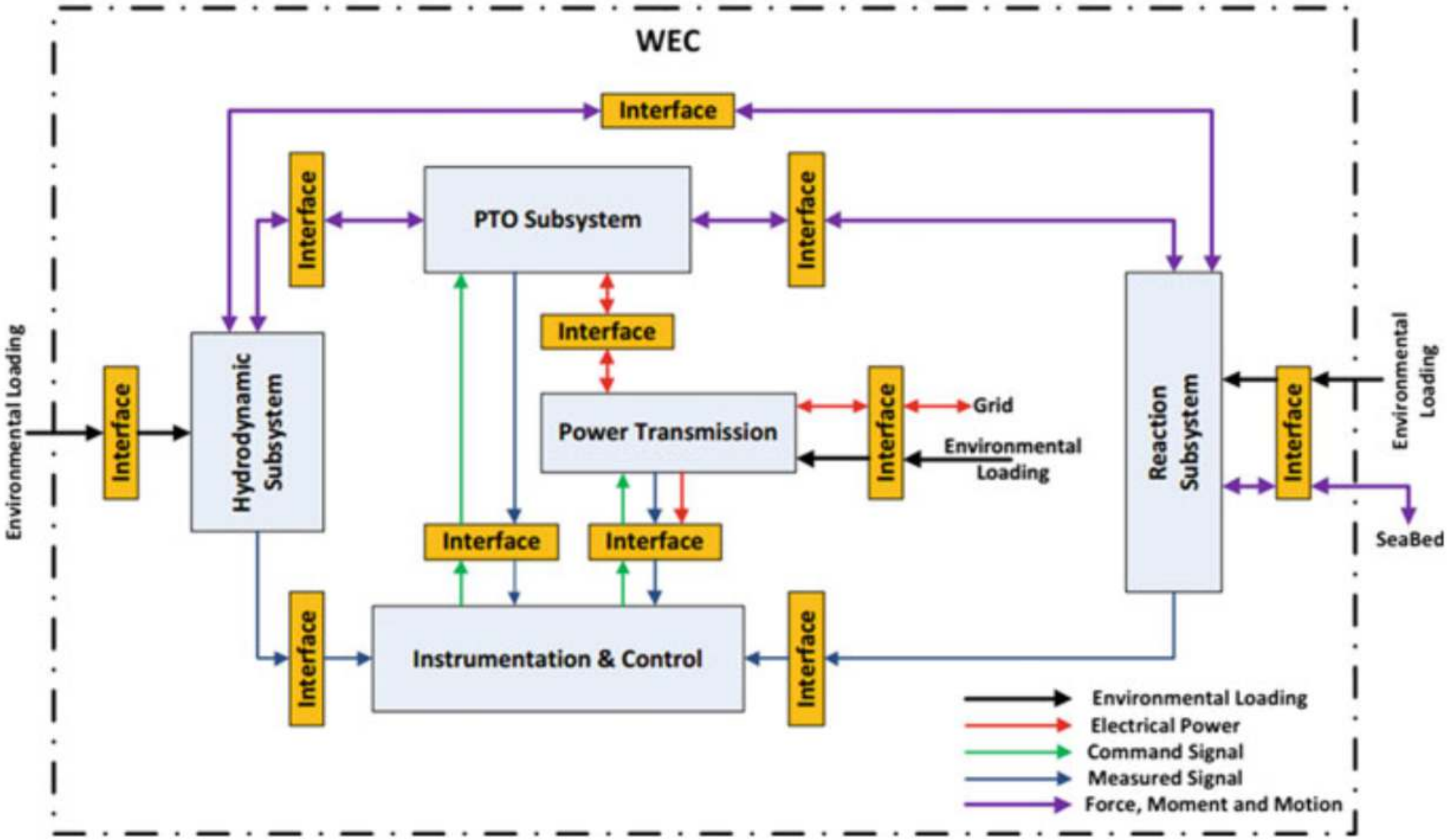




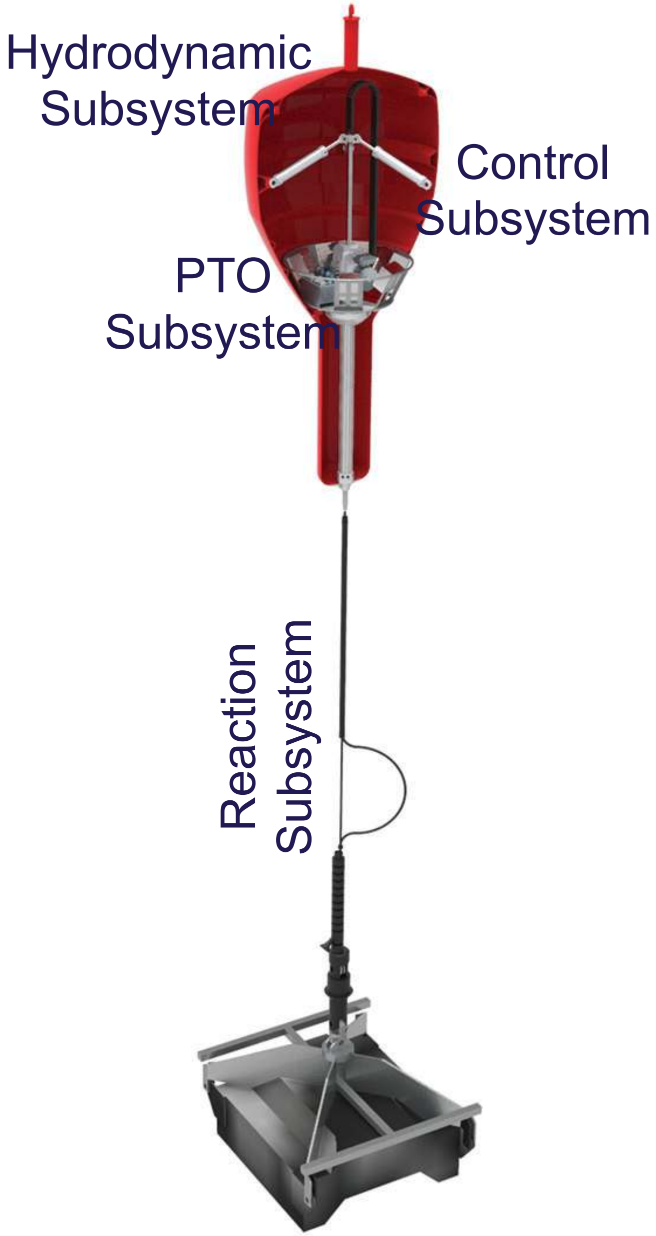




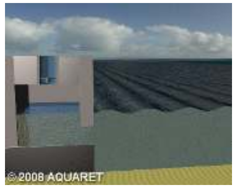

WEC SUBSYSTEMS



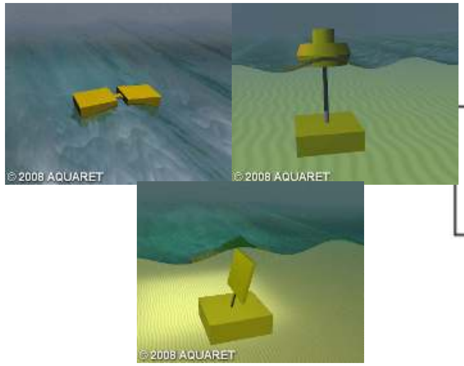
Perceher & Kofoed (2016)



WEC CATEGORIES



- **Oscillating water columns**
  - **Fixed structure**
    - **Isolated:** *Pico*
    - **In breakwater:** *Mutriku*
  - **Floating:** *Oceanlinx, Leancon*



- **Wave activated bodies**
  - **Floating**
    - **Essentially translation:** *Wavebob, OPTs PowerBuoy, SeaBased, Fred Olsen's Lifesaver*
    - **Essentially rotation:** *Pelamis, Crestwing, Dexa, Wavestar, FPP, Weptos*
  - **Submerged**
    - **Essentially translation (heave):** *Carnegies CETO*
    - **Rotation (bottom-hinged):** *WaveRoller, Oyster, RME,*

- **Overtopping**
  - **Fixed structure (without concentration):** *SSG*
  - **Floating structure (with concentration):** *Wave Dragon*

Waves4Power

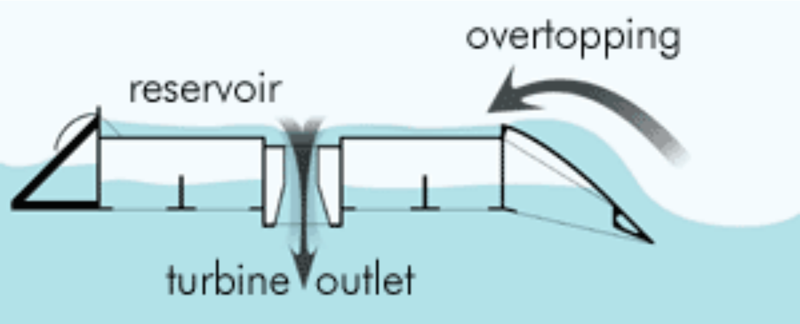
Göteborg

2010

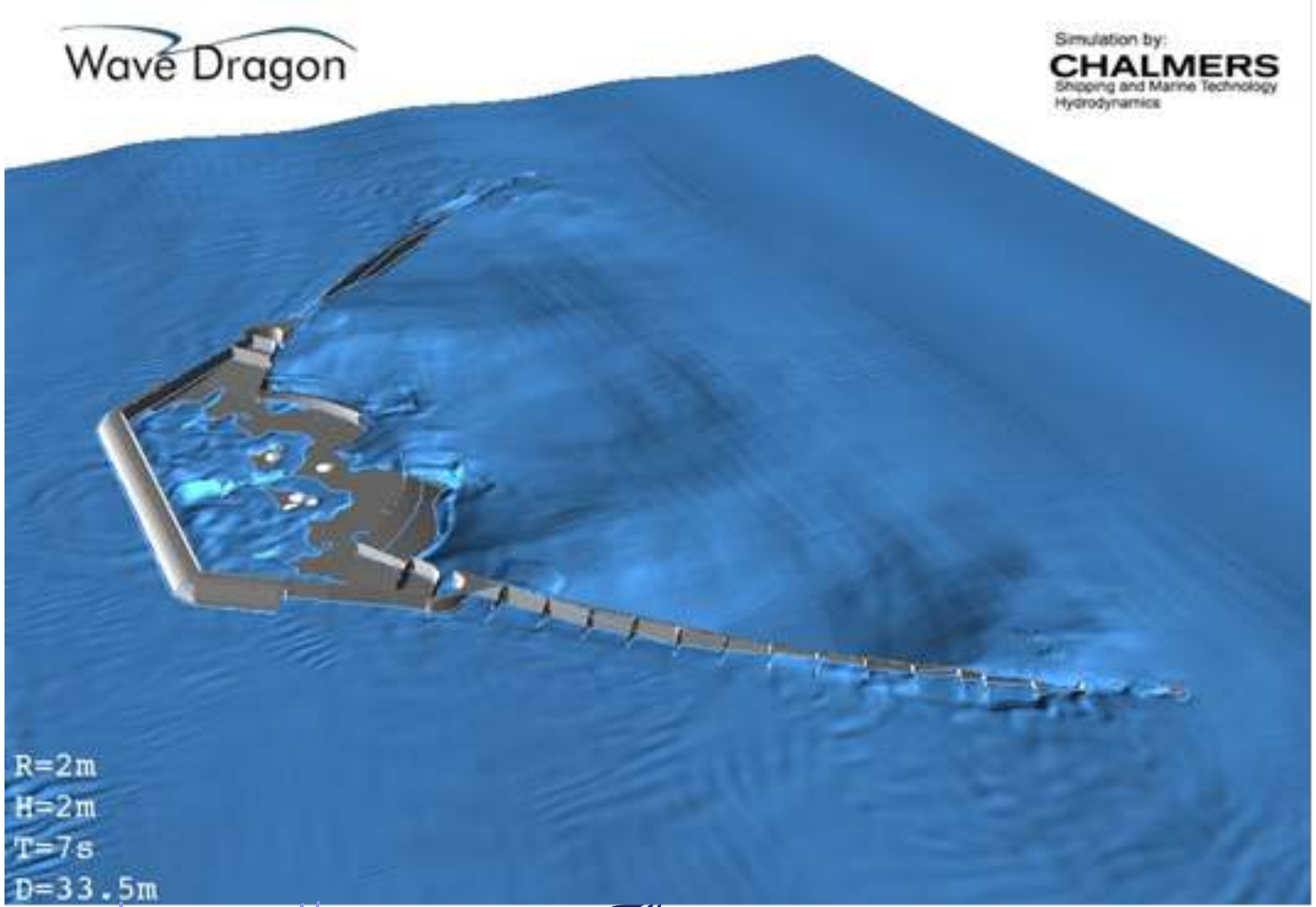
RUNDE

2017

Wave Dragon



WEC Modelling Using OpenFOAM



http://www.wavedragon.net/

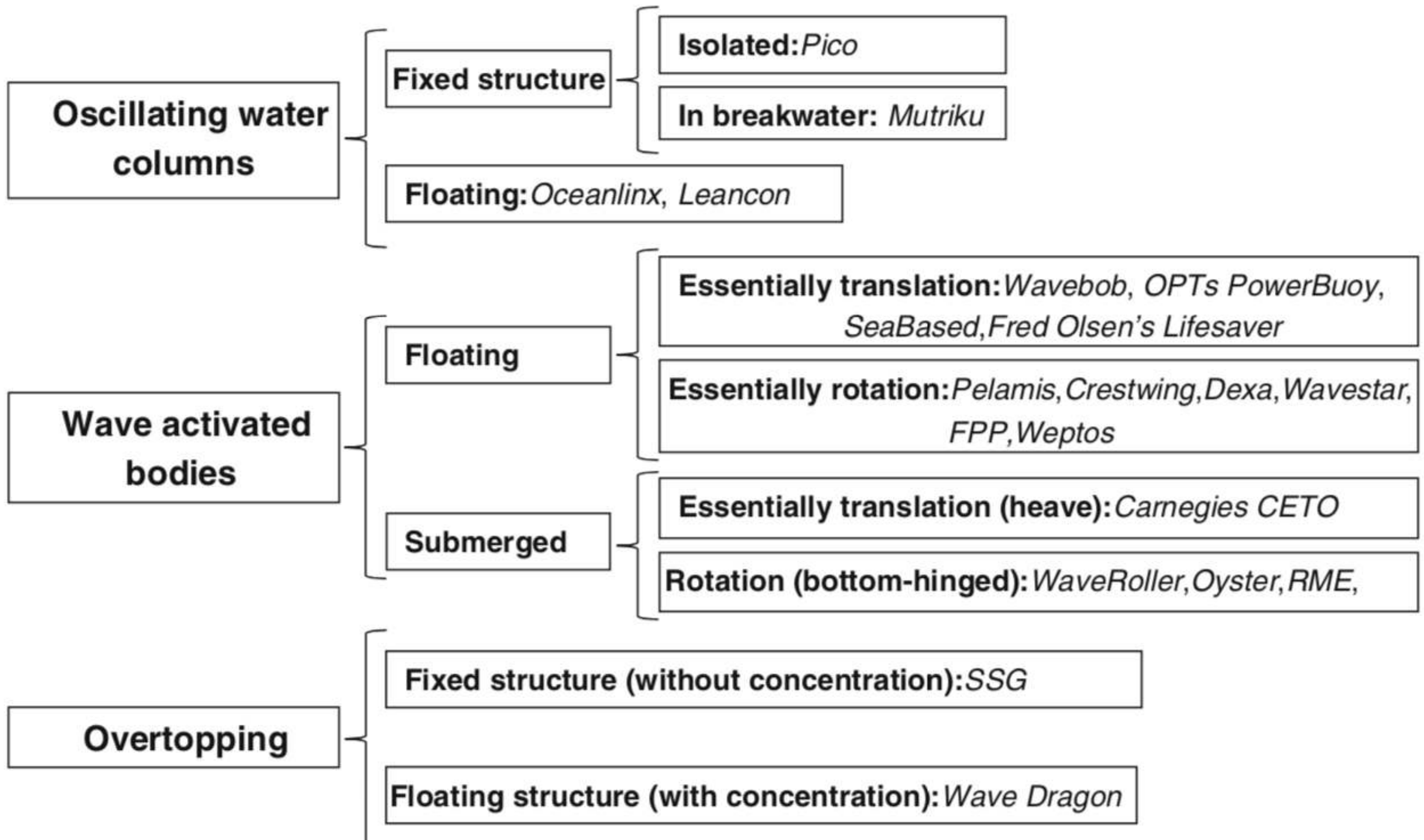
Oyster 1

http://www.aquamarinepower.com/

Oyster 800, June 2012 at EMEC

THINK-SHARE-PAIR 3MIN

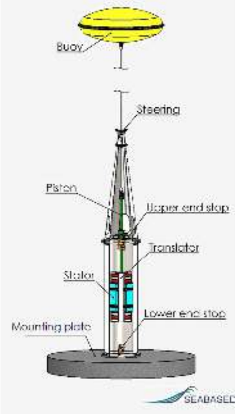
- WHICH TECHNOLOGY DO YOU THINK HAS BEEN MOST SUCCESFUL?
- WHY DO YOU THINK SO?



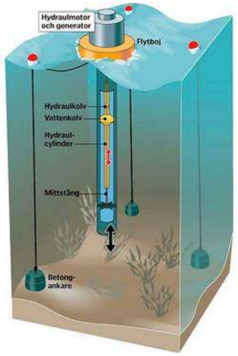
TECHNOLOGY CONVERGENCE

SWEDEN - exciting times!
Technology convergence towards point absorbers

Seabased

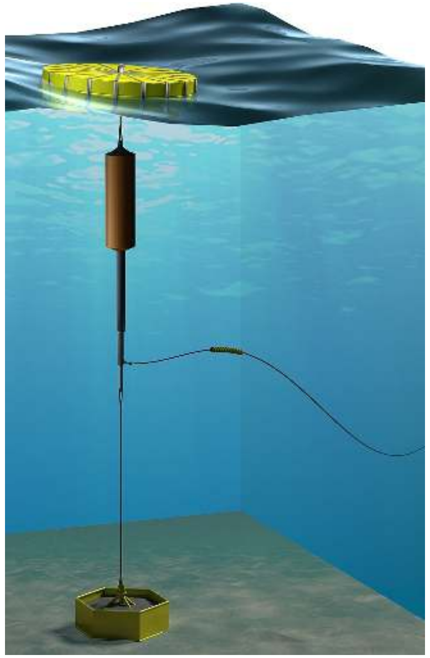


Waves4Power

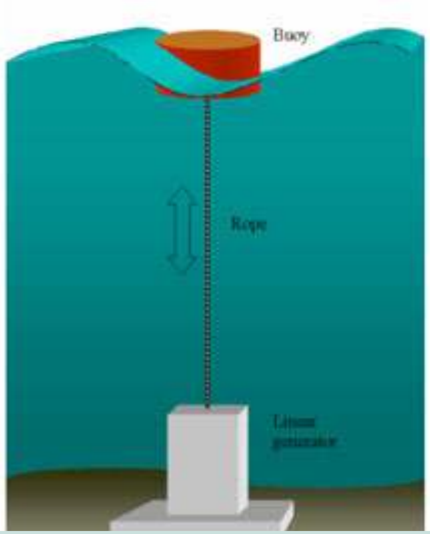


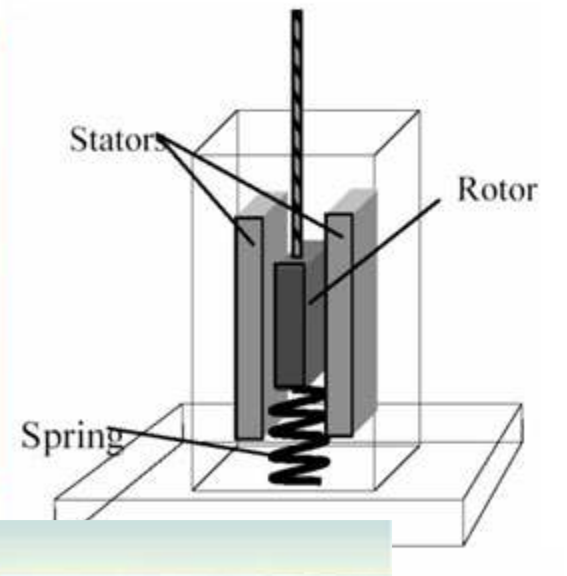
CorPower

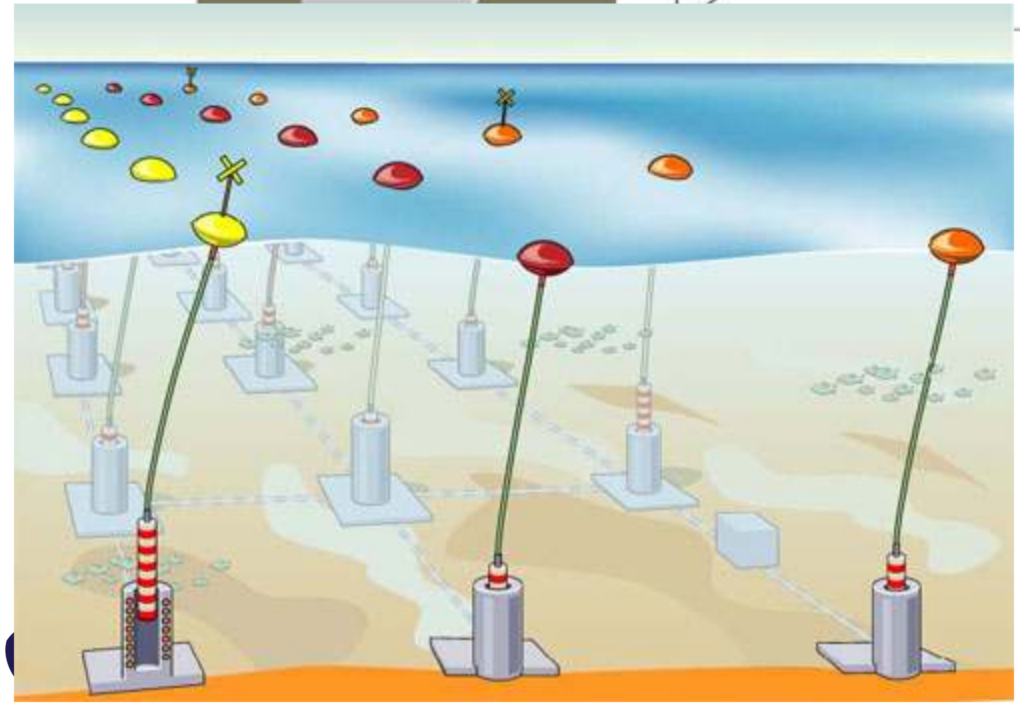
Ocean Harvesting



Uppsala University/ Seabased



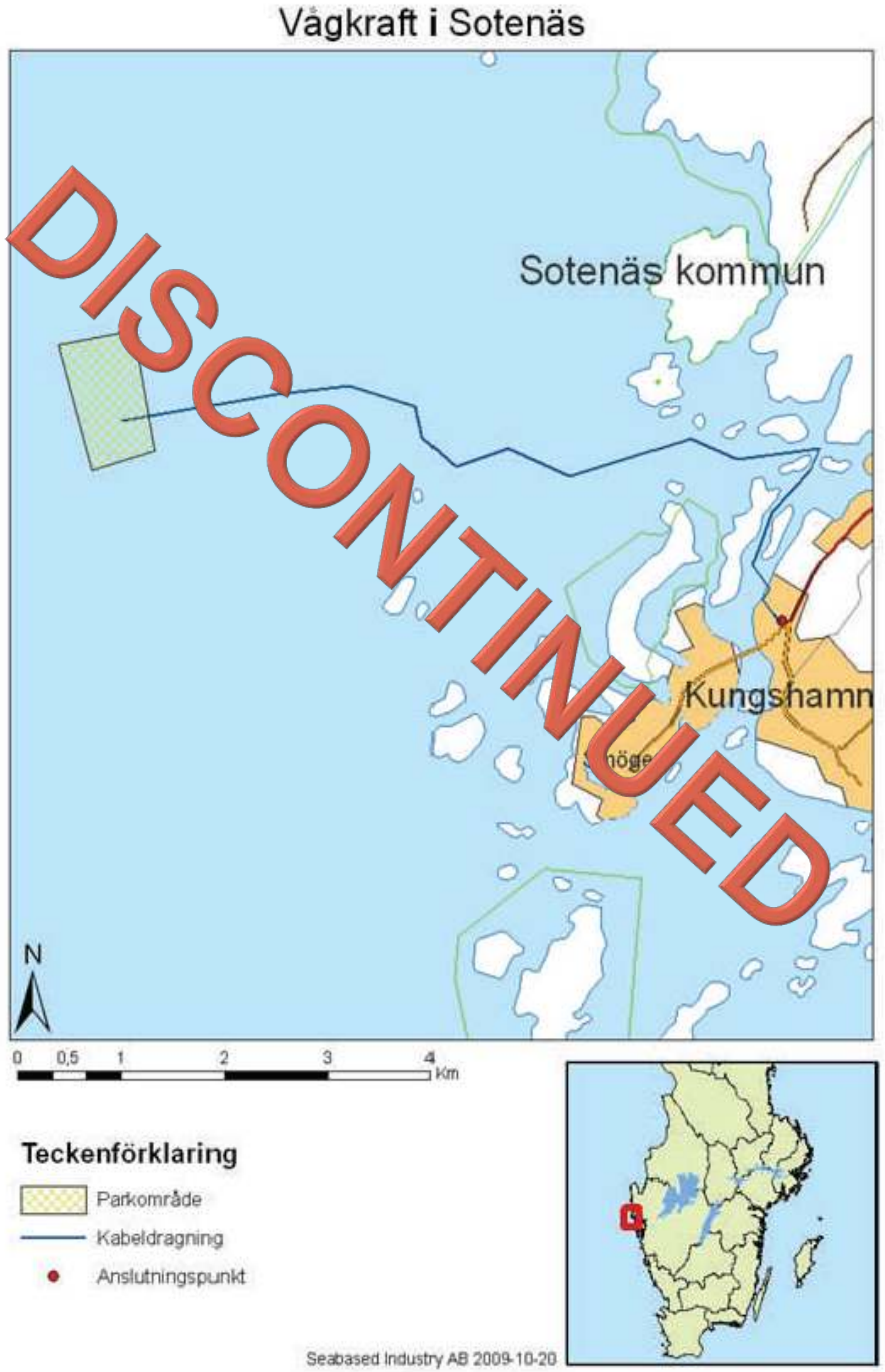




Seabased / Fortum
Permission to build
24 June 2010 (M 3086-09).
EU Permit Nov 2011
Contract 2011-12-09

Data:

- Max 420 units
- First phase 42 units
- Installed power 10 MW
- Area 0.5 km^2
- Generator height 10 m
- Base area 35 m^2
- Design life time 20 yrs
- Prod. 25 GWh/yr (28 %)



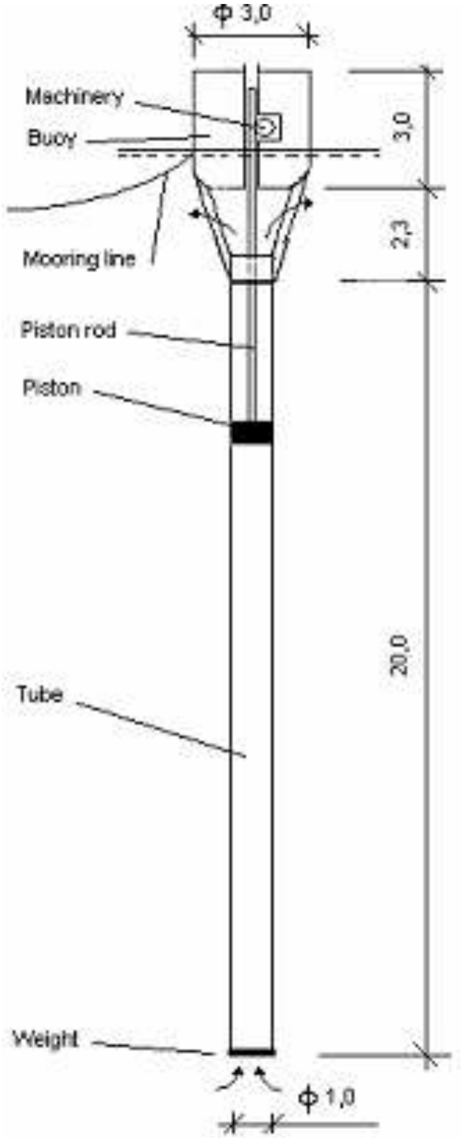


Figure 4.1 The IPS-Buoy Elskling I

The IPS Buoy Elskling at Gamla Gumman, Göteborg 1980 - 1981

Waves4Power

Göteborg

2010

RUNDE

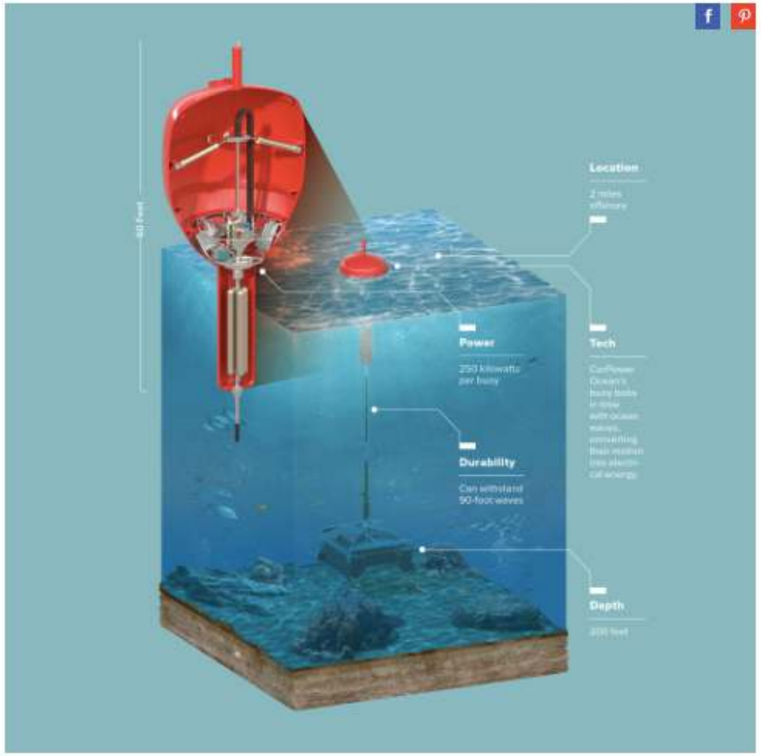
2017

Power-take-off machinery
Hydraulic motor, generator and ackumulator

CORPOWER: PASSIVE CONTROL

RACHEL NUWER MAGAZINE 04.06.16 4:10 PM

THE WONDER-BUOY THAT MAY FINALLY MAKE WAVE ENERGY FEASIBLE



CRISTIANO RINALDI

5 times higher Annual Energy / mass compared to conventional point absorbers without phase control. [MWh/ton]
3 times higher Annual Energy / PTO Force compared to conventional point absorbers without phase control. [MWh / kN]

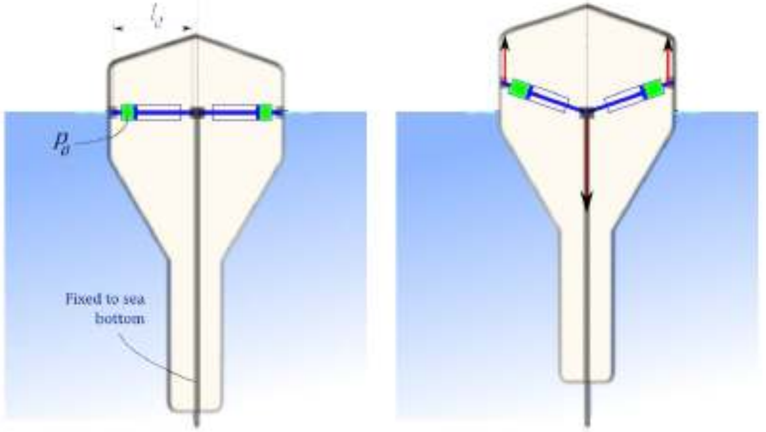


Fig. 5. Illustration of how the buoy displacement induces a vertical spring force with negative stiffness. Buoy in mean vertical position (left) and displaced upwards (right).

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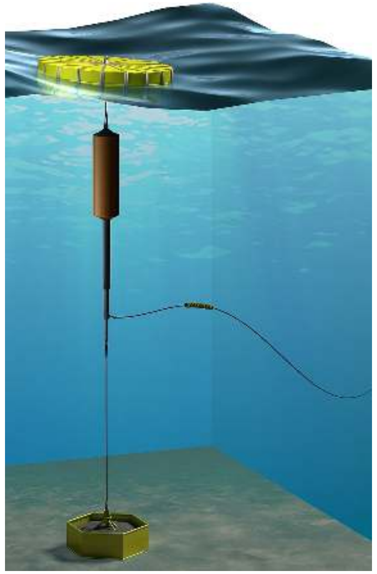
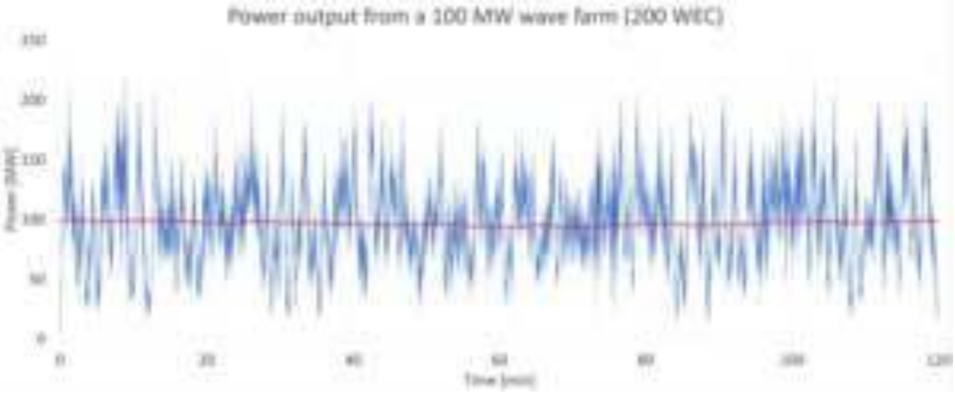
Hals et al (EWTEC 2015)



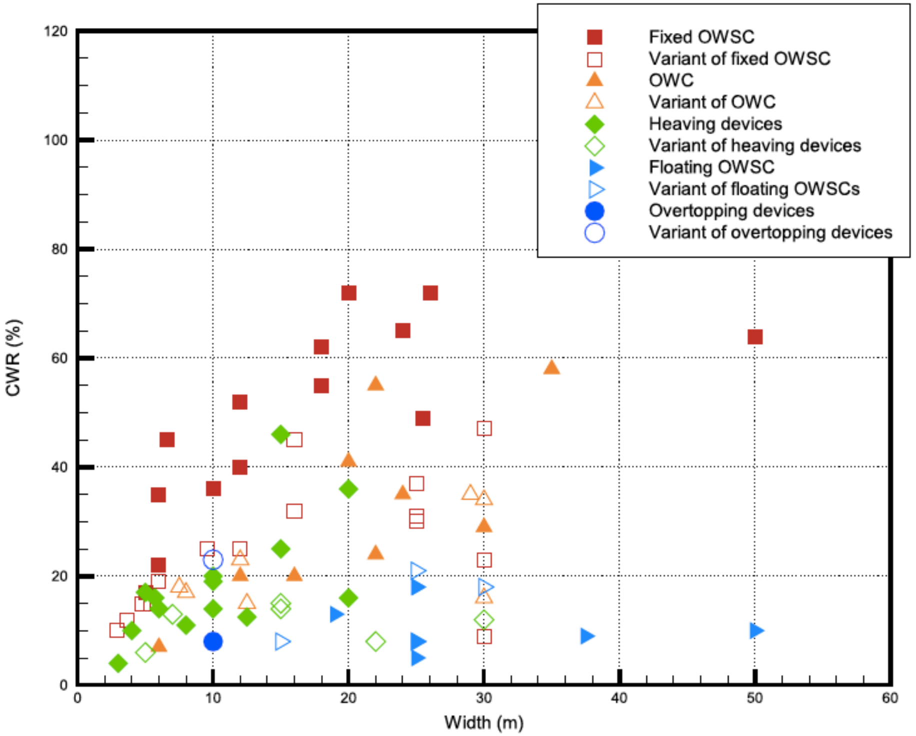

Power output from a 100 MW wave farm (200 WEC)

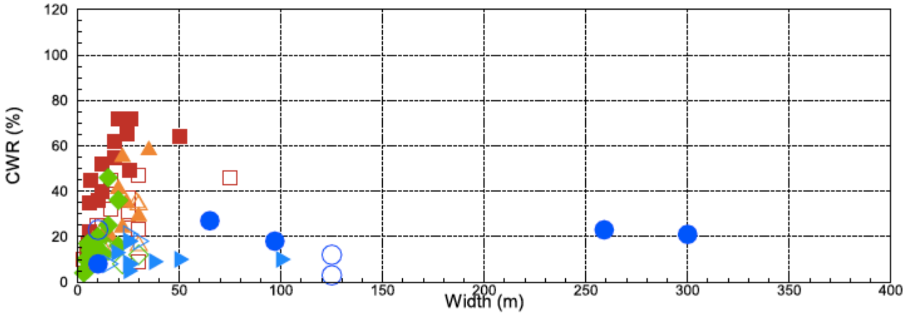
Why point absorbers? Have they better efficiency?

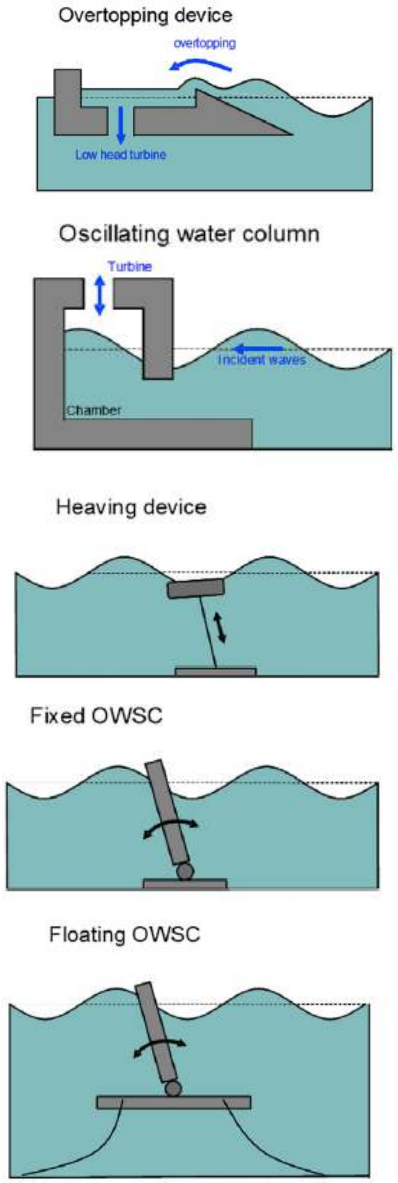
CWR = P/JD = capture width ratio = absorbed power / wave resource / characteristic dimension of device

- 158 estimates of CWR
- Fixed OWSCs most efficient.
- Heaving devices and OWCs medium
- Floating OWSCs and overtopping devices least efficient devices

A. Babarit / Renewable Energy 80 (2015) 610–628







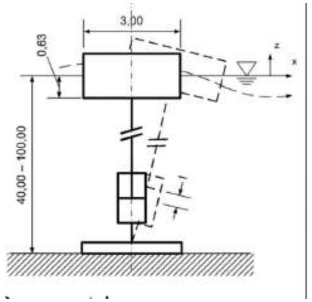
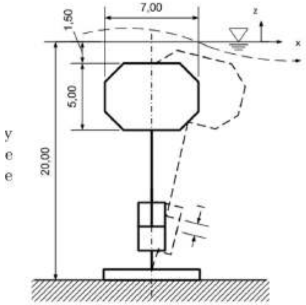


Fig. 1. Components of the Seabased WEC.



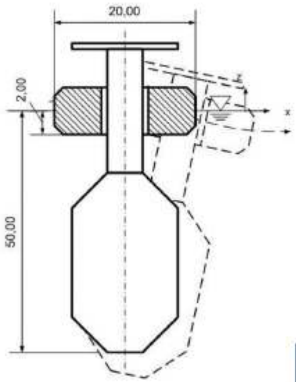


Fig. 3. 1/4 scale model of the Wavebob at sea.

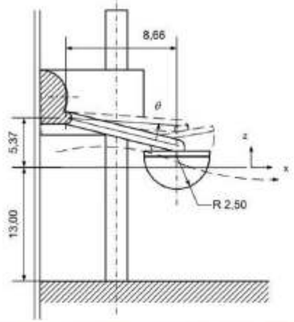
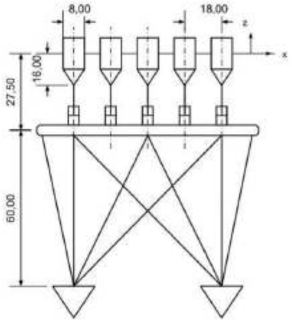


Fig. 4. Picture of the test section of the Wavestar WEC.



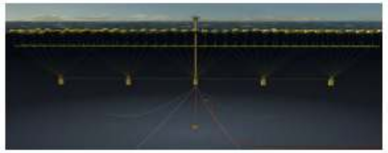
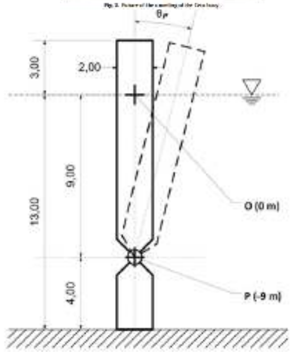


Fig. 5. Artistic view of the Pontoon Power Converter WEC.



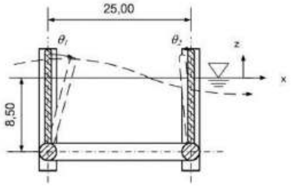


Fig. 7. Artistic view of the Langlee WEC.

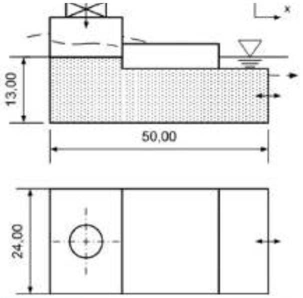
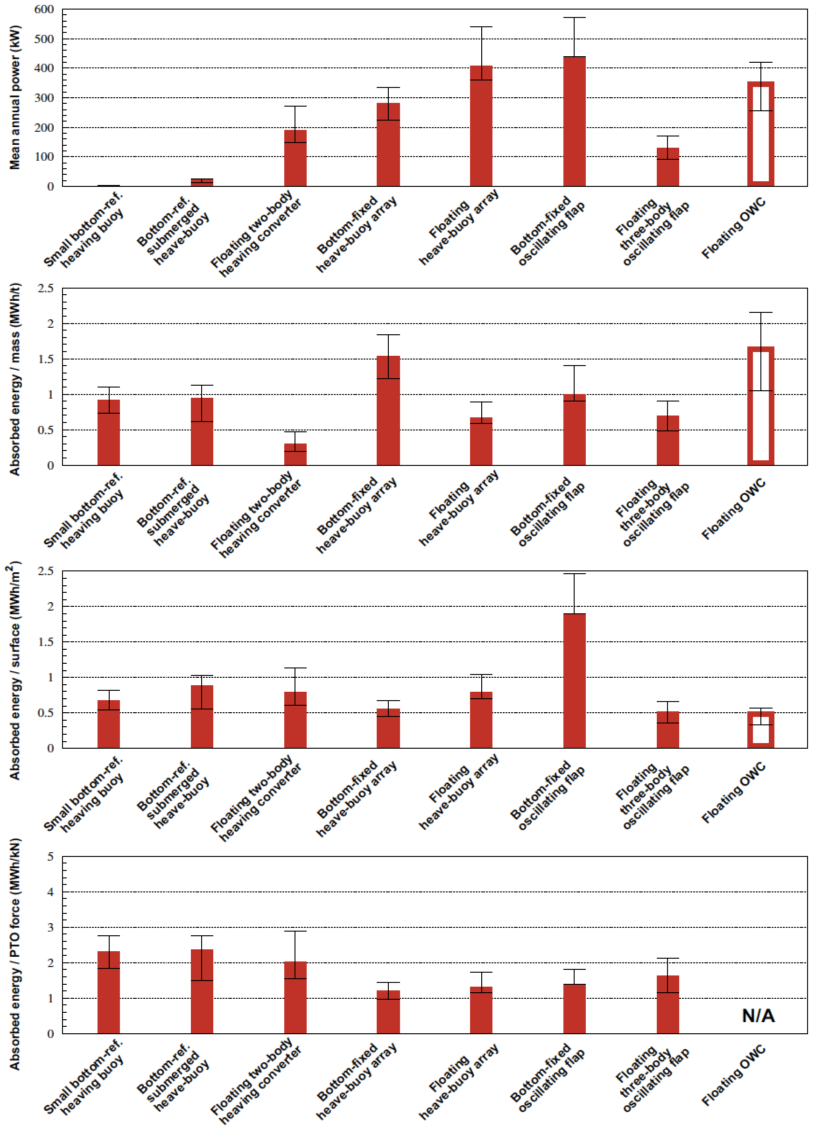
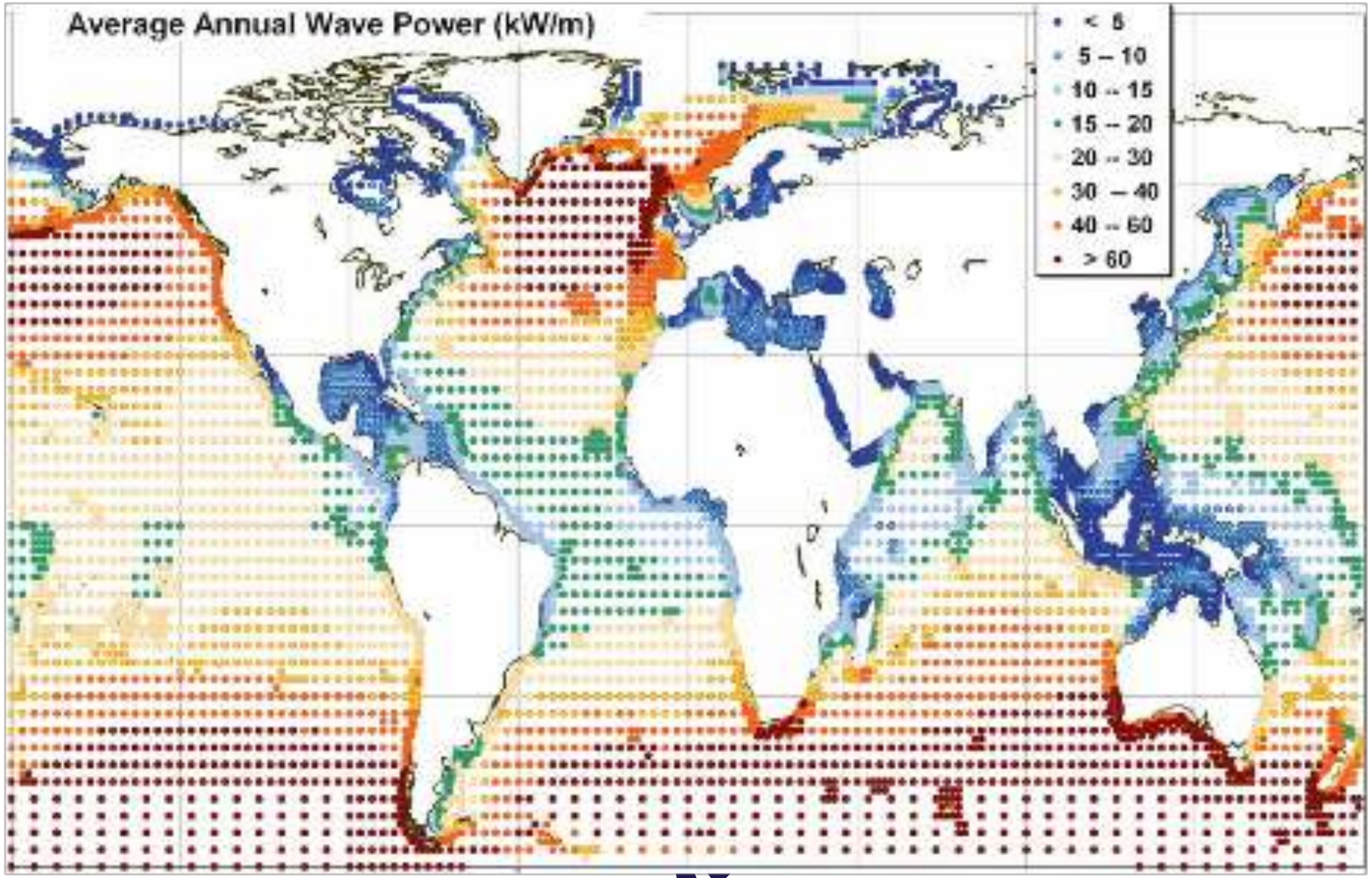


Fig. 8. 1/4 scale model of the OE buoy at sea.

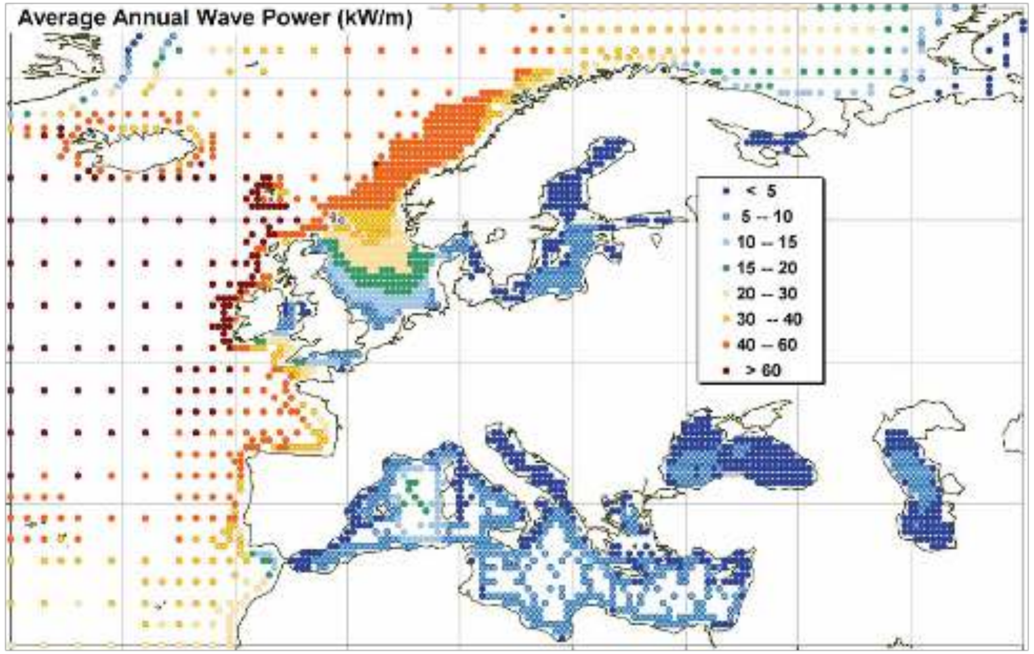
A. Babarit et al. / Renewable Energy 41 (2012) 44–63



RESOURCE



Average Annual Wave Power (kW/m)
< 5
5 – 10
10 – 15
15 – 20
20 – 30
30 – 40
40 – 60
> 60



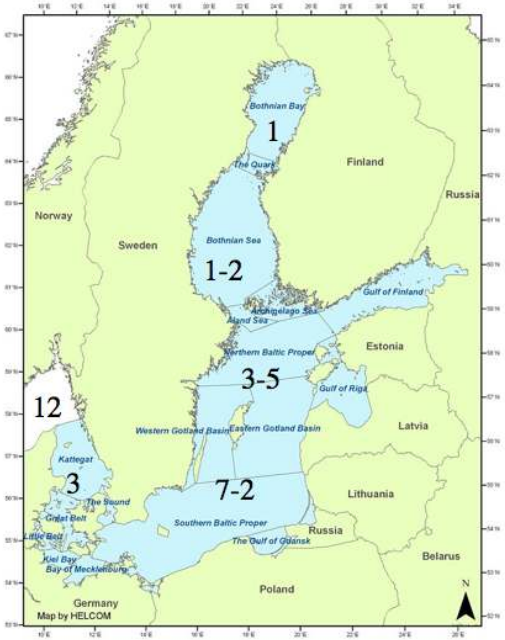
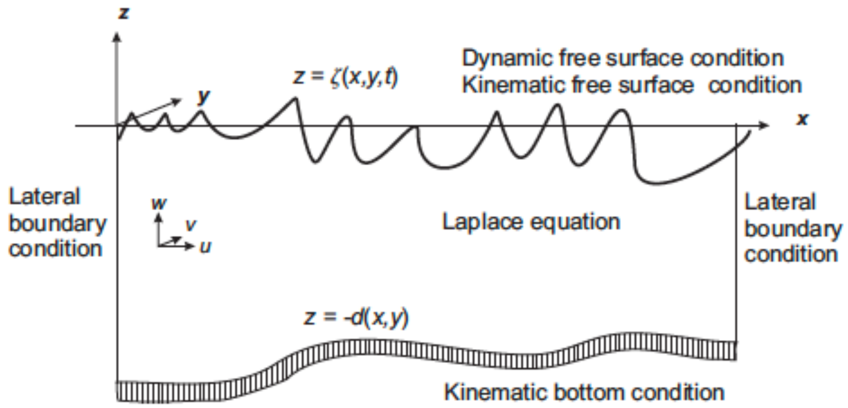


Table 6.1 | Regional theoretical potential of wave energy (Mørk et al., 2010).

REGION	Wave Energy TWh/yr (EJ/yr)
Western and Northern Europe	2,800 (10.1)
Mediterranean Sea and Atlantic Archipelagos (Azores, Cape Verde, Canaries)	1,300 (4.7)
North America and Greenland	4,000 (14.4)
Central America	1,500 (5.4)
South America	4,600 (16.6)
Africa	3,500 (12.6)
Asia	6,200 (22.3)
Australia, New Zealand and Pacific Islands	5,600 (20.2)
TOTAL	**29,500 (106.2)**

WATER WAVES



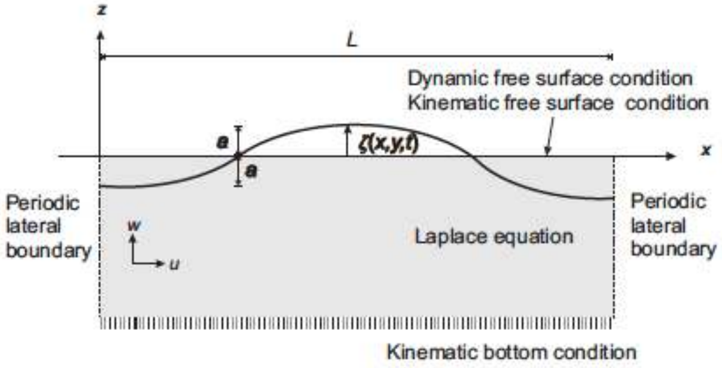
$$\bar{\nabla}^2\phi + \partial_{zz}\phi = 0 \qquad -d < z < \zeta$$

$$g\zeta + \partial_t\phi + \frac{1}{2}\left(\bar{\nabla}\phi \cdot \bar{\nabla}\phi + (\partial_z\phi)^2\right) = 0 \qquad z = \zeta$$

$$\partial_t\zeta + \bar{\nabla}\phi \cdot \bar{\nabla}\zeta - \partial_z\phi = 0 \qquad z = \zeta$$

$$\partial_z\phi + \bar{\nabla}\phi \cdot \bar{\nabla}d = 0 \qquad z = -d$$

WATER WAVES: LINEAR



In dimensional variables we write the equations as

$$
\begin{aligned}
\partial_{zz}\phi + \partial_{xx}\phi &= 0\,, && -d < z < 0\,,\\
\partial_z\phi &= 0\,, && z = -d\,,\\
\partial_t\zeta - \partial_z\phi &= 0\,, && z = 0\,,\\
g\zeta + \partial_t\phi &= 0\,, && z = 0\,,\\
\phi(x,t) = \phi(x+L,t)\,, \phi(x,t) &= \phi(x,t+T)\,, && \text{at lateral boundaries}\,.
\end{aligned}
$$

- Linear waves allows for superposition

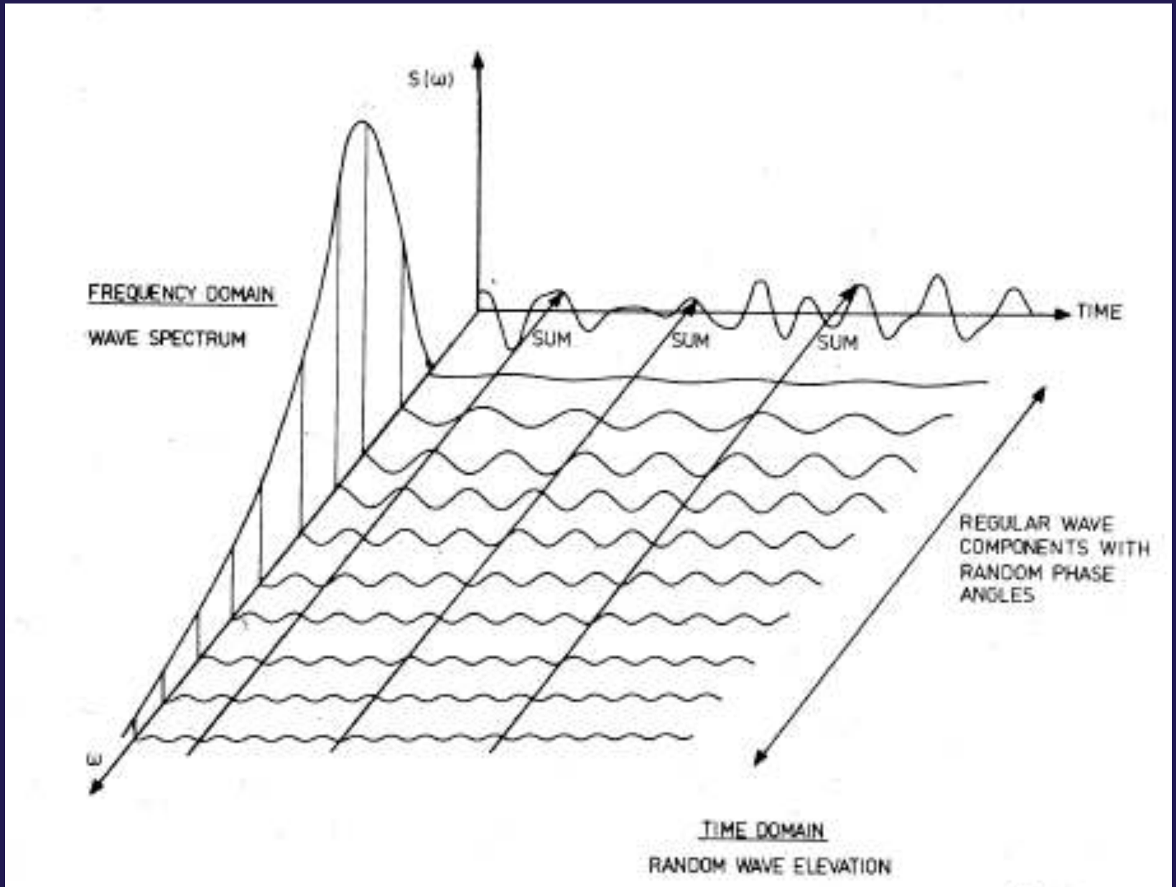
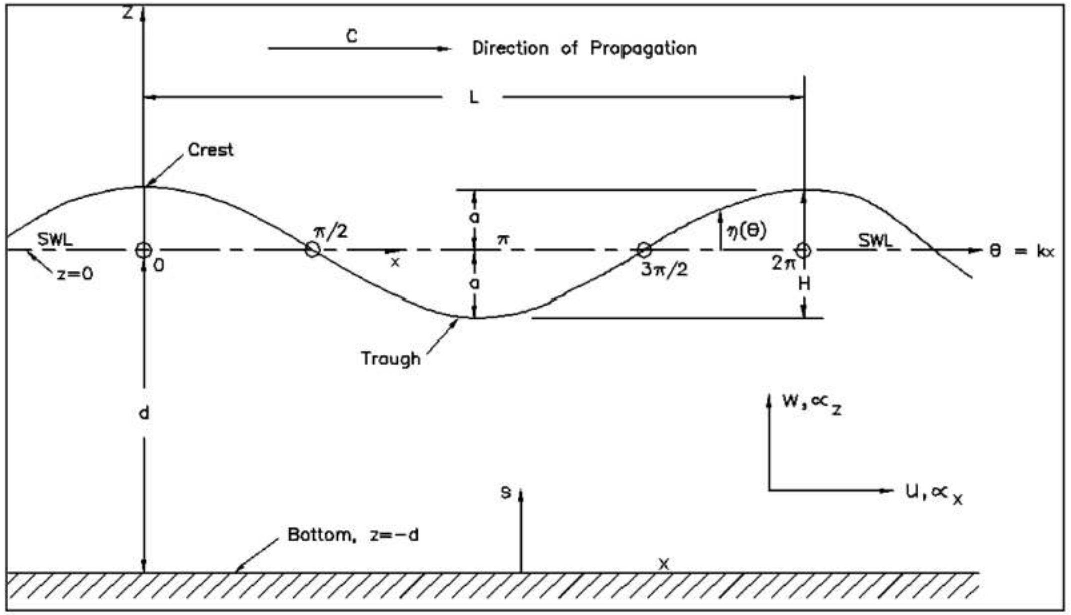


Fig. 2.5. Figure illustrating the connection between a frequency domain and time domain representation of waves in a long-crested short term sea state.

LINEAR WAVE



$$\phi = \frac{ag\cosh(k(d+z))}{\omega\cosh(kd)}\sin(kx-\omega t),$$

$$\zeta = a\cos(kx-\omega t).$$

- Completely determined by
- Amplitude
- Period
- Still water depth

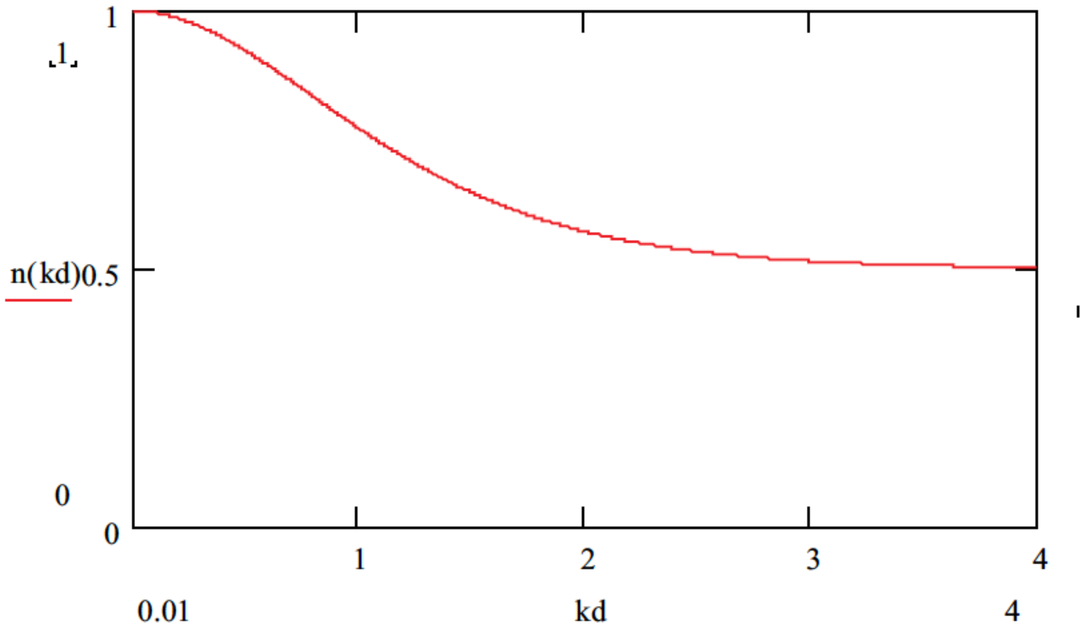
ENGINEERING WAVE PROPERTIES

Relative Depth	Shallow Water $\frac{d}{L} < \frac{1}{20}$, $kd < \frac{\pi}{10}$	Transitional Water $\frac{1}{20} < \frac{d}{L} < \frac{1}{2}$, $\frac{\pi}{10} < kd < \frac{\pi}{2}$	Deep Water $\frac{d}{L} > \frac{1}{2}$, $kd > \frac{\pi}{2}$
1. Wave profile	Same As >	$\eta = \frac{H}{2}\cos\left[\frac{2\pi x}{L} - \frac{2\pi t}{T}\right] = \frac{H}{2}\cos\theta$	< Same As
2. Wave celerity	$C = \frac{L}{T} = \sqrt{gd}$	$C = \frac{L}{T} = \frac{gT}{2\pi}\tanh\left(\frac{2\pi d}{L}\right)$	$C = C_0 = \frac{L}{T} = \frac{gT}{2\pi}$
3. Wavelength	$L = T\sqrt{gd} = CT$	$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi d}{L}\right)$	$L = L_0 = \frac{gT^2}{2\pi} = C_0 T$
4. Group velocity	$C_g = C = \sqrt{gd}$	$C_g = nC = \frac{1}{2}\left[1 + \frac{4\pi d/L}{\sinh(4\pi d/L)}\right]C$	$C_g = \frac{1}{2}C = \frac{gT}{4\pi}$
5. Water particle velocity (a) Horizontal	$u = \frac{H}{2}\sqrt{\frac{g}{d}}\cos\theta$	$u = \frac{H}{2}\frac{gT}{L}\frac{\cosh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}\cos\theta$	$u = \frac{\pi H}{T}e^{\left(\frac{2\pi z}{L}\right)}\cos\theta$
(b) Vertical	$w = \frac{H\pi}{T}\left(1+\frac{z}{d}\right)\sin\theta$	$w = \frac{H}{2}\frac{gT}{L}\frac{\sinh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}\sin\theta$	$w = \frac{\pi H}{T}e^{\left(\frac{2\pi z}{L}\right)}\sin\theta$
6. Water particle accelerations (a) Horizontal	$a_x = \frac{H\pi}{T}\sqrt{\frac{g}{d}}\sin\theta$	$a_x = \frac{g\pi H}{L}\frac{\cosh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}\sin\theta$	$a_x = 2H\left(\frac{\pi}{T}\right)^2 e^{\left(\frac{2\pi z}{L}\right)}\sin\theta$
(b) Vertical	$a_z = -2H\left(\frac{\pi}{T}\right)^2\left(1+\frac{z}{d}\right)\cos\theta$	$a_z = -\frac{g\pi H}{L}\frac{\sinh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}\cos\theta$	$a_z = -2H\left(\frac{\pi}{T}\right)^2 e^{\left(\frac{2\pi z}{L}\right)}\cos\theta$
7. Water particle displacements (a) Horizontal	$\xi = -\frac{HT}{4\pi}\sqrt{\frac{g}{d}}\sin\theta$	$\xi = -\frac{H}{2}\frac{\cosh[2\pi(z+d)/L]}{\sinh(2\pi d/L)}\sin\theta$	$\xi = -\frac{H}{2}e^{\left(\frac{2\pi z}{L}\right)}\sin\theta$
(b) Vertical	$\zeta = \frac{H}{2}\left(1+\frac{z}{d}\right)\cos\theta$	$\zeta = \frac{H}{2}\frac{\sinh[2\pi(z+d)/L]}{\sinh(2\pi d/L)}\cos\theta$	$\zeta = \frac{H}{2}e^{\left(\frac{2\pi z}{L}\right)}\cos\theta$
8. Subsurface pressure	$p = \rho g(\eta - z)$	$p = \rho g\eta\frac{\cosh[2\pi(z+d)/L]}{\cosh(2\pi d/L)} - \rho g z$	$p = \rho g\eta\, e^{\left(\frac{2\pi z}{L}\right)} - \rho g z$

PHASE VS GROUP VELOCITY

The group velocity is sometimes written as $C_g = nC$ where

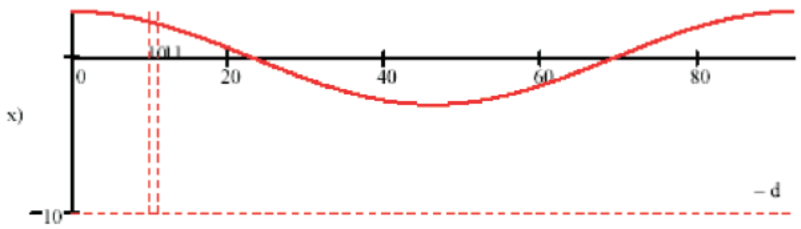
$$n = \frac{1}{2}\left(1 + \frac{2kd}{\sinh(2kd)}\right)$$



WAVE ENERGY

the energy in a progressive Airy wave can be estimated by integrating the potential and kinematic energy in the wave over a wavelength.

The potential energy is a result of the displacement of mass from a position of rest, i.e. potential energy at a time, say $t = 0$, is the deformation work needed to give the form of the wave: $\zeta = a\cos(kx)$.



The mass of the lifted water mass between the two dashed verticals is $\rho g \zeta dx$ and this mass is lifted the height $\zeta/2$.

WAVE ENERGY

The mean energy over a wavelength thus becomes

$$E_p = \frac{1}{L}\int_0^L \rho g \zeta \frac{\zeta}{2} dx = \frac{\rho g}{2L}\int_0^L \zeta^2 dx = \frac{\rho g a^2}{2L}\int_0^L (\cos(kx))^2 dx$$

We find that the potential energy is proportional to the square of the amplitude

$$E_p = \frac{\rho g a^2}{4}$$

WAVE ENERGY

The kinetic energy is total kinetic energy contained in all the water from the free surface to the bottom. However, in Airy theory we can only integrate up to the still water level. So finite waves are badly computed.

We consider a small moving parcel with mass dm. The kinetic energy is

$$dE_k = dm\frac{u^2+w^2}{2} = \rho dxdz\frac{u^2+w^2}{2}.$$

Integrate over both the depth and over a wave length:

$$E_k = \frac{1}{L}\int_0^L\int_{-d}^0 \rho\frac{u^2+w^2}{2}dzdx.$$

WAVE ENERGY

Substituting the known values for the velocities from Airy theory

$$E_k = \frac{\rho}{2L}\left(\frac{gak}{\omega}\frac{1}{\cosh(kd)}\right)^2 \int_0^L \int_{-d}^0 \big(\cosh^2(k(d+z))\cos^2(kx-\omega t) + \sinh^2(k(d+z))\sin^2(kx-\omega t)\big)\, dz dx$$

which can be simplified and integrated to give

$$E_k = \frac{\rho g a^2}{4}$$

WAVE ENERGY

Adding the potential and kinematic energies we obtain the total energy per unit surface area as

$$E = E_p + E_k = \frac{\rho g a^2}{2}$$

Finally, it should be stressed that the energy propagates with the group velocity, so the wave power read:

$$P = EC_g$$

WAVE POWER RESOURCE

$$J_{reg} = \frac{\rho g^2}{32\pi} H^2 T$$

$$J_{irreg} = \frac{\rho g^2}{64\pi} H_s^2 T$$

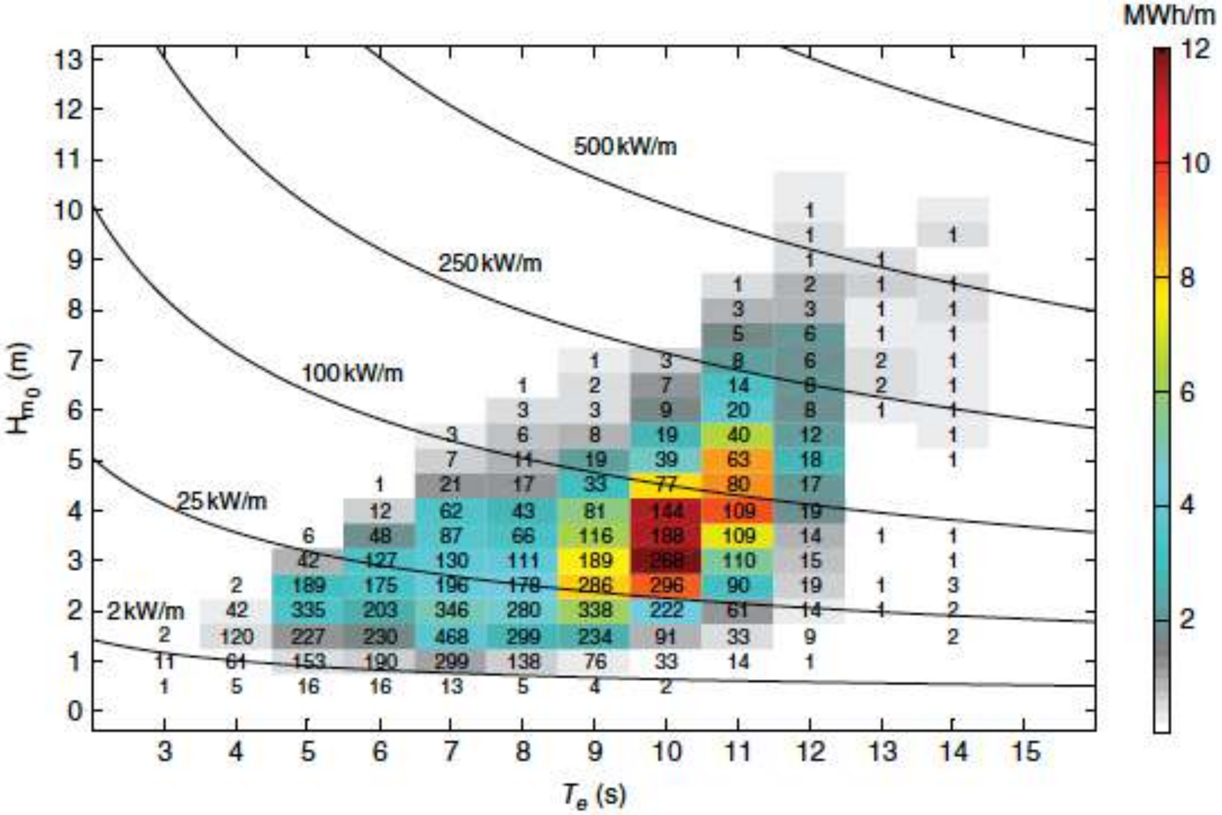


Figure 2.2 Offshore resource characterisation matrix including wave power isolines for the Death Coast (*Costa da Morte*), Galicia, NW Spain. The numbers in the greyed squares represent the occurrence of the respective *energy bins*, expressed in hours in a typical year. The greyscale indicates the contribution of each *energy bin* to the annual resource.

$$T_e = T_{-10} = \frac{m_{-1}}{m_0} \qquad m_n = \sum_i f_i^n S_i \Delta f_i \qquad S_i = \sum_j S_{ij} \Delta\theta_j$$

WAVE POWER RESOURCE

		Regular waves power matrix [kW] –1:1 scale masuda buoy, for $H < 5.5$ m											
		Wave period T [s]											
		6	7	8	9	10	11	12	13	16	18	20	22
Wave height H [m]	0.50	0.137	3.773	2.325	1.126	0.626	0.594	1.010	0.469	0.000	0.000	0.000	0.000
	1.50	3.302	27.593	38.127	20.306	10.818	9.676	6.232	3.472	0.106	0.029	0.028	0.038
	2.50	10.396	61.793	110.247	69.637	32.960	24.838	13.800	8.126	0.218	0.098	0.083	0.101
	3.50	14.181	101.288	193.511	143.898	65.691	44.269	23.297	14.254	1.400	0.298	0.152	0.276
	4.50	26.123	153.131	296.310	236.387	101.410	68.080	33.873	21.296	2.956	0.555	0.301	0.687
	5.50	40.492	223.575	298.653	326.293	146.654	95.622	44.860	29.968	5.752	1.228	0.547	1.210

Figure 7.18 Regular waves power matrix of an OWC Masuda buoy model, 1 : 50 scale [38].

X

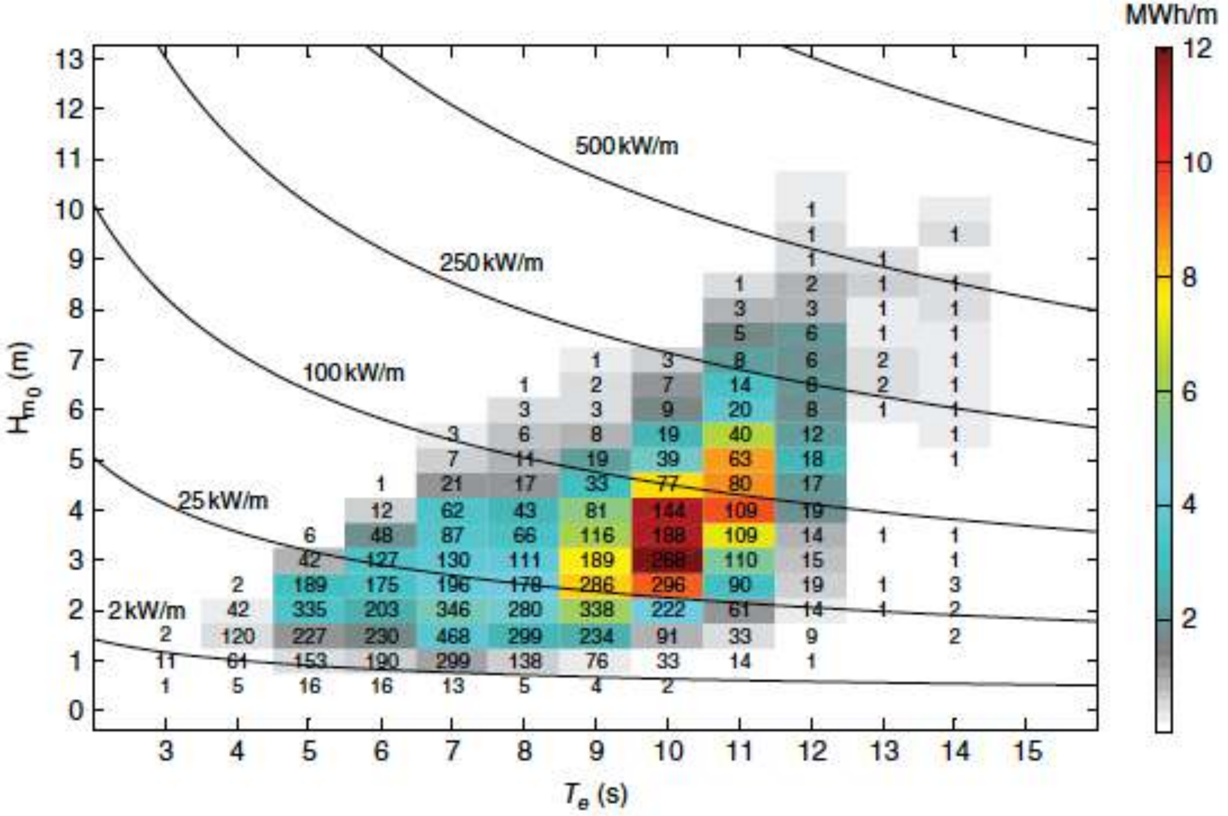
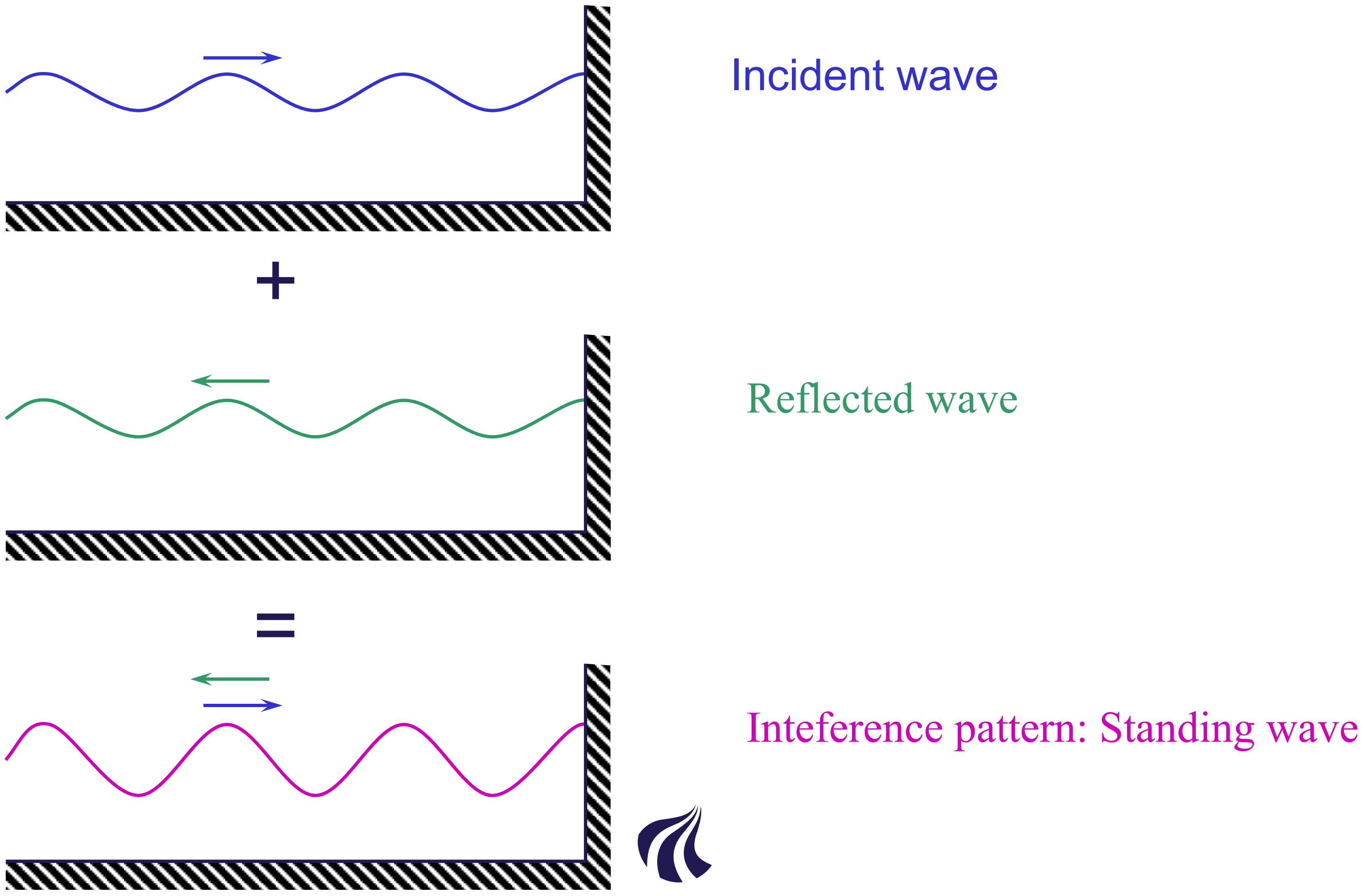


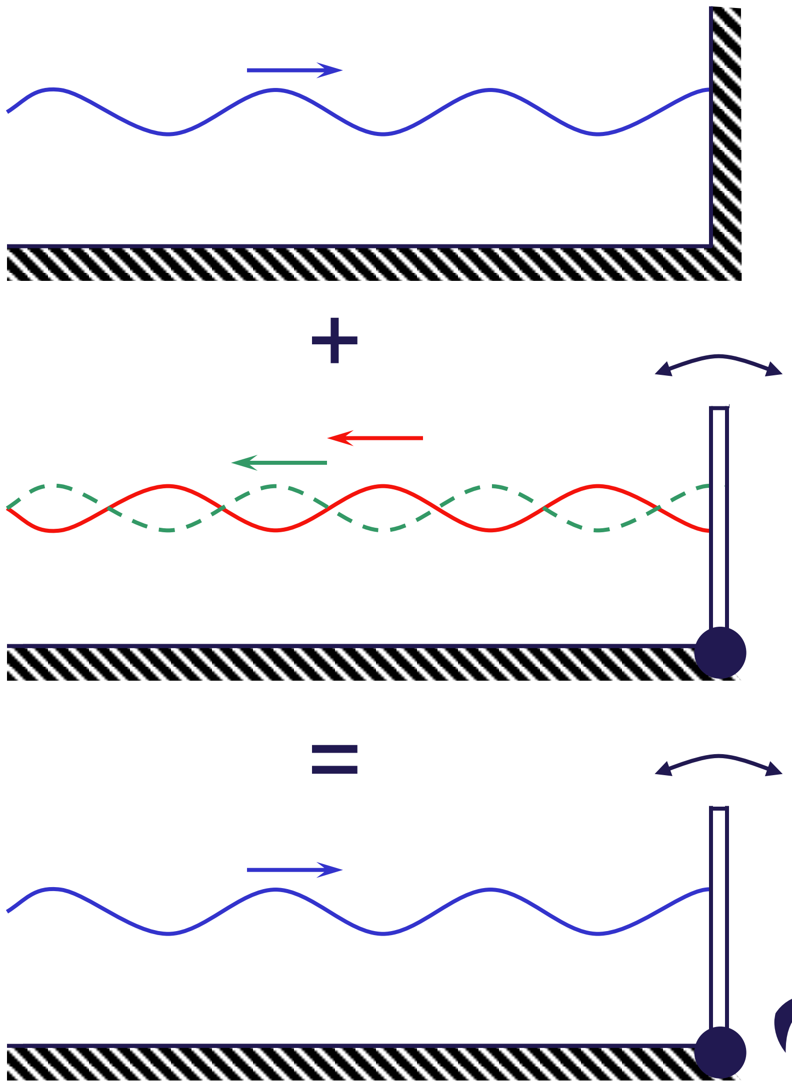
Figure 2.2 Offshore resource characterisation matrix including wave power isolines for the Death Coast (*Costa da Morte*), Galicia, NW Spain. The numbers in the greyed squares represent the occurrence of the respective *energy bins*, expressed in hours in a typical year. The greyscale indicates the contribution of each *energy bin* to the annual resource.

BREAK

“To absorb a wave is to generate a wave”
Prof Falnes



“To absorb a wave is to generate a wave”
Prof Falnes

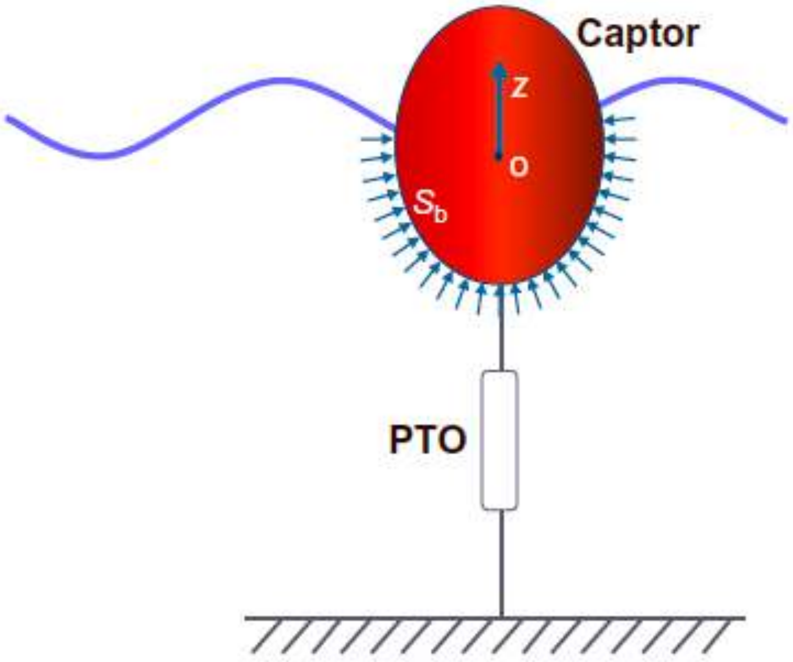


Incident wave

Reflected wave
Generated wave

Inteference pattern: incident wave absorbed as the generated wave cancels the reflected wave

Newtons II Law



$$m\ddot{x} = F_{pe}(t) + F_{re}(t),$$

m is total inertia

x is displacement

F_{pe} force due to external pressure

F_{re} reaction forces

Newtons II Law

$$m\ddot{x} = F_{pe}(t) + F_{re}(t),$$

Time domain

$$x(t) = \mathrm{Re}(\hat{x}(\omega)\exp^{i\omega t})$$

$$-\omega^2 m\hat{x}(\omega) = \hat{F}_{pe}(\omega) + \hat{F}_{re}(\omega)$$

Frequency domain

FORCE DUE TO PRESSURE ACTING ON FLOATER

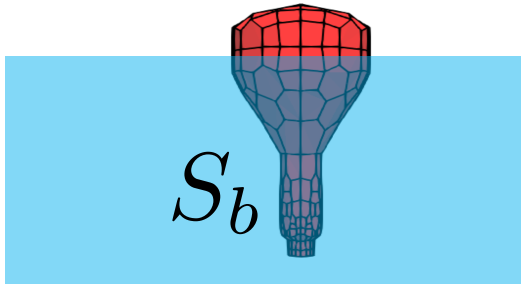
$$-\omega^2 m\hat{x}(\omega) = \hat{F}_{pe}(\omega) + \hat{F}_{re}(\omega)$$

$$\hat{F}_{pe}(\omega) = \hat{F}_{hd}(\omega) + \hat{F}_{hs}(\omega),$$

$\hat{F}_{hd}(\omega)$ is the hydrodynamic force

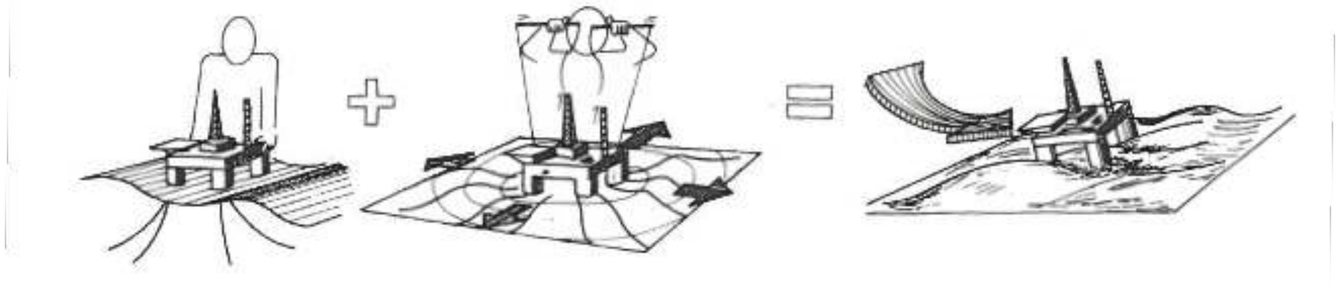
$\hat{F}_{hs}(\omega)$ is the hydrostatic force

HYDRODYNAMIC FORCE



$$F_{hd} = \int_{S_b} p_e n \mathrm{d}S_b = \rho \int_{S_b} \frac{\partial \phi}{\partial t} n \mathrm{d}S_b$$

$$\hat{F}_{hd} = \hat{F}_e + \hat{F}_r$$



Faltinsen (1990)

- Assumption of linear waves allows superposition of forces

FROUDE-KRYLOV FORCE

$$\hat{F}_e = \hat{F}_{FK} + \hat{F}_S,$$

$$\hat{F}_{FK} = i\omega\rho \int_{S_b} \hat{\phi}_0 n \mathrm{d}S_b$$

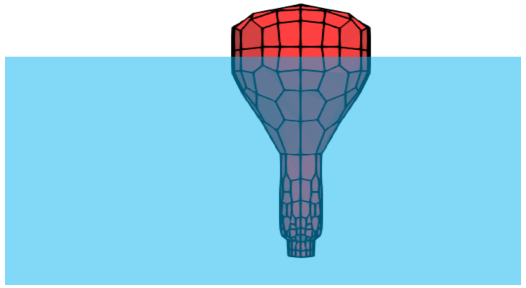
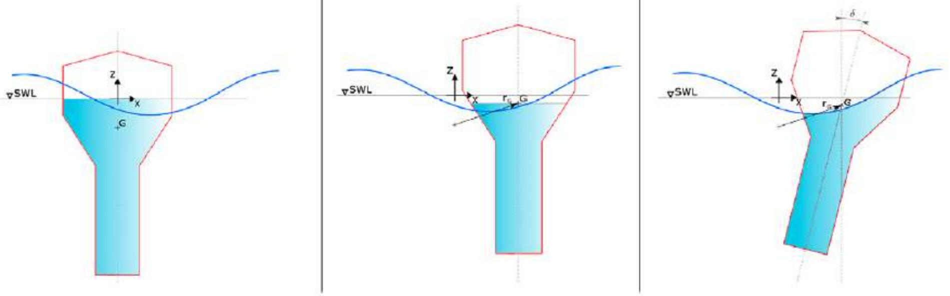


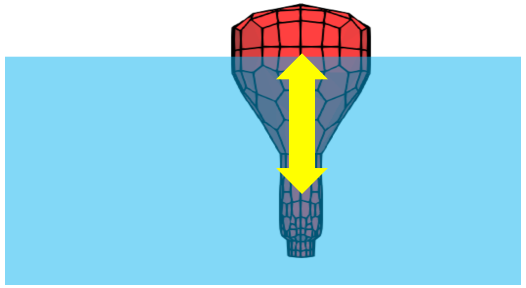
Table 1
Summary of the main difference between the three Froude-Krylov modelling approaches for axisymmetric buoys.

	LFK Linear Froude-Krylov (FK)	**VFK** Algebraic nonlinear FK	**RFK** Numerical nonlinear FK
Wetted surface $S(t)$	Constant	Instantaneous	Instantaneous
Pitch angle δ	0	0	δ
Free surface $\eta(x,t)$	0	$\eta(t)$	$\eta(x,t)$
Computational time	+	++	+++



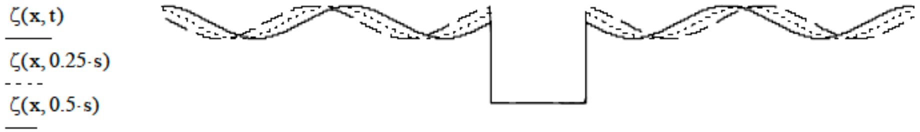
Giorgio and Ringwood (2018)

RADIATION FORCE



$$\hat{F}_r = \omega^2 \rho \hat{x} \int_{S_b} \hat{\phi}_r n \mathrm{d}S_b,$$

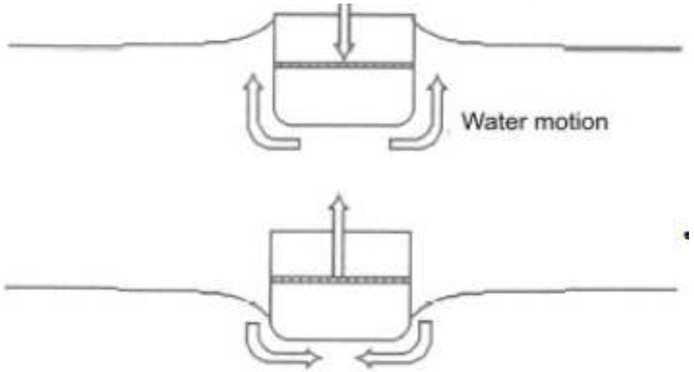
Radiation damping



$$\hat{F}_r = -i\omega Z \hat{x}$$

$$Z = -i\omega\rho \int_{S_b} \hat{\phi}_r n \mathrm{d}S_b = R + iX = R + i\omega A,$$

Added mass



$$\hat{F}_r = -i\omega R \hat{x} + \omega^2 A \hat{x}$$

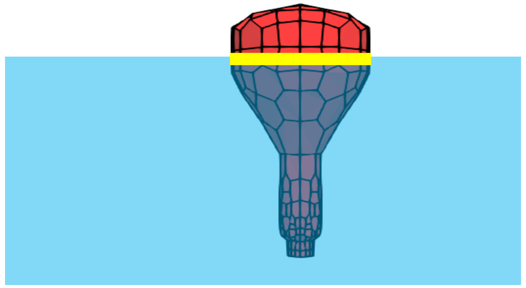
HYDROSTATIC FORCE

$$\hat{F}_{hs} = -G\hat{x},$$

$$G = \rho g S,$$

G is the hydrostatic stiffness

S is the waterplane area



REACTION FORCES

$$-\omega^2 m\hat{x}(\omega) = \hat{F}_{pe}(\omega) + \hat{F}_{re}(\omega)$$

$$\hat{F}_{re}(\omega) = \hat{F}_{pto}(\omega) + \hat{F}_{m}(\omega),$$

$\hat{F}_{pto}(\omega)$ is the reaction force from PTO

$\hat{F}_{m}(\omega)$ is the reaction force from mooring

REACTION FORCES

$$\hat{F}_{pto} = -i\omega B_{pto}\hat{x} - K_{pto}\hat{x},$$

B_{pto} is the PTO damping

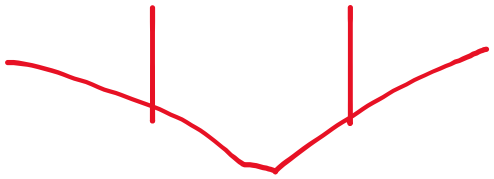
K_{pto} is the PTO spring

$$\hat{F}_m = -K_m\hat{x},$$

K_m mooring spring stiffness

MOTION

$$-\omega^2 m\hat{x}(\omega) = \hat{F}_{pe}(\omega) + \hat{F}_{re}(\omega)$$



$$\hat{x} = \frac{\hat{F}_e}{[-\omega^2(m + A) + G + K_{pto} + K_m] + [i\omega(R + B_{pto})]}$$

POWER

$$P = \frac{1}{T}\int_0^T B_{pto}u^2 \mathrm{dt} = \frac{1}{2}B_{pto}\omega^2|\hat{x}|^2$$

$$P = \frac{1}{2}\frac{B_{pto}\omega^2|\hat{F}_e|^2}{\left[-\omega^2(m+A)+G+K_{pto}+K_m\right]^2-\omega^2(R+B_{pto})^2}$$

MAXIMUM POWER

$$P = \frac{1}{2} \frac{B_{pto}\omega^2|\hat{F}_e|^2}{\left[-\omega^2(m+A)+G+K_{pto}+K_m\right]^2 - \omega^2(R+B_{pto})^2}$$

The first condition states that power absorption is maximized at resonance. When this condition is achieved the velocity is in phase with the excitation force

The second condition states that the PTO damping must be equal to the hydrodynamic radiation damping. This highlights that the ability to generate waves is a fundamental aspect in the design of WECs.

1 $K_{pto} = \omega^2(m+A) - G - K_m$

2 $B_{pto} = R$

$$P_{max} = \frac{|\hat{F}_e|^2}{8R}$$

THINK-
SHARE_PAIR

- ARE WE MIOSSIG SOMETHING HERE?
- ASSUMPTIONS?

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DENMARK

MISSING: VISCOUS FORCES

- Linear theory does not include viscous forces and greatly overpredicts response in the resonance region
- FIX: use Morison drag. Need to calibrate the Morrison drag – NB: the calibrated drag coefficient will be 'all-inclusive' including all nonlinearities (Scaling problem)

$$F_V = -C_d \dot{X} |\dot{X}|$$

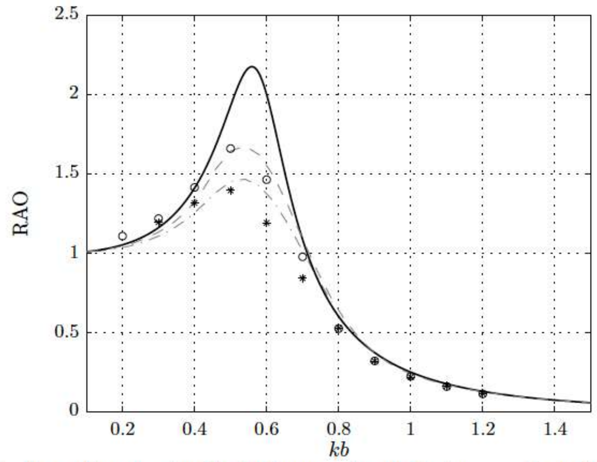

Figure 6.4: Heave Response Amplitude Operator (RAO) showing experimental data due to incident waves of steepness $A_I k =$ ∘ 0.05 and ∗ 0.10, —— Linear potential flow prediction (WAMIT), and TD simulation with $C_{D2} = 350\text{Ns}^2/\text{m}^2$ for — — $A_I k = 0.05$ and — · — $A_I k = 0.10$

Rodriguez (2016)

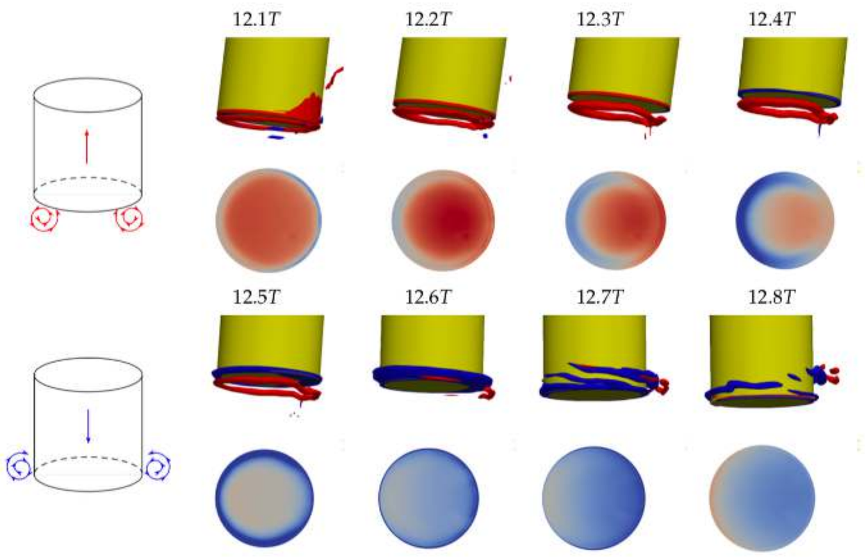

Figure 9. Vortex formation over the wave period T with corresponding dynamic pressure distribution on the bottom of the buoy for the W1 RANS model scale simulations. Vortices are visualized by the $Q = 200$ iso-surface and colored by rotation direction (inward rotation is blue and outward is red, see schematics on the left). Top two rows are upward motion, top bottom rows are downward motion. The colour-scale of the pressure distribution goes from blue to red in $[-0.25, 0.25]$, in non-dimensionalised values. The wave propagates from left to right in all figure y-direction is into the figure in the top row, and is directed downwards in the p

Palm et al (2018)

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CORPOWER: PASSIVE CONTROL

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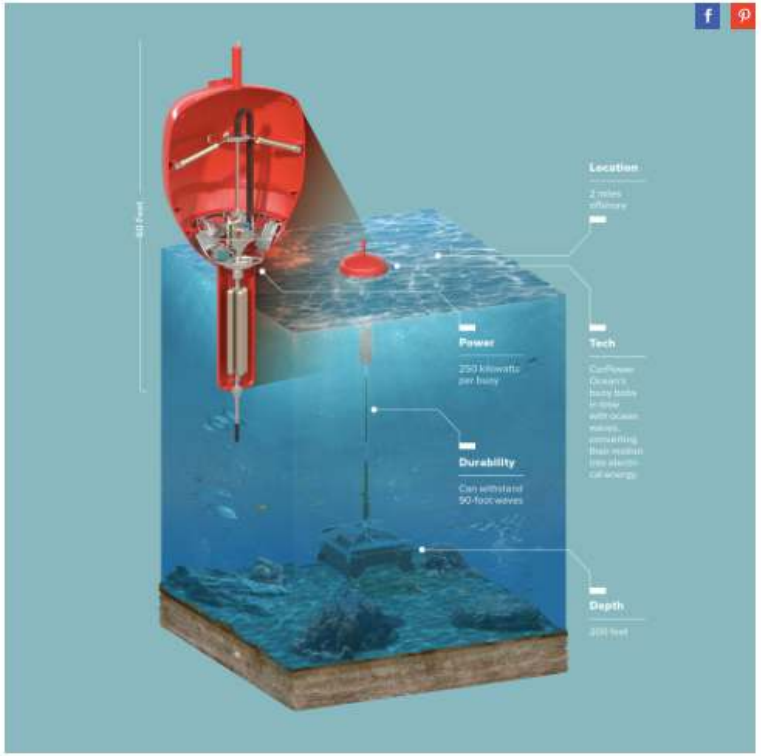
THE WONDER-BUOY THAT MAY FINALLY MAKE WAVE ENERGY FEASIBLE



CRISTIANO RINALDI

5 times higher Annual Energy / mass compared to conventional point absorbers without phase control. [MWh/ton]
3 times higher Annual Energy / PTO Force compared to conventional point absorbers without phase control. [MWh / kN]

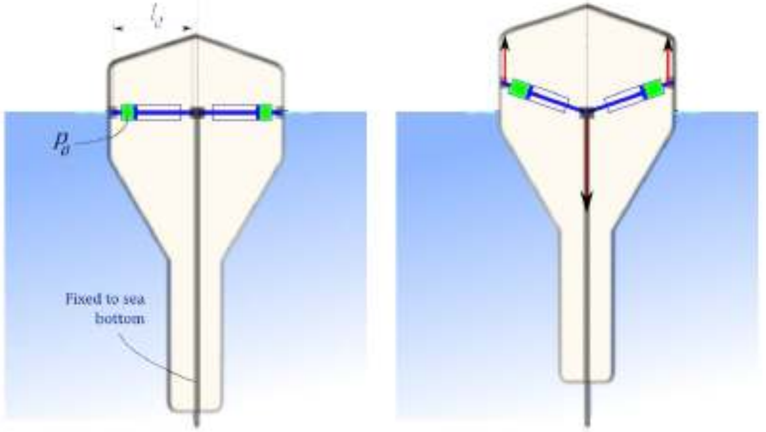


Fig. 5. Illustration of how the buoy displacement induces a vertical spring force with negative stiffness. Buoy in mean vertical position (left) and displaced upwards (right).

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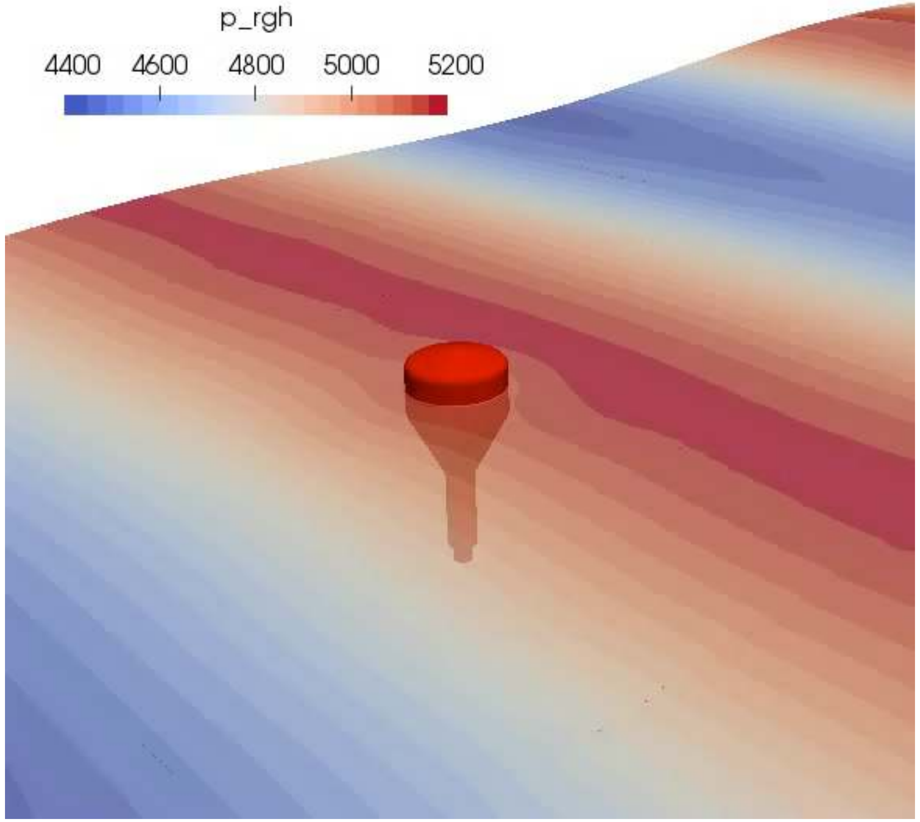
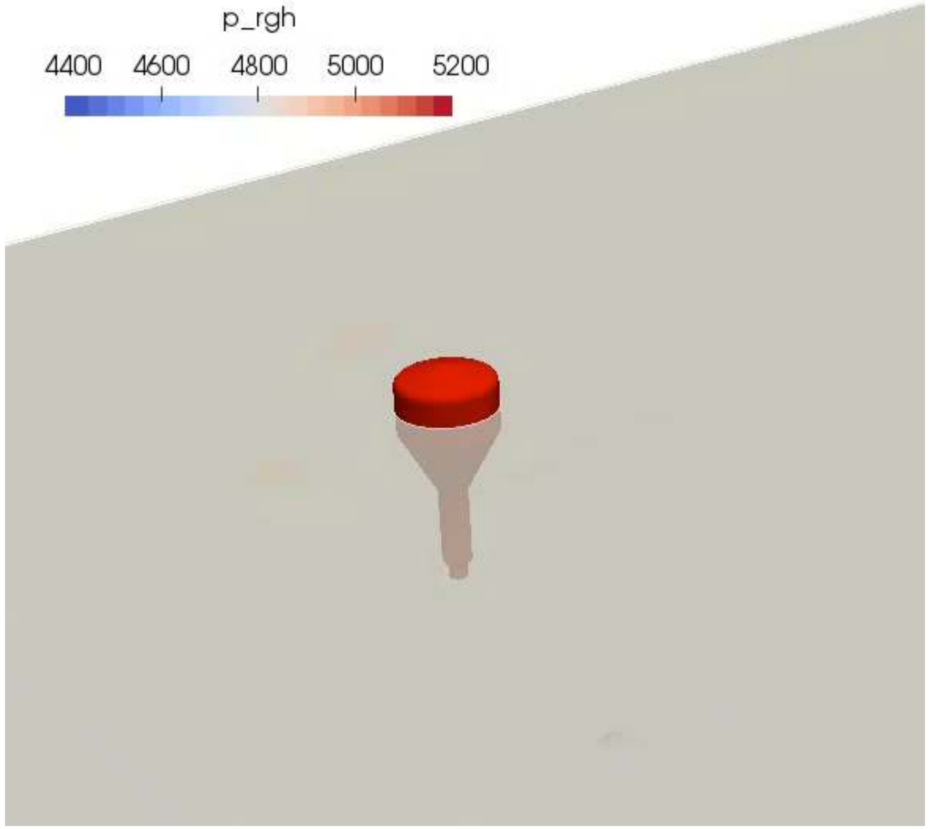
Hals et al (EWTEC 2015)





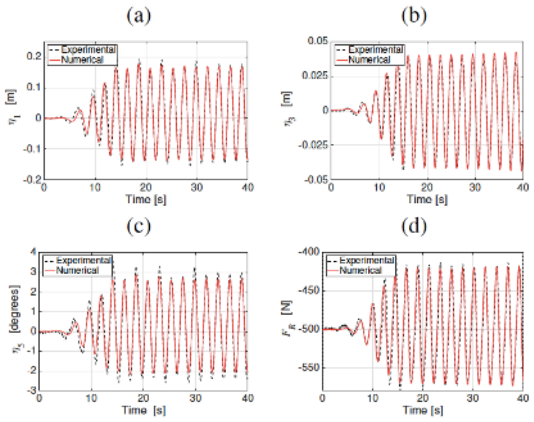
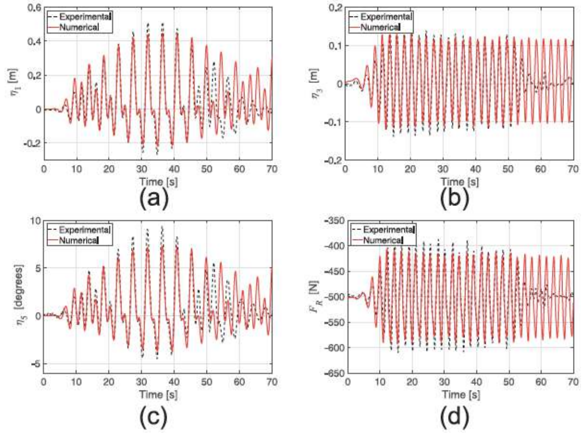


Figure 7. Motion response and force with linear damper PTO:



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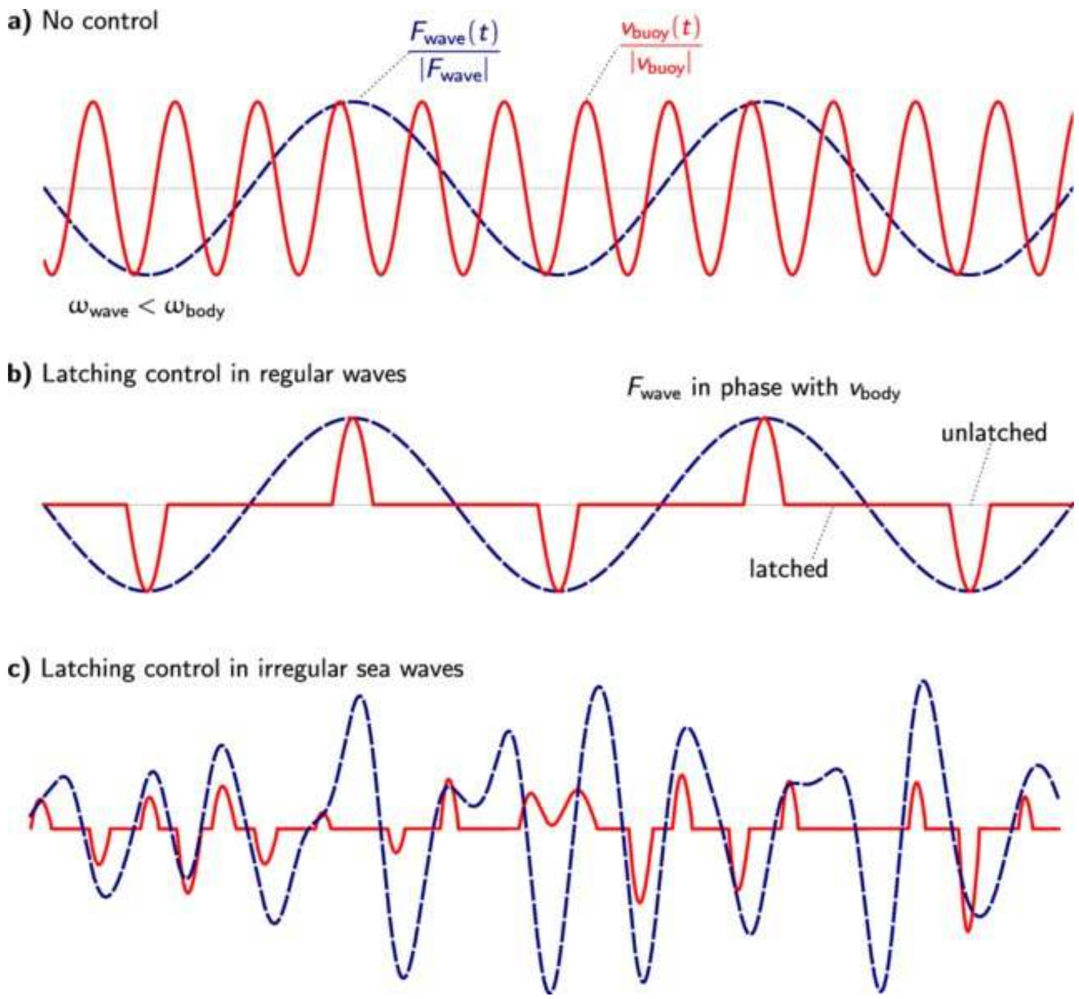
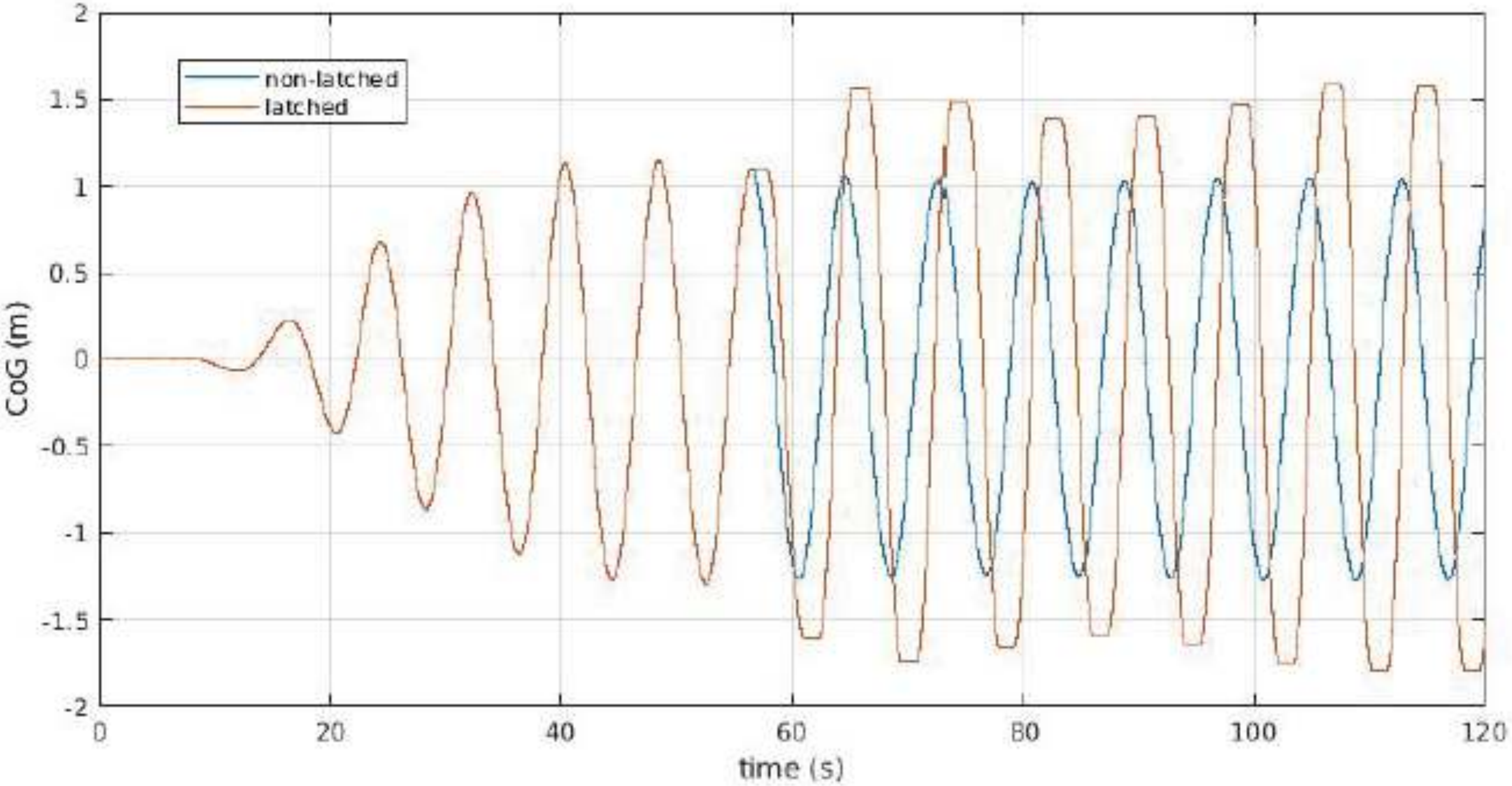
LATCHING: REACTIVE CONTROL

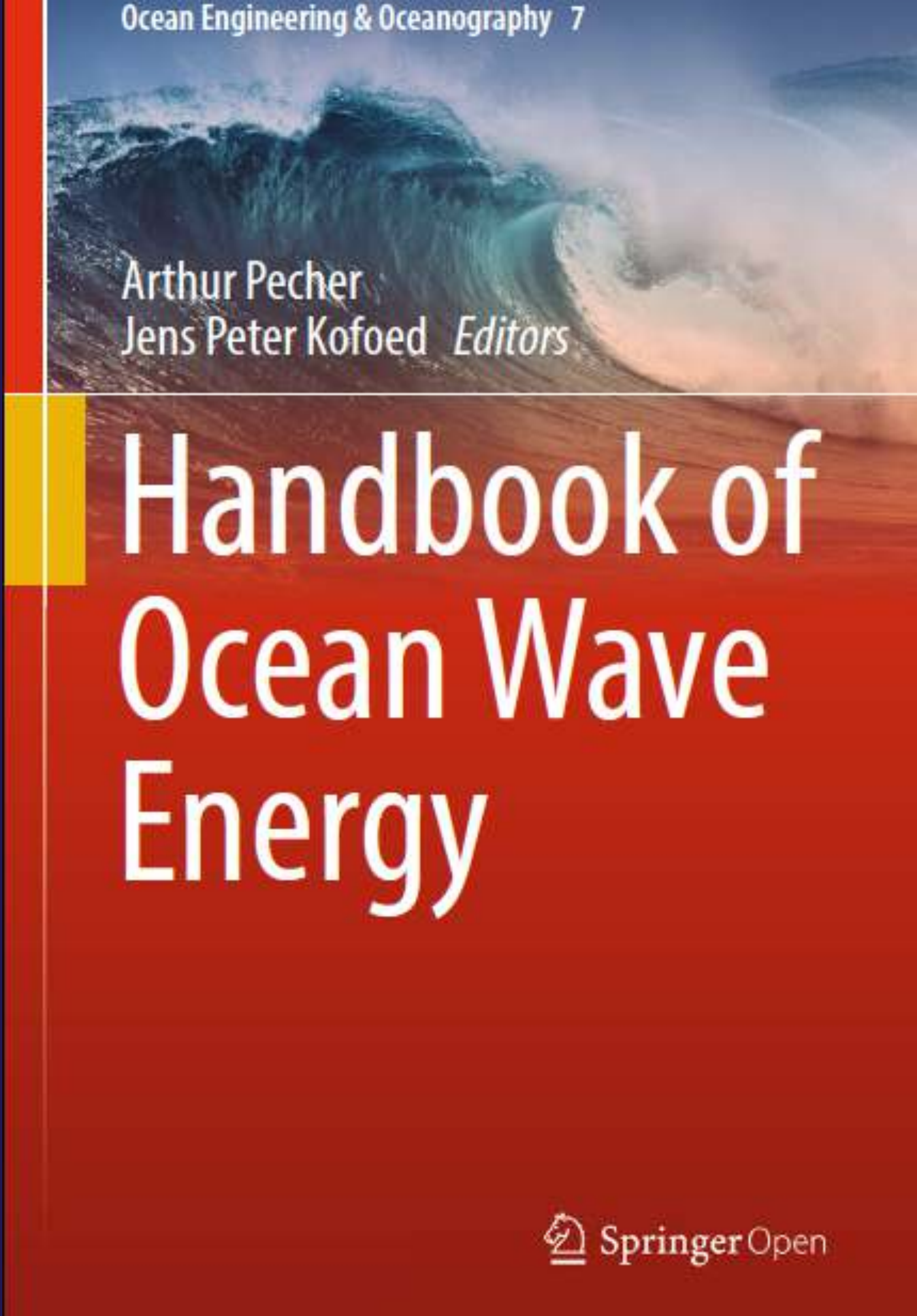


CFD LATCHING



QUESTIONS

- I CAN RECOMMEND “HANDBOOK OF OCEAN WAVE ENERGY” OPEN ACCESS BOOK FROM SPRINGER



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