Best Practices & considerations to evaluate WECs

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Once you leave

You should be aware

- ✓ What are waves and how we describe wave
- ✓ What is wave energy & wave resource assessments
- ✓ Wave energy converters & how to estimate power

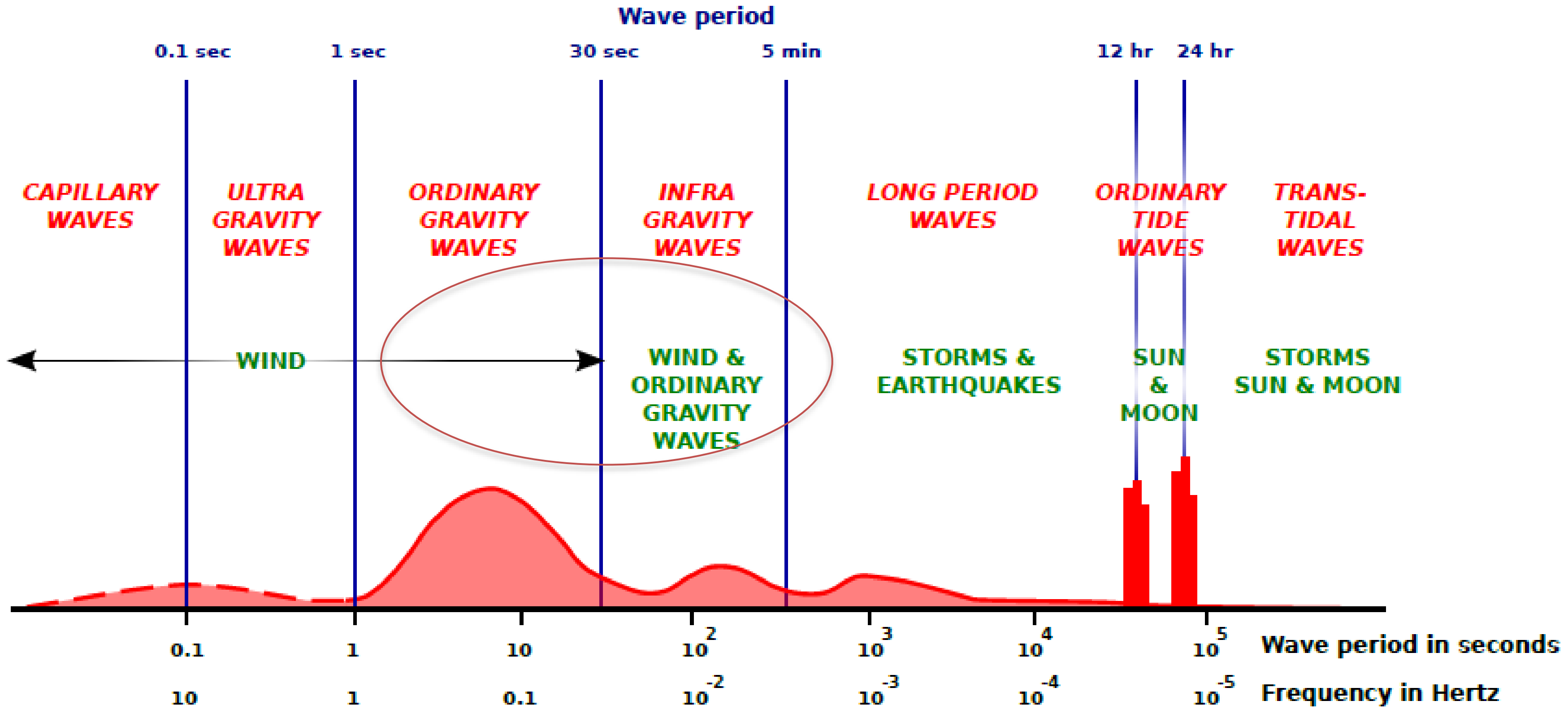
Introducing waves as a resource

Definition

In general an ocean/sea wave is:

"the mean of vertical motion of the ocean surface"

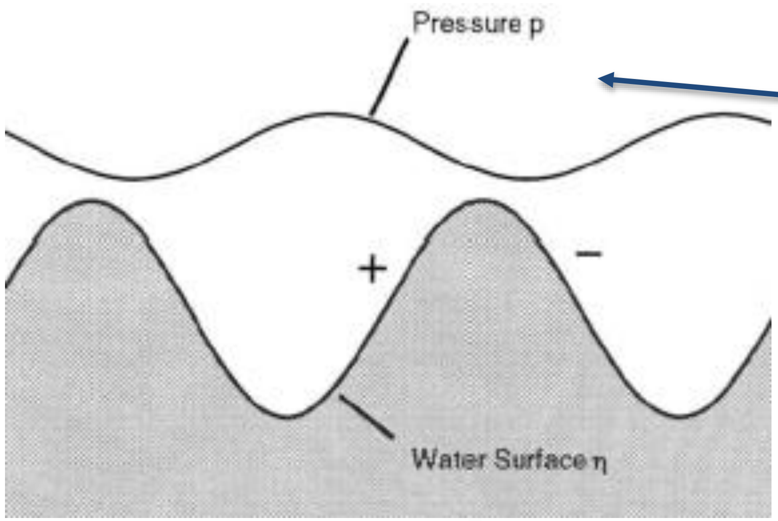
*Vertical motion can be either due to **wind**, **gravity**, tectonic plates, etc.. There are numerous "wave" version(s), however we focus at **<u>wind generated waves</u>**.*



Ardhuin 2018

Wind generated waves

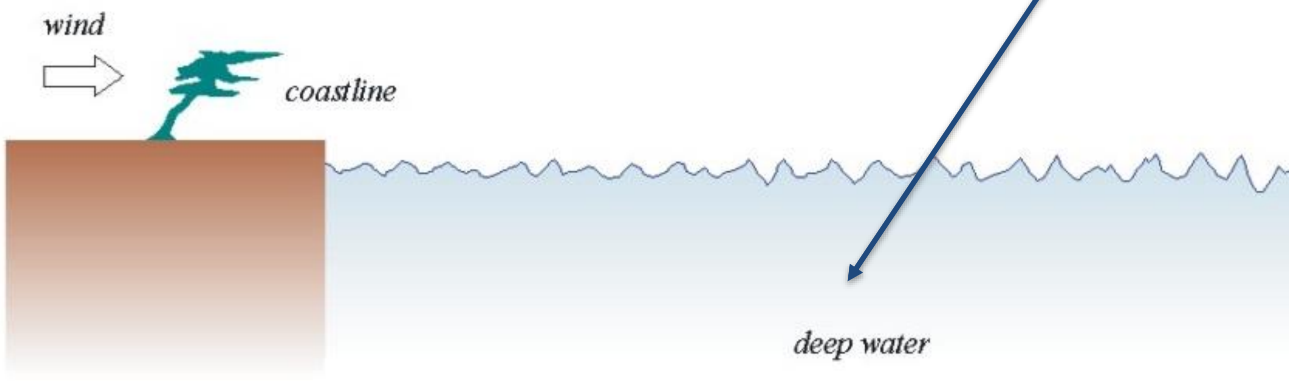
Real ocean waves are more complex and most are irregular waves



Wind pressure is applied to sea surface

Wind generated waves often occur at small regions and are usually of lower height.

Komen et al 1994



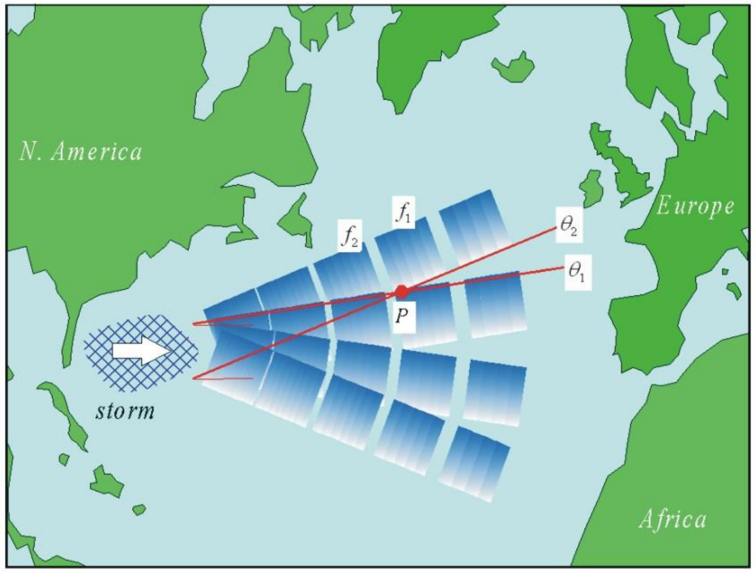
However.....

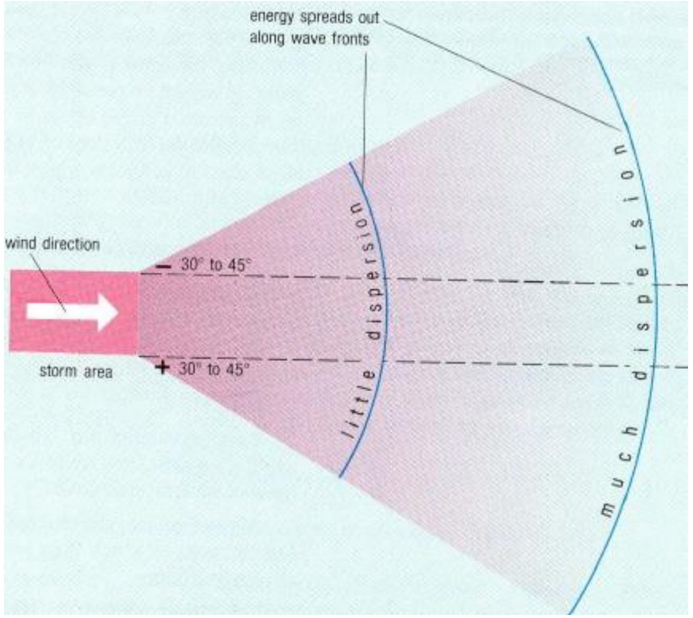
Holthuijsen 2010

Swells

Wind generated waves travelling long distances, "transform“ into swells

They tend to maintain a constant direction with some directional spreading



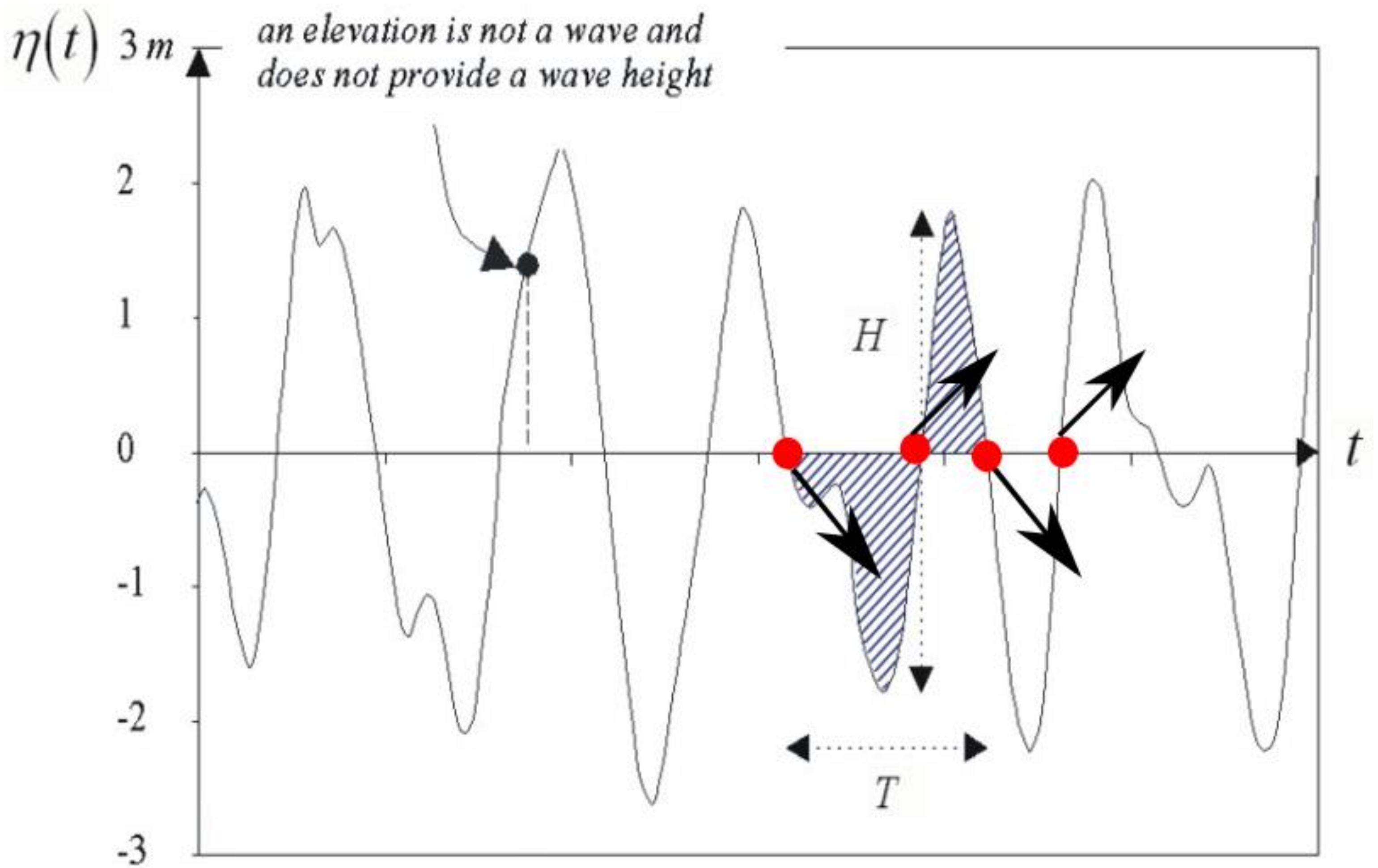


- High frequency (low periods) "merge" to form lower frequency
- Lower frequency waves, travel faster

Holthuijsen 2010

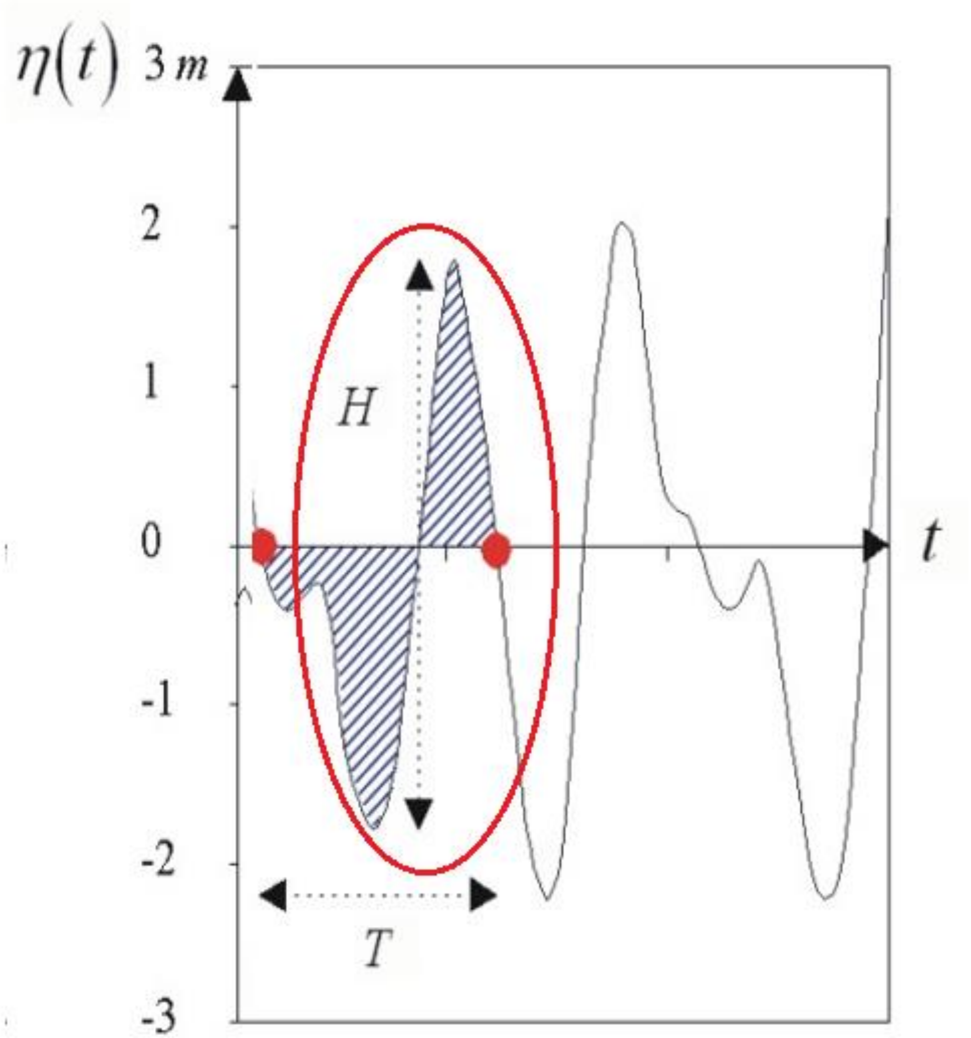
Metocean characteristics

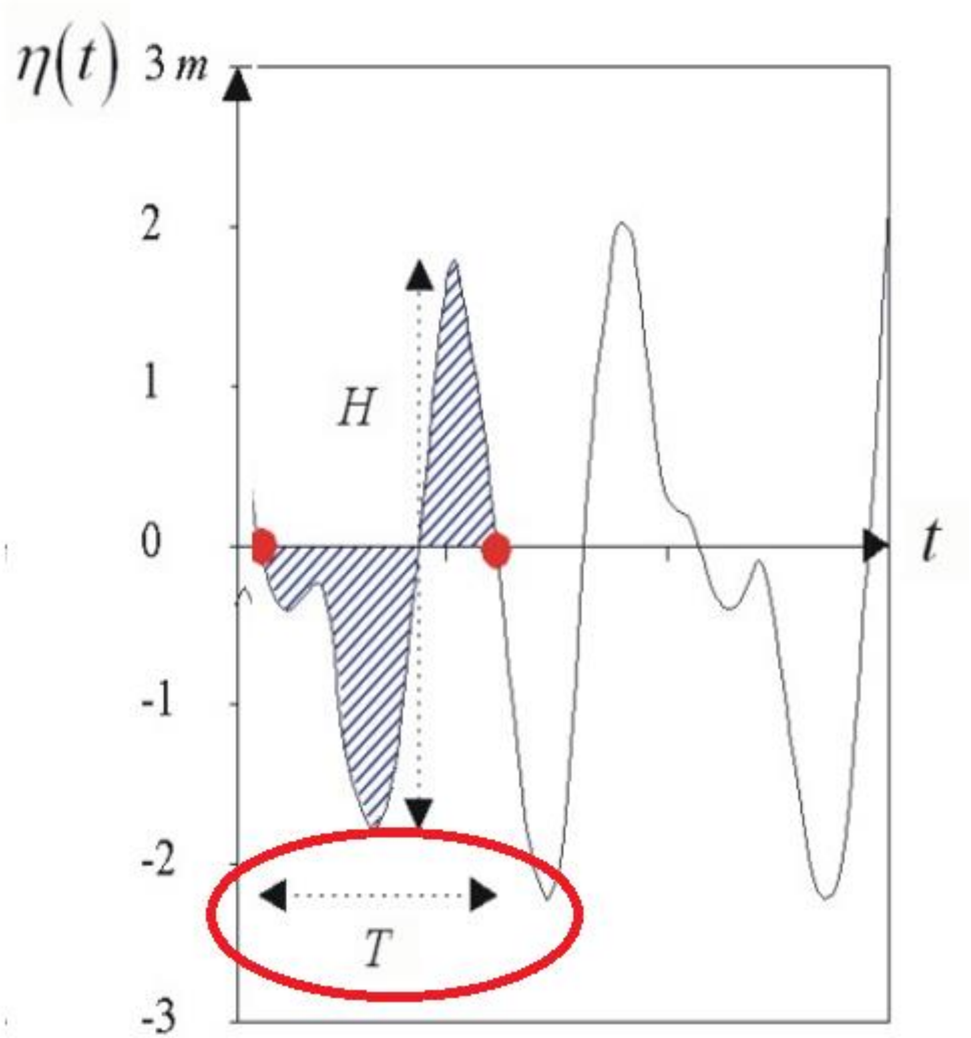
A wave **is not** every surface elevation



Holthuijsen 2010

Height & Period(s)

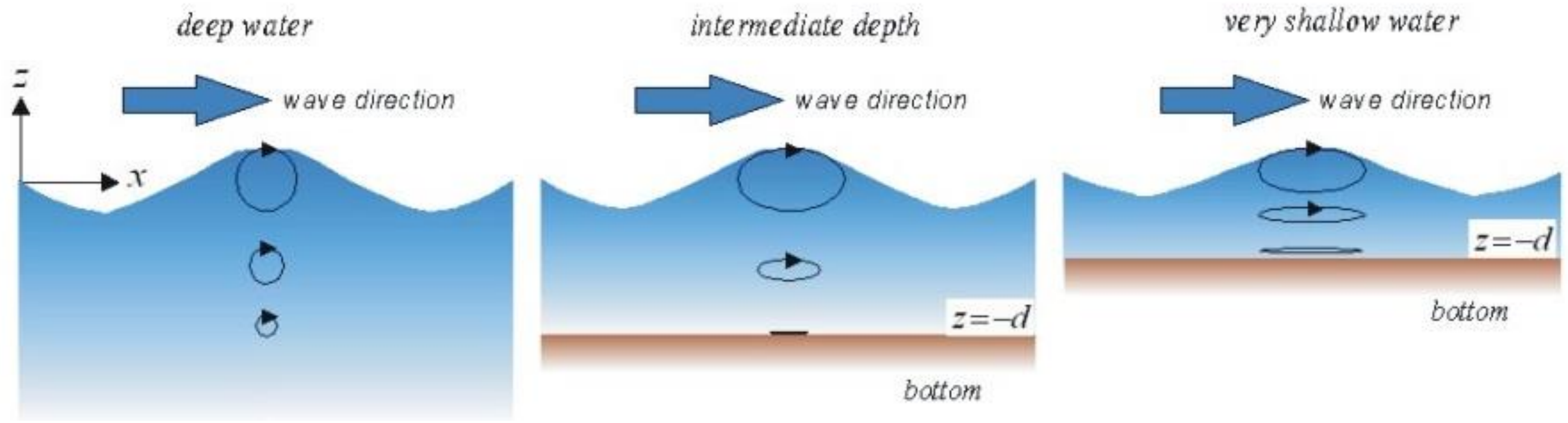




Holthuijsen 2010

Non Linear Waves

Local characteristics affect waves

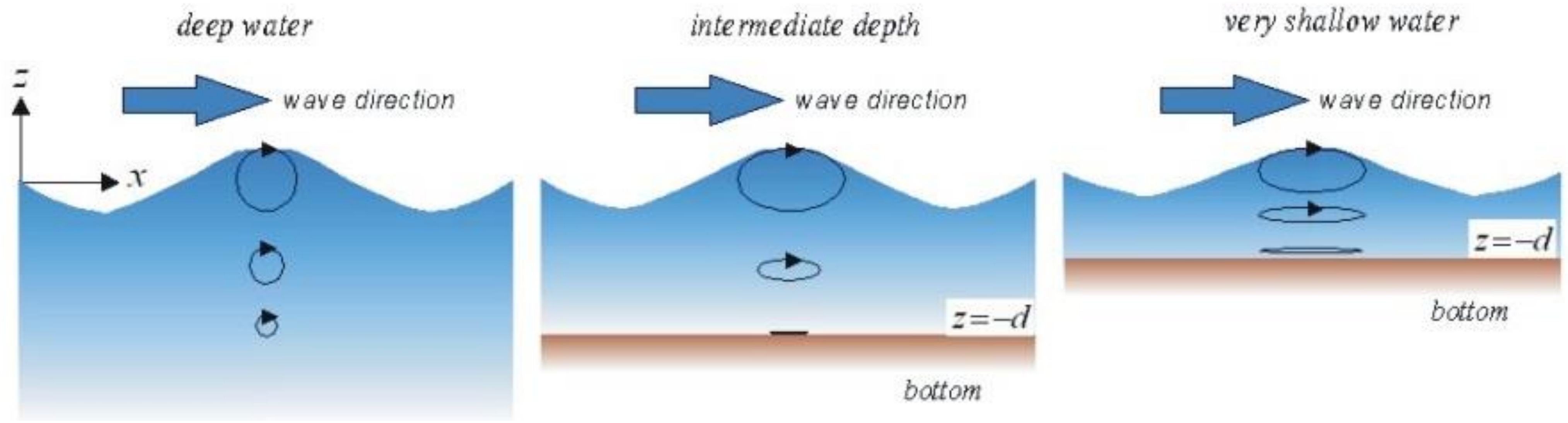


- ✓ No interaction with the bottom
- ✓ Water particles moves in circle
- ✓ Diameter of orbital motion decreases with depth
- ✓ Wave speed (celerity) proportional to wavelength

$$L = 1.56 \cdot T^2$$
$$C = 1.56 \cdot T$$
$$C = 1.56 \cdot \sqrt{L}$$

Holthuijsen 2010

Non Linear Waves



$$C = \sqrt{g\,h}$$

- ✓ Orbital motion changes due to bottom interactions
- ✓ Transforming wave column into ellipse
- ✓ Surge motion is more common.
- ✓ Celerity proportional to depth of water.

Holthuijsen 2010

Depth Effects

Bottom friction

- Effects of seabed on water column
- Negative effects
- Depends on seabed particles roughness
- Site specific
- Material specific

Depth breaking

- At shallow depth breaking is more often
- Cannot be predicted always
- Preferred to obtain by a ration of wave height-to-depth

$$\frac{H_{max}}{d} \approx 0.75$$

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Near & Shallow waters

Shoaling & Reflection

- ✓ Phase speed = Group velocity
- ✓ Waves disperse less
- ✓ Waves will reflect on coastlines
- ✓ Pending on morphology (i.e. sloped, vertical etc.)
- ✓ Returning waves cause higher non-linear losses

Refraction & Diffraction

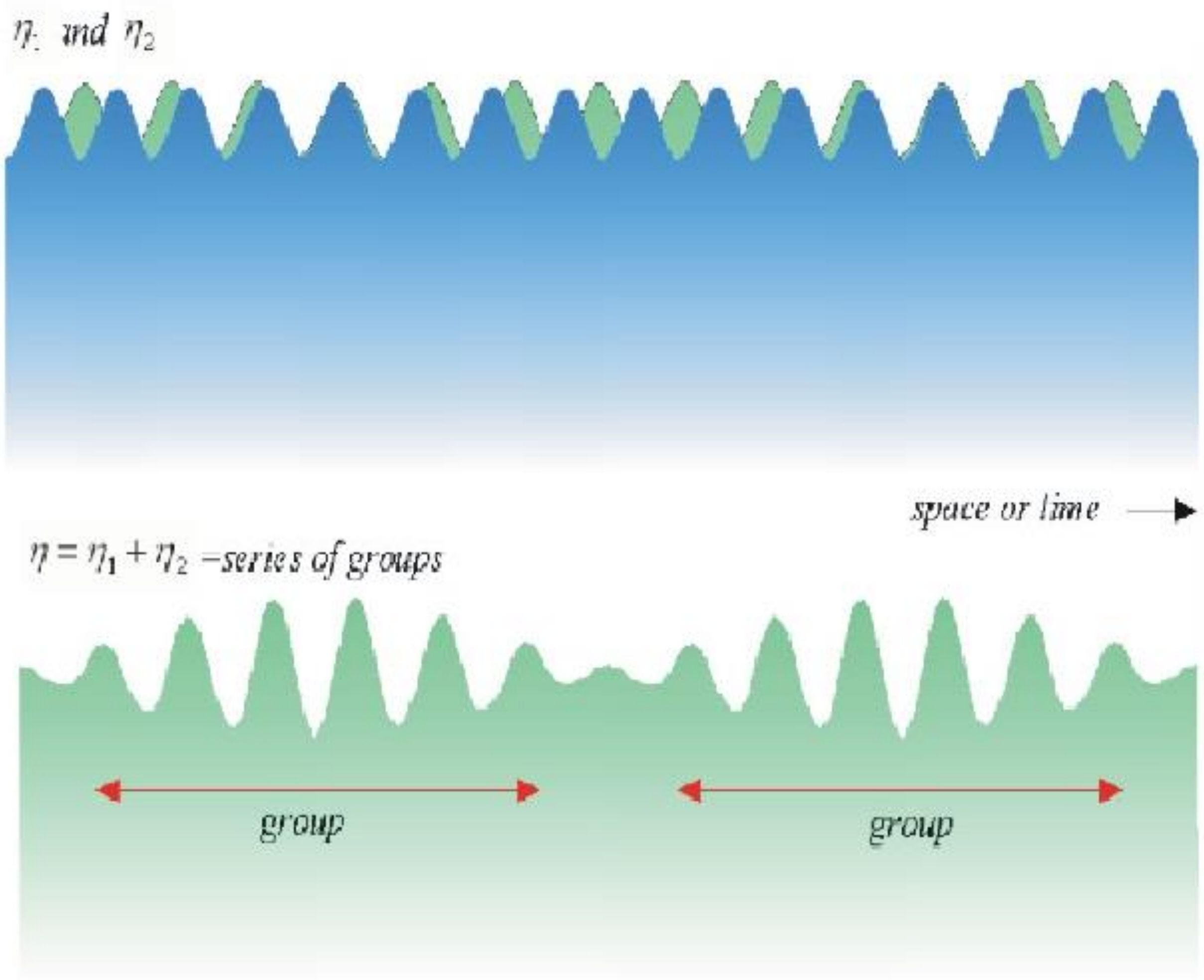
- ✓ Waves slowly change direction as they move ashore
- ✓ As in the case of other wave types (i.e. Snel's Law similarities)
- ✓ Long-crested waves prefer to propagate to lower energy region
- ✓ Waves **will** propagate to sheltered lower resource region

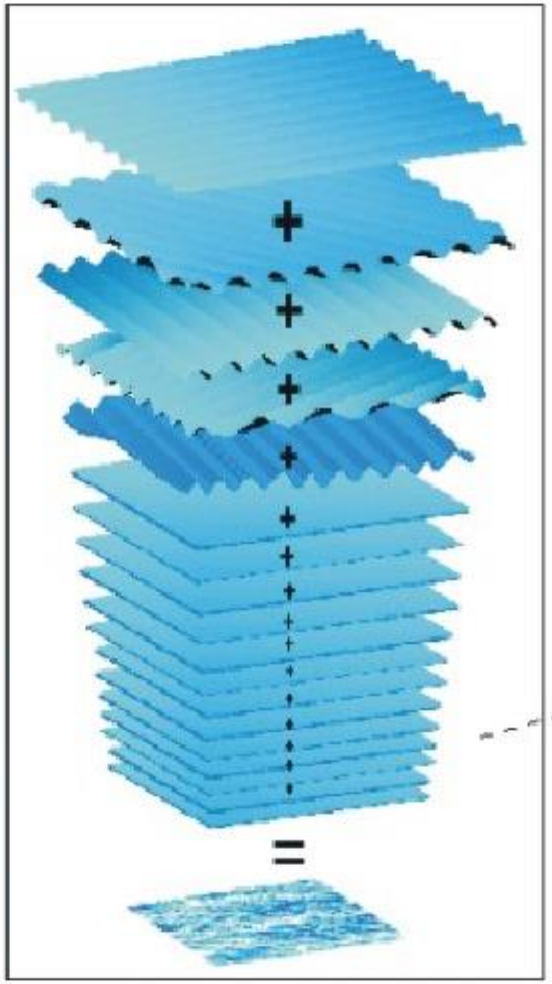
Dominant physical processes in nearshore environments and can affect the wave characteristics

Waves in reality

Real waves

Real Seas encompass waves that have multiple characteristics (irregular, swells, wind-waves etc.).





They constitute a variety of periods/frequencies and elevations.

Holthuijsen 2010

Wave Spectra

Basic concept : Wave spectrum is surface elevation as a function of time, always considering numerous harmonic waves

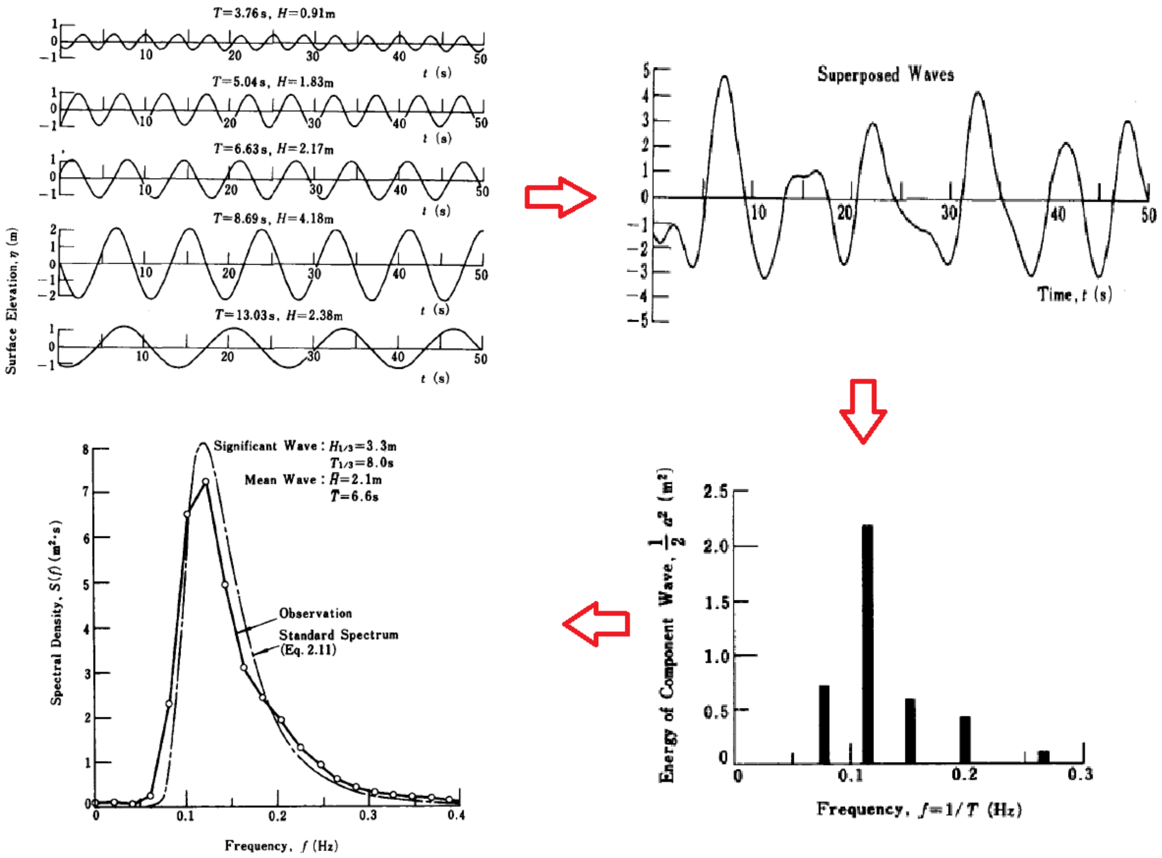
- ✓One directional spectrum (1D)
- ✓Two directional spectrum (2D)

$$n(t) = \sum_{i=1}^{N} a_i \cdot \cos(2\pi \cdot f_i \cdot t + \varphi_i)$$

This is the random-phase amplitude model !!

1D Spectrum

Seas **do not** have pre-defined **OR** discrete range of frequencies, **nor** are they stationary in time.



$$E(f) = \lim_{\Delta f \to 0} \frac{1}{\Delta f} \cdot E \cdot \left\{\frac{1}{2} \cdot a^2\right\}$$

$$E_{energy}(f) = \rho \cdot g \cdot E(f)$$

Units in

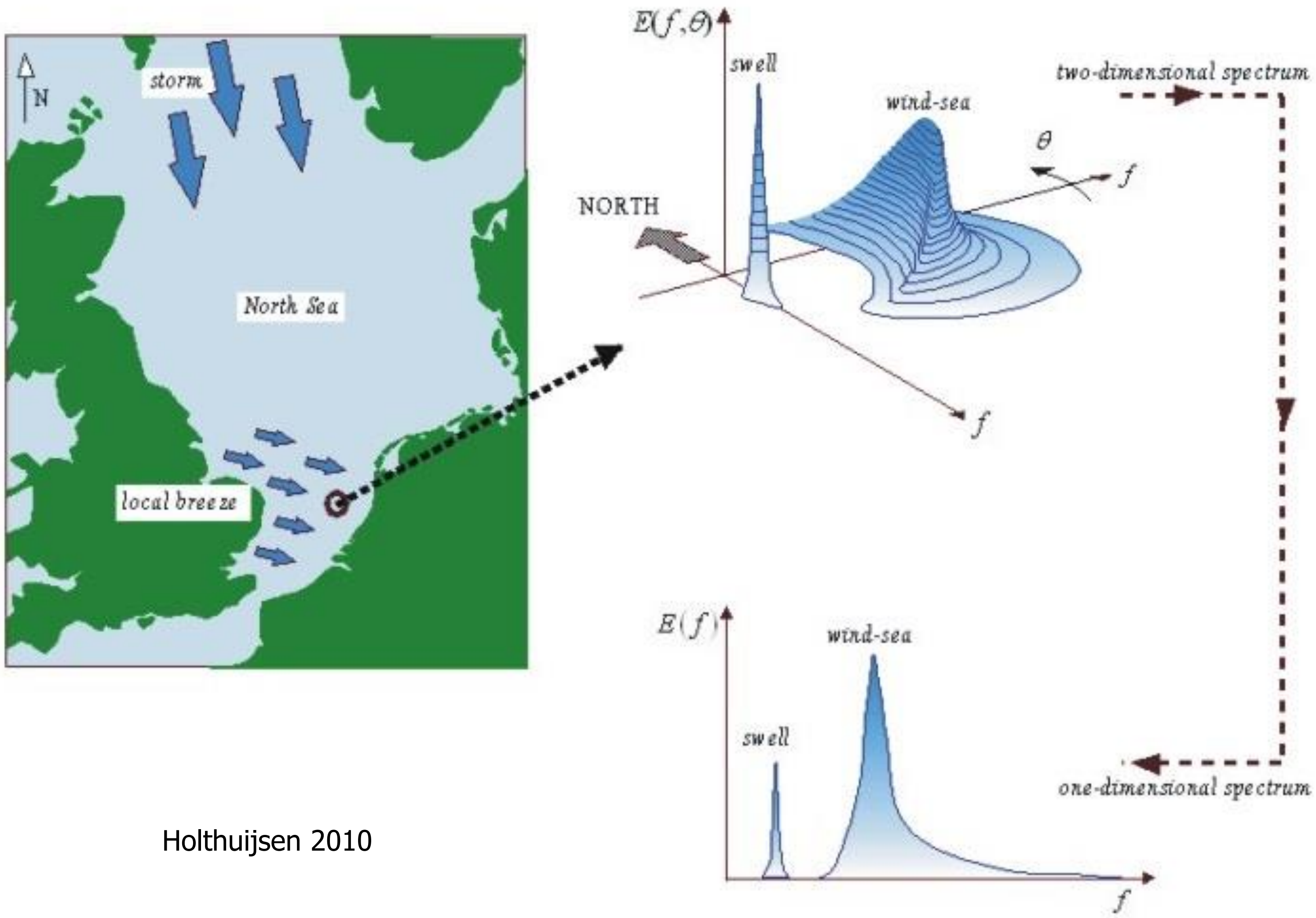
$\boldsymbol{m^2 \cdot s}$

or

$\boldsymbol{m^2/Hz}$

The 1D spectrum describes large number of waves in the time/frequency domain

2D spectrum



Holthuijsen 2010

$$E(f,\theta) = \lim_{\Delta f \to 0} \lim_{\Delta\theta \to 0} \frac{1}{\Delta f \cdot \Delta\theta} \cdot E \cdot \left\{\frac{1}{2} \cdot a^2\right\}$$

$$E_{energy}(f,\theta) = \rho \cdot g \cdot E(f,\theta)$$

Units in
$m^2/Hz/rad$
Or
$m^2/Hz/degrees$

Description of spectral for real waves

Wave Spectra

- ✓ Wind generated waves are random
- ✓ Superposition of larger number of waves
- ✓ Waves is described according to amplitudes and energy variance
- ✓ Some variations of spectra exist

Spectra (Empirical)

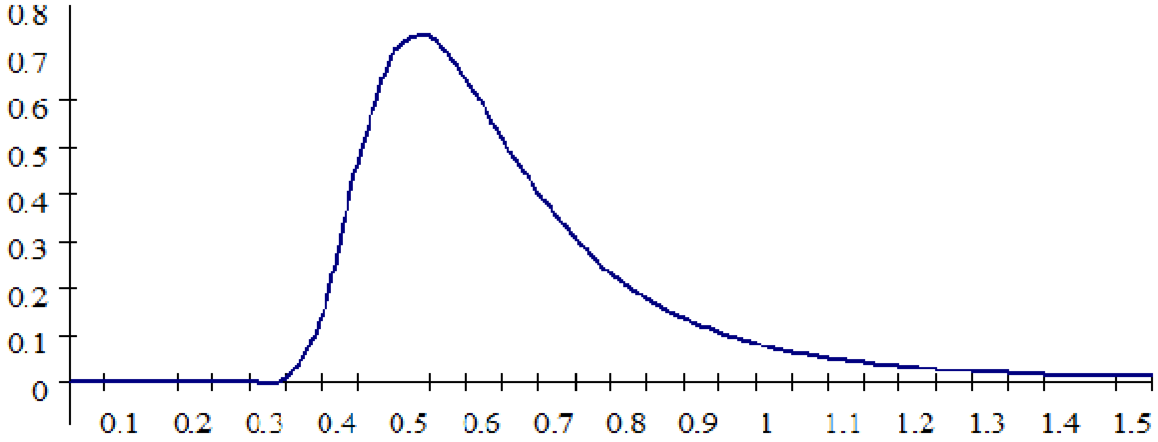
- ✓ Pierson-Moskowitz (PM)
- ✓ Joint North Sea Wave Project (JONSWAP)
- ✓ Other empirical formulations

Ocean spectra of real waves provide realistic descriptions.

Major consideration is that wind acts as the generating and propagating force

Spectra

Pierson-Moskowitz (PM)



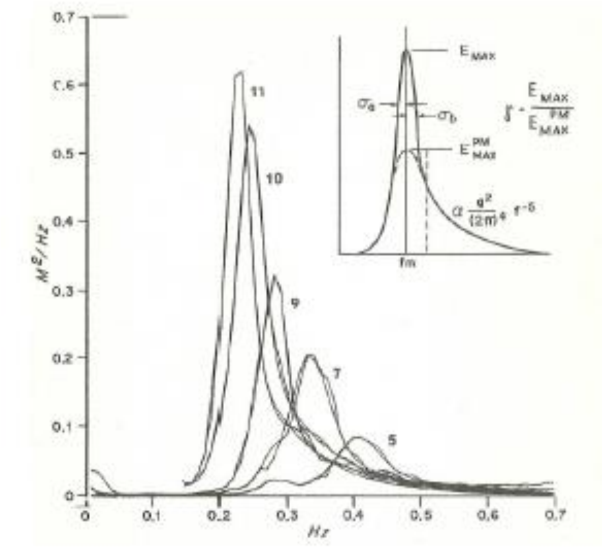
$$E(f,\theta) = \alpha_{PM}\cdot g^2\cdot(2\pi)^{-4} f^{-5}\cdot exp\left[-1.25\cdot\left(\frac{f}{f_m}\right)^4\right] \cdot\left[-\frac{1}{2}\cdot\left(\frac{\frac{f}{f_m^{-1}}}{\sigma_{peak,param}}\right)\right]$$

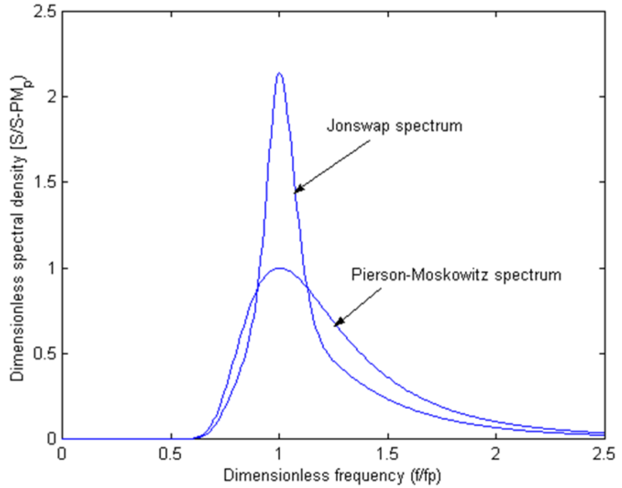
$$f_m = \frac{\nu^{PM}_{19.5} g}{U_{19.5}} \ \& \ H_{m0} = 0.023\cdot U^2_{19.5}$$

with:

$$\sigma_{peak,param} = \begin{cases} \sigma_\alpha & f \leq f_m \\ \sigma_\beta & f > f_m \end{cases}$$

JONSWAP





Hasselmann et al 1973

Tides & currents

- ✓ Local environmental characteristics also include, local wave current and tidal resources.
- ✓ Pending on region and resolution at which is observed, tidal & current effects can alter direction and reduce wave energy propagated.
- ✓ These consideration will depend on the level of study, and application
- ✓ Different approach to higher non-linear physical solution is needed

Wave Monitoring

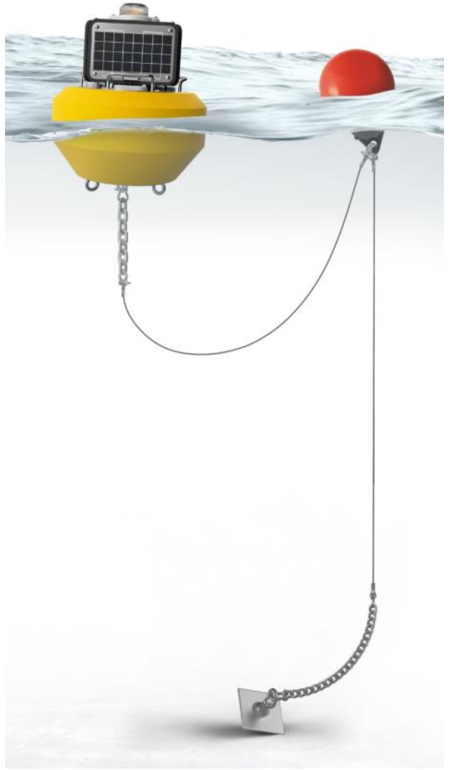
Why data acquisition & monitoring ….

Applications	Objectives	Methods
✓ Maritime	✓ Hindcasts	✓ In-Situ
✓ Marine structures	✓ Forecast studies (short/long & term)	✓ Ship/human observations
✓ Offshore platforms	✓ Climate Change	✓ Satellites
✓ M&O	✓ More ……	✓ Numerical Wave Models (NWM)
✓ Offshore energies		
✓ More…..		

In-Situ

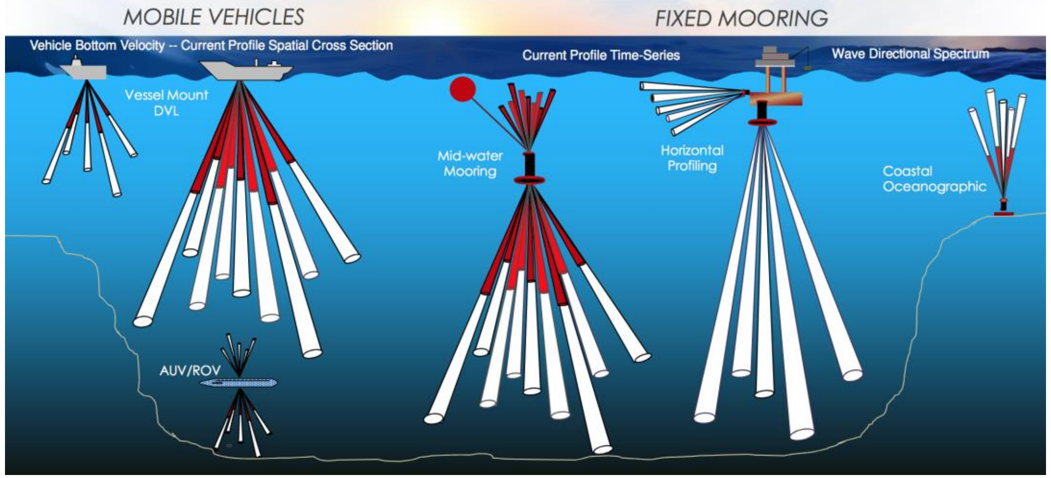
Limitations for wave buoys

- ✓ Area coverage
- ✓ Time recording duration
- ✓ Monitored quantities
- ✓ Dependence on moorings
- ✓ Breakdown events (non-recording)
- ✓ Filtering processes required



Limitations for ADCP

- ✓ Limited vertical resolution
- ✓ Limited measurement range
- ✓ Susceptibility to noise
- ✓ Influence of surface roughness
- ✓ Influence of current



Ship/Human Observation

Limitations

- ✓ Requires experienced personnel
- ✓ Short duration-expedition
- ✓ Limited applicability & range
- ✓ Subjectivity & Human error
- ✓ Incomplete information
- ✓ Lack of precision

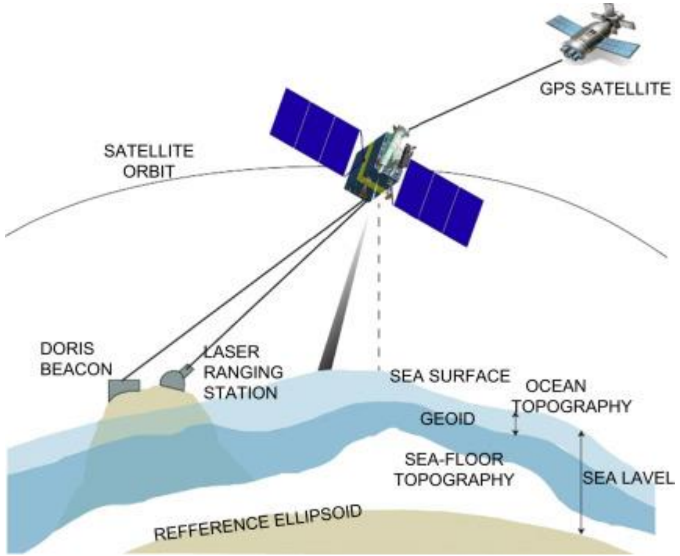
Some examples can be

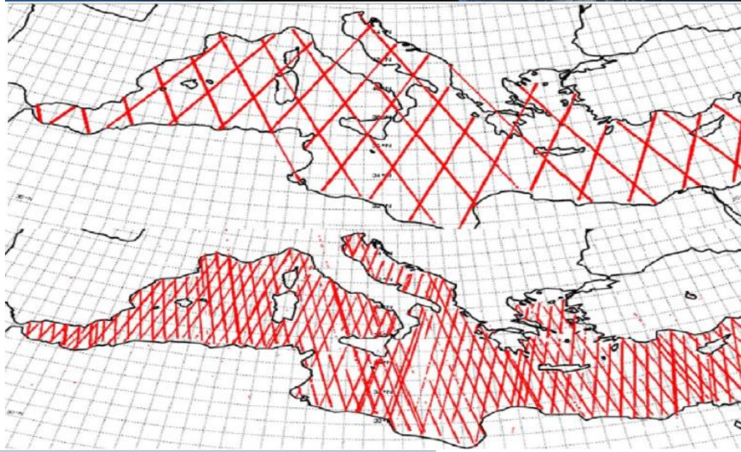
- Shore based observation
- Boat-based observations
- Aerial observations
- Video observations
- Human observations

Satellites/Altimeter/Radar Altimetry

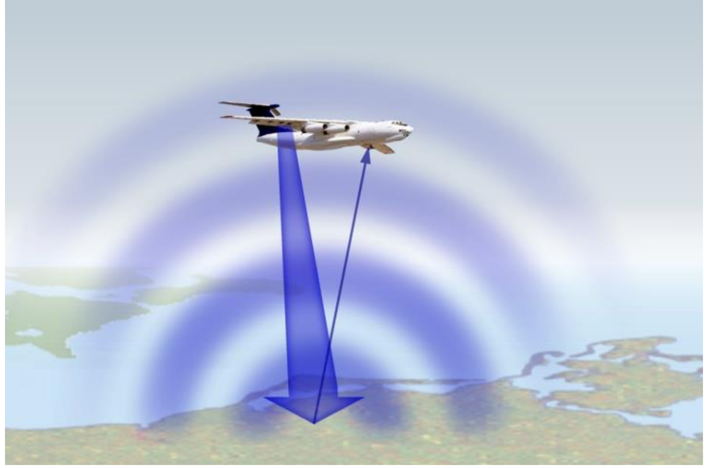
Limitations

- ✓ Temporal recordings
- ✓ Coverage
- ✓ Applicability nearshore & coastal waters
- ✓ Filtering processes are necessary
- ✓ Not immediately available
- ✓ Affected by weather phenomena
- ✓ Affected by other human tech (radar, etc)
- ✓ Not suitable for measuring in shallow or near shorelines





Cavaleri et al 2019



Numerical Wave Models

Continuous improvements on models have enhanced our knowledge on waves, past, present and future.

- ✓Wave resource
- ✓Boundary interaction
- ✓Ocean feedback to atmosphere
- ✓Temperature
- ✓Tsunami, extreme storms
- ✓etc.....

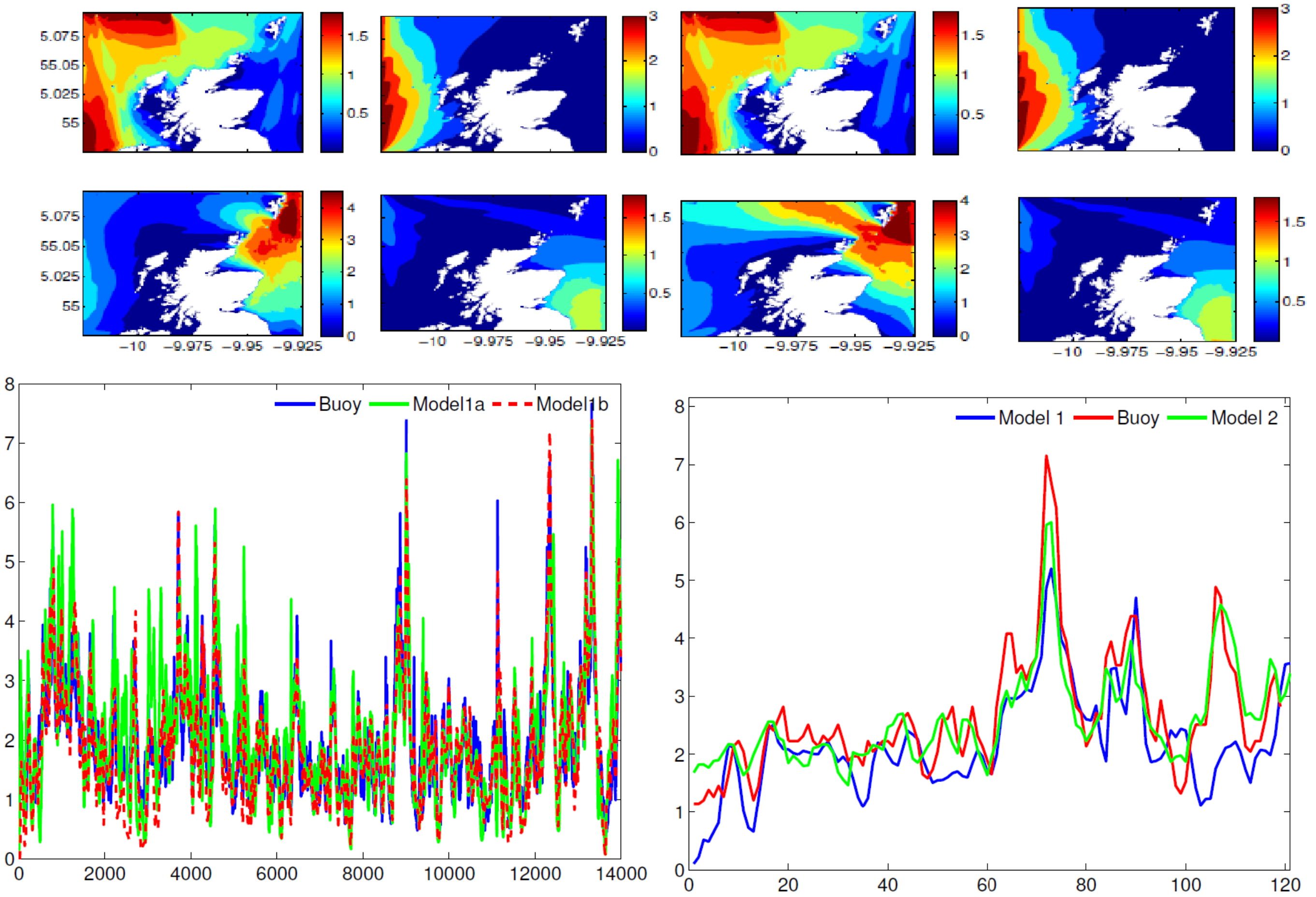
Strengths	Weaknesses
Global and/or Local coverage Computing Speed Accuracy Historical data Forecast data Results for multiple industries Multiple nesting Physical solutions of complex terms Timescale of results Tuning of physical properties Data Assimilation HPC multi-threading (computing)	Experience of User Data for calibration, validation Storage requirement Computing requirements Tuning of physical properties Improvements for physical terms Quality of inputs
Opportunities	**Threats**
Data assimilation Multi-model communication HPC multi-threading (computing) Quality of Inputs	User Experience Instability of propagation schemes Allocation of computing resources Processes based on empirical formulations

Lavidas et al 2018

Numerical Wave Models

Limitations

- ✓ Inputs quality
- ✓ Physical calibration
- ✓ Need benchmarking
- ✓ Computational resources
- ✓ Experienced User
- ✓ High level of tuning



Lavidas et al 2017

Waves as Energy

Why is the wave resource important?

Short answer: It helps us with day-to-day operations

Long answer: It provides necessary information that can be expanded to many different sectors

- ✓ Naval, maritime (Commercial & Military)
- ✓ Weather forecasting
- ✓ Structures/platforms
- ✓ Ships
- ✓ Fisheries
- ✓ Climate Analysis
- ✓ Climate Change
- ✓ Energies
- ✓ ….

Some applications vital for wave resource

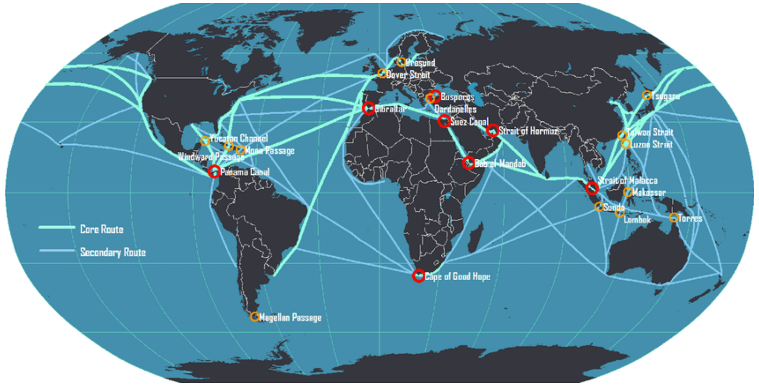
- WEC applications

https://www.offshore-energy.biz/corpower-launches-its-first-commercial-scale-wave-energy-converter

- Design of offshore structures

https://www.nesfircroft.com/blog/2021/06/the-6-biggest-offshore-structures-in-the-world?source=google.com

- Optimal ship routes and safe navigation



https://www.researchgate.net/figure/Major-maritime-shipping-routes-and-strategic-passages_fig1_315398501

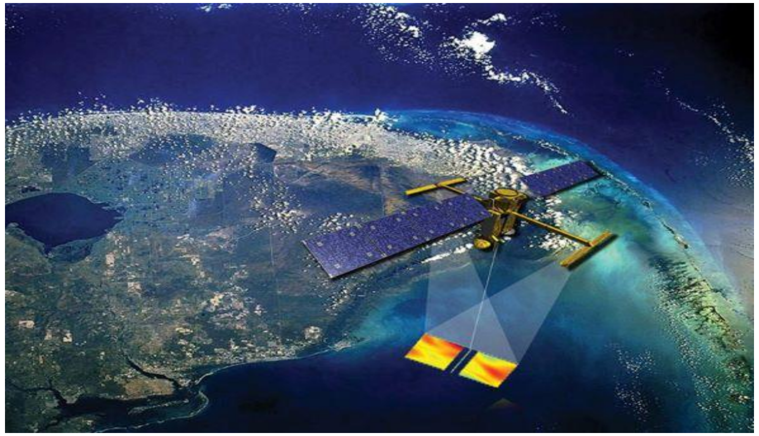
- Ports and harbours

https://zeymarine.com/worlds-biggest-ports/

- Maritime activities

https://en.wikipedia.org/wiki/Commercial_fishing

- SSB Correction



https://www.whoi.edu/satellite-altimetry-mission-promises-huge-advances-for-physical-oceanography-and-hydrology/

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Distribution(s)

Pending on the description desired, waves can be distinguished in two ways:

I. Weather

II. Climate

These two will ultimately use different approaches & outcomes: **Short-term & Long-term** Statistical analysis.

- For shorter periods changes are easily observed i.e. foreshores and shallow water waves.
- Local Characteristics have serious effects

Short-term vs Long-term

Short	Long
✓15-30 min or for a storm 6-12 hr ✓Easily "accessible" ✓Suitable short time intervals & storm ✓Assume Gaussian and stationary ✓Used analyse structures, fatigues and instantaneous characteristics ✓Determine physical wave characteristics	✓Non-stationary ✓Design condition for offshore & coastal structures ✓For energy applications ✓Climate analysis ✓Difficult to obtain data ✓No theoretical distribution model ✓Requires preparation of dataset

Extreme Value Analysis (EVA) is useful in many sector and very important for estimating survivability, applicable to the energy sector

Extreme Value Analysis (EVA)

Usually 20, 50, 100 years of return periods are investigated.

✓Suitable method/empirical distributions need proper selection

✓Access/Development and preparation of datasets

✓"Goodness-of-Fit" assessment

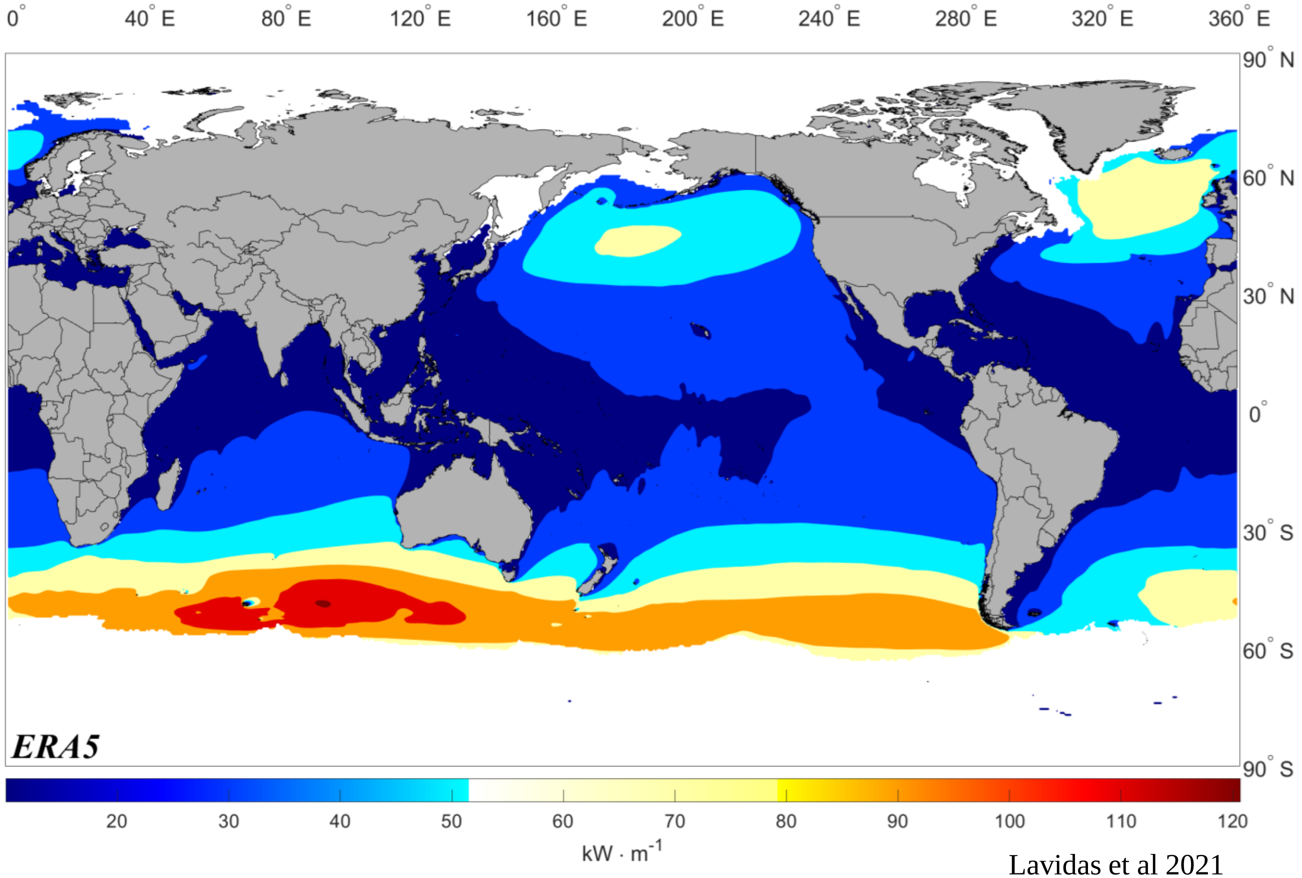
✓Estimation and determination of probabilities of exceedance that **may** occur in the future

✓Awareness of extreme events and expected return values is vital to the design in offshore industries

Recommended duration > 10 years, ideally not less that 20% of the desired return period

Renewable Energy

Asides from the "traditional" application and utilization of ocean & Sea resources by human societies, waves are an inexhaustible source of energy.



Lavidas et al 2021

Wave power is expressed as the energy flux per one unit of crest width (W/m)

Wave power (regular waves)

$\boldsymbol{E_{wave}}$ is the summation of kinetic and potential energy per unit surface area of a wave

$$E_{wave} = E_{kinetic} + E_{pot} = \frac{1}{8} \cdot \rho \cdot g \cdot H_{m0}^2 \cdot C_g$$

$$\lambda_{wave} = T \cdot \sqrt{\frac{g}{k} \cdot tanh \cdot (k \cdot h)}$$

$$C = \frac{\lambda_{wave}}{T}$$

$$C_g = \frac{1}{2} \cdot \left[1 + \frac{2kh}{\sinh(2kh)}\right] \cdot C$$

$$P_{wave} = \frac{\rho \cdot g^2 \cdot H_{m0}^2 \cdot T}{32 \cdot \pi}$$

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Wave power (irregular waves)

$$C_g\,(f,h) = \frac{1}{2}\cdot\left[1+\frac{2kh}{\sinh(2kh)}\right]\cdot C$$

$$E_{wave} = \frac{1}{8}\cdot\rho\cdot g\cdot H_{m0}^2\cdot C_g(f,h)$$

In this case (f) is represented by the Energy period: $T_e = \frac{m_{-1}}{m_n}$

$$m_n = \int_0^{2\pi}\int_0^{\infty}\sigma^n\cdot E(f,\theta)\cdot df\cdot d\theta$$

$$P_{wave} = \frac{\rho\cdot g^2\cdot H_{m0}^2\cdot T_e}{64\cdot\pi}$$

In W/m or kW/m

Wave power (irregular waves) | Spectral formulation

$$H_{m0} = 4\sqrt{\iint E(f,\theta)\cdot df\cdot d\theta}$$

$$P_{wave} = \rho\cdot g\cdot \int_0^{2\pi}\int_0^{\infty} \mathrm{C}_g\cdot E(f,\theta)\cdot df\cdot d\theta$$

$$P_{\chi} = \rho\cdot g\cdot \int\int \mathrm{C}_{g\chi}\cdot E(f,\theta)\cdot df\cdot d\theta$$

$$P_{y} = \rho\cdot g\cdot \int\int \mathrm{C}_{gy}\cdot E(f,\theta)\cdot df\cdot d\theta$$

$$P_{wave} = \sqrt{P_x^2 + P_y^2}$$

In W/m or kW/m

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Resource assessment

A resource assessment that is applicable over wide spatio-temporal conditions can be done (predominately in two ways):

- Satellite Data
- Numerical Wave Modelling

Preparation is Key!!

Depending on data produced or sampled filtering, clearing, modelling and set-up is vital.
Usually to ensure proper assessment a numerical multi-model is the most suitable method.

- ✓Wind Components
- ✓Bathymetry information
- ✓Constructing the model code
- ✓Boundary conditions
- ✓Initial conditions
- ✓Determine time duration
- ✓Determine parameters
- ✓Nesting \& Multi-model combination
- ✓and many more intrinsic and project specific details.

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Action Balance Equation

The Action Balance Equation is applicable both on Cartesian & Spherical, with a full spectral non-stationary solution.

$$\frac{\partial N \cdot (\sigma;\lambda;\theta;t)}{\partial t} + \frac{\partial C_{g,\lambda} \cdot N \cdot (\sigma;\lambda;\theta;t)}{\partial \lambda} + \cos\phi^{-1} \cdot$$

$$\frac{\partial C_{f,\phi} N(\sigma;\lambda;\theta;t)}{\partial \phi} + \frac{\partial C_{f,\theta} \cdot N \cdot (\sigma;\lambda;\theta;t)}{\partial \theta} +$$

$$\frac{\partial C_{f,\sigma} \cdot N \cdot (\sigma;\lambda;\theta;t)}{\partial \sigma} = \frac{S \cdot (\sigma;\theta;\lambda;\varphi;t)}{\sigma}$$

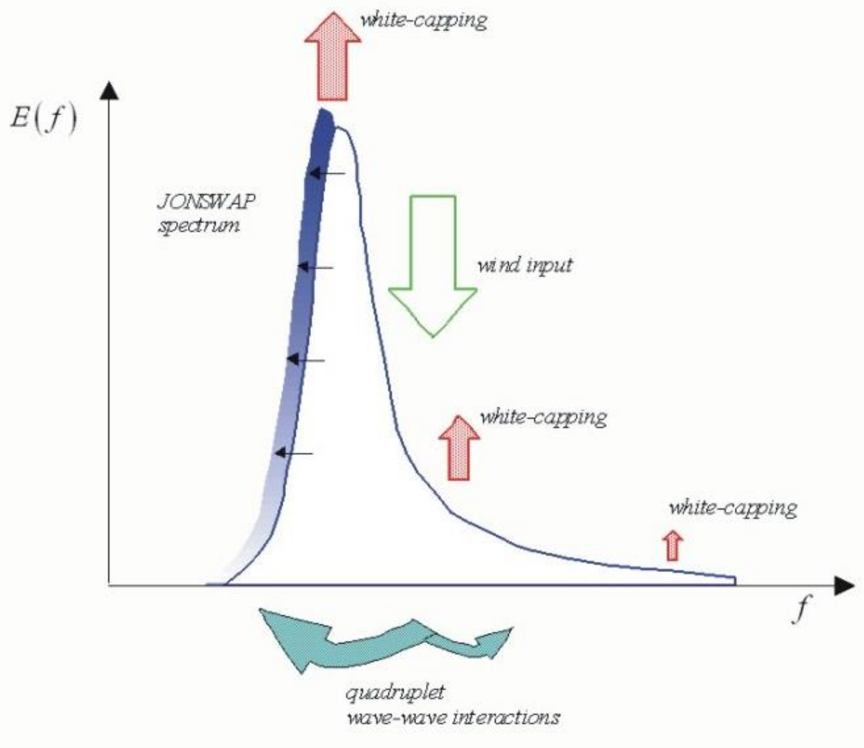
radian frequency=(σ), time $= t$ solution, latitude= λ, longitude $=$ φ, frequency= σ, direction= θ, and group velocities $= C_g$ (for latitude & longitude)

Sink terms

Wave theory and its translation into a working numerical model is presented in terms of the action density balance equation, with an overview of the physics and their importance in the resource analysis (per regional applicability)

$$S_{tot} = S_{in} + S_{nl4} + S_{ds,w} + S_{nl3} + S_{ds,b} + S_{ds,br} + S_{xx}$$

Deep water	Nearshore/Shallow
S_{in}=Wind Input	S_{nl3}=Triad Interactions
S_{nl4}=Quadruplet Interactions	$S_{ds,b}$=Bottom Friction
$S_{ds,w}$=Whitecapping	$S_{ds,br}$=Depth Breaking
	S_{xx}=user defined



Model distinction

	Oceanic waters	Coastal water		
Process		Shelf Seas	Nearshore	Shallow
Wind generation	■ ■ ■	■■	■■	□
Quadruplets	■ ■ ■	■ ■ ■	■	□
Whitecapping	■ ■ ■	■ ■ ■	■	□
Bottom Friction	□	■■	■ ■ ■	■
Depth breaking	□	■	■ ■ ■	■■
Currents	□	■	■■	■ ■ ■
Triads	□	■	■■	■
Reflection	□	□	■ ■ ■	■ ■ ■
Refraction	□	□	■ ■ ■	■ ■ ■

■ ■ ■=Dominant,■■=Significant,■=Minor,□ = Negligible

Holthuijsen 2010

WEC History

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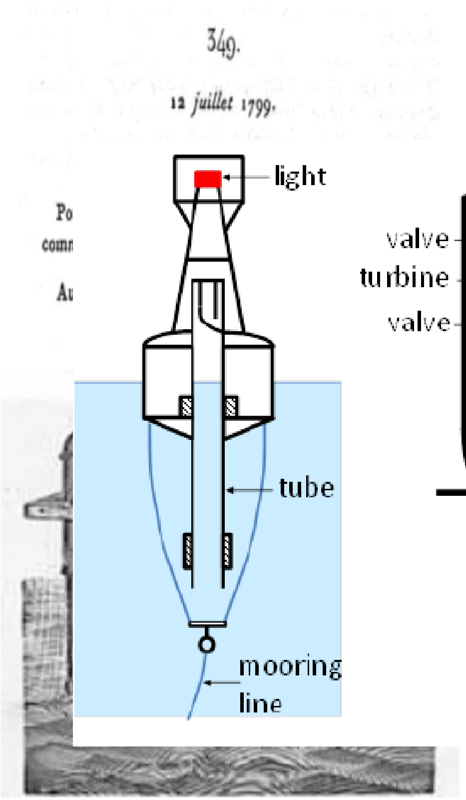
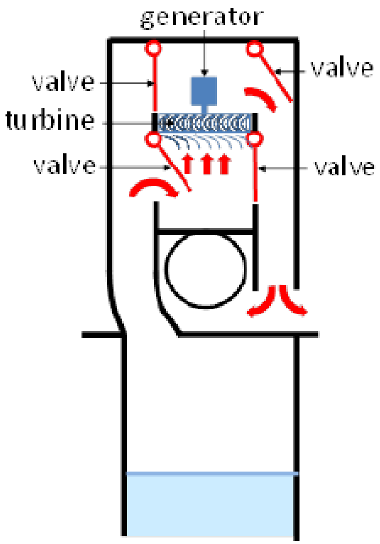
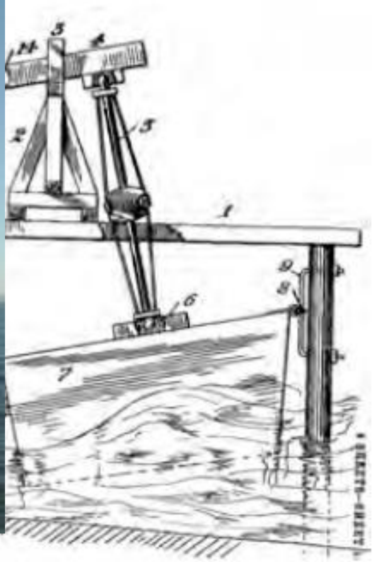
Early sparks

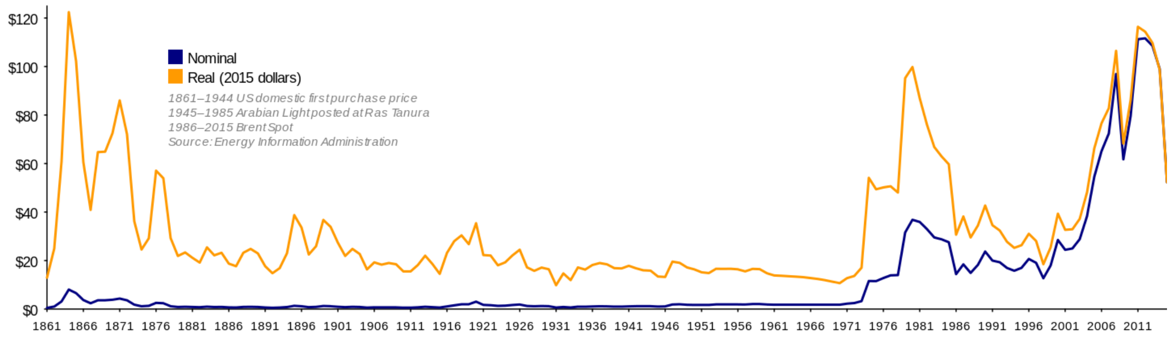
19th & early 20th Century

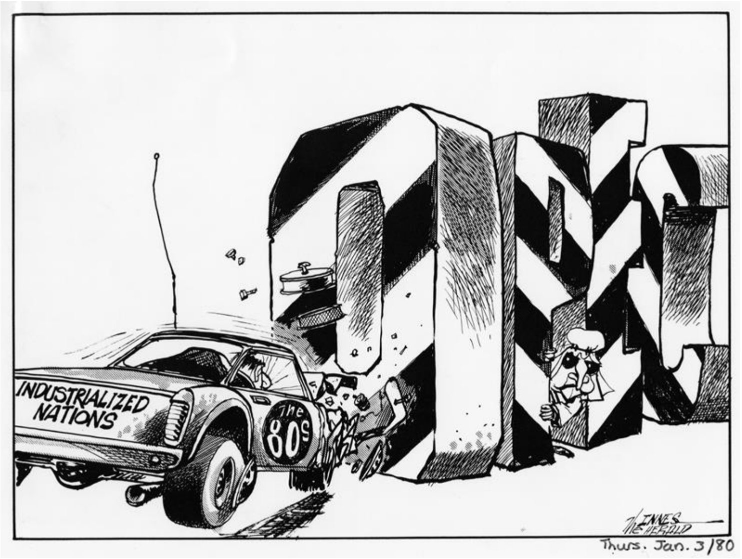


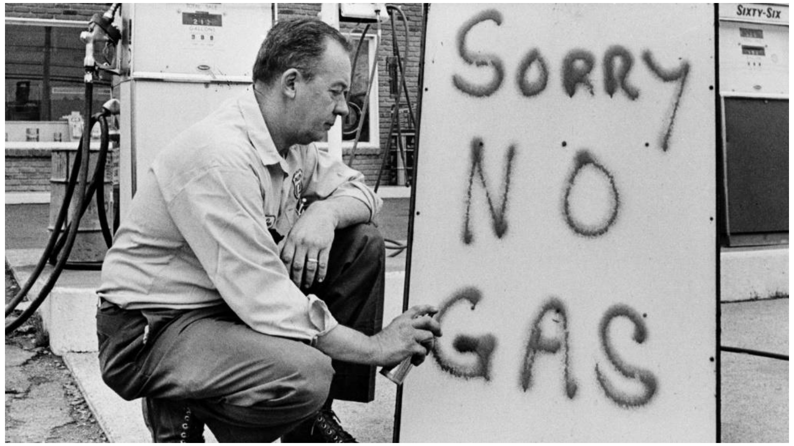




Revival & energy "thirst"







1970s "wave revolt"

Wave power

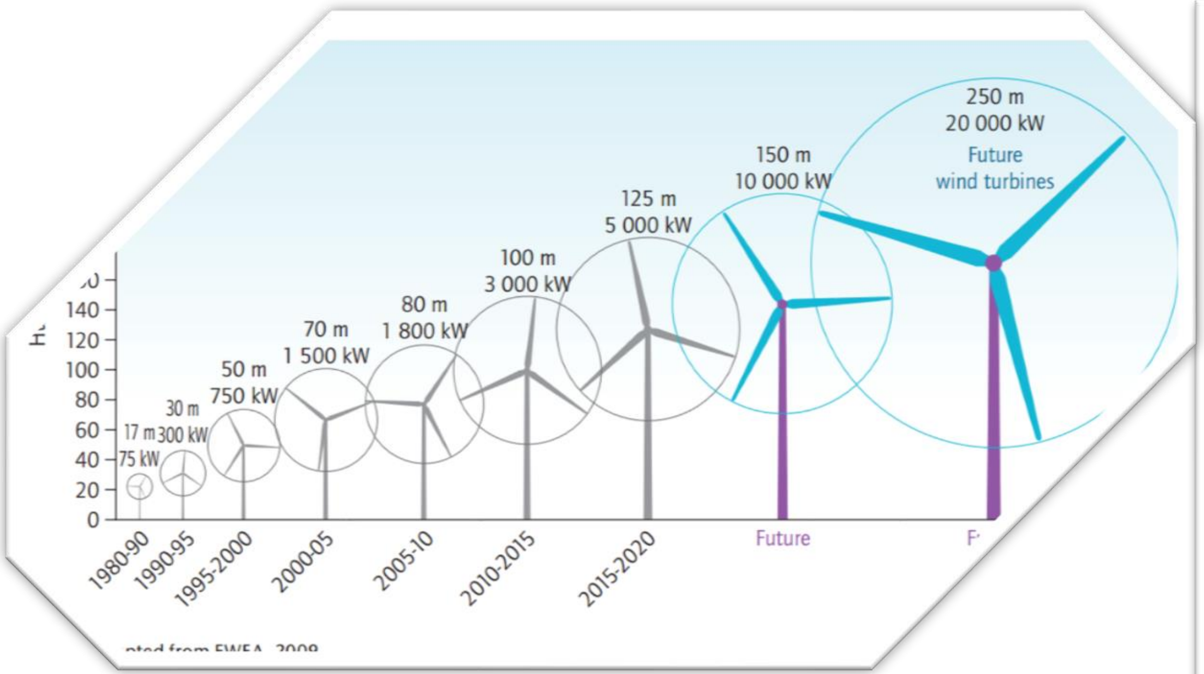
S. H. Salter

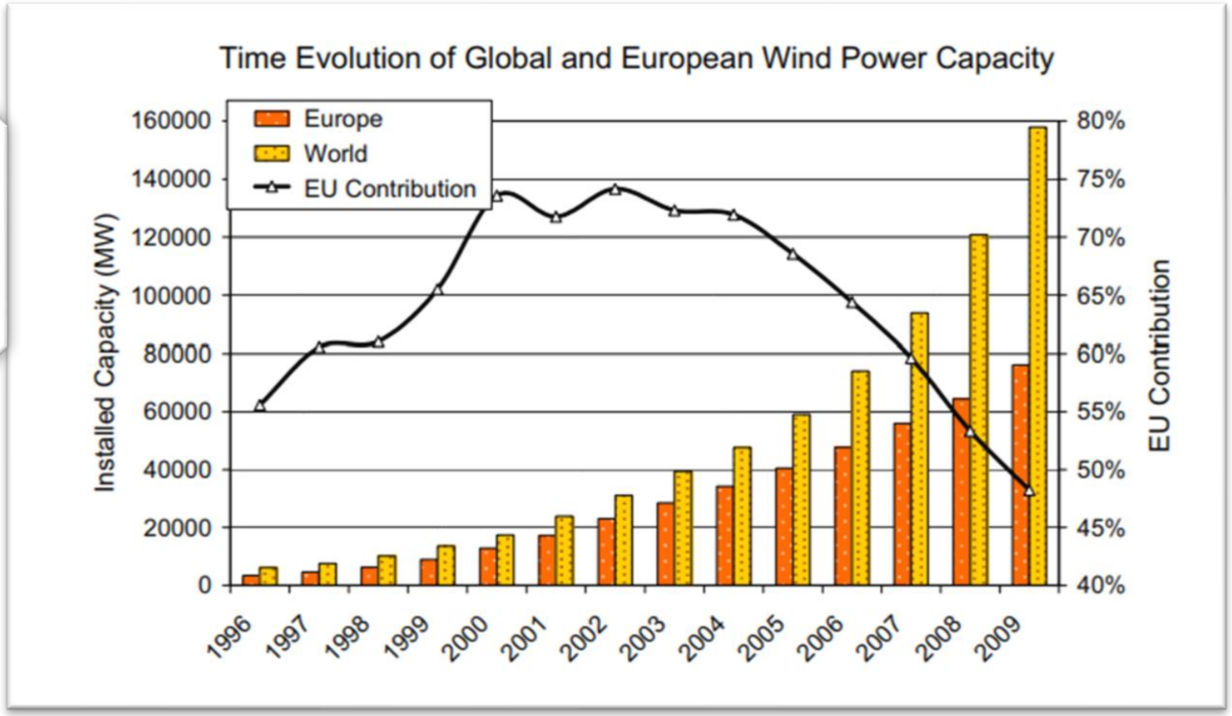
Bionics Research Laboratory, University of Edinburgh, Edinburgh EH1 2QL, UK

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.

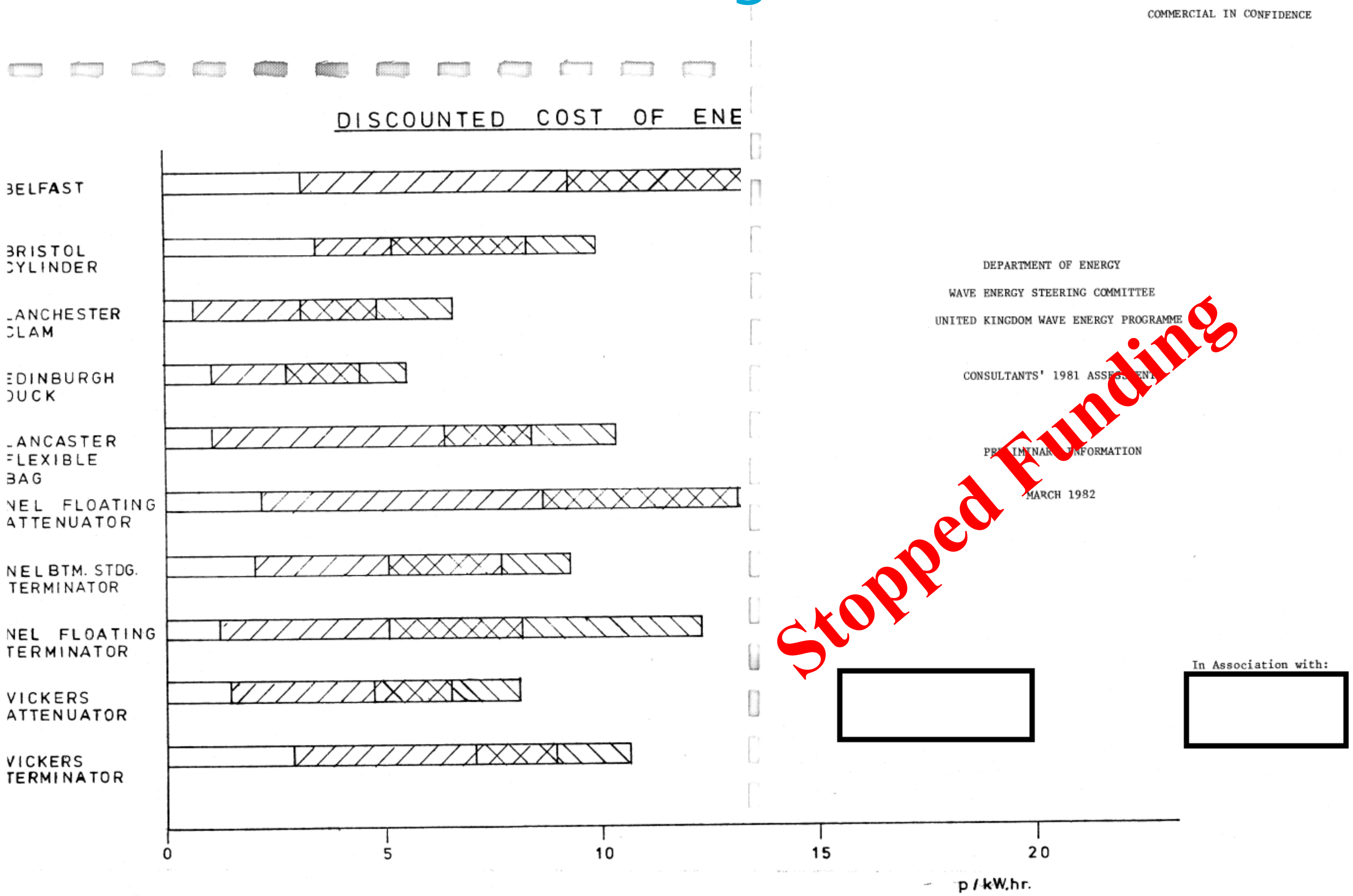
THE amount of po
calculating the chan
above sea level falls
If the sea water has
is W, then the mas

Ambitious goals





Ambitious goal



Evolution and progress

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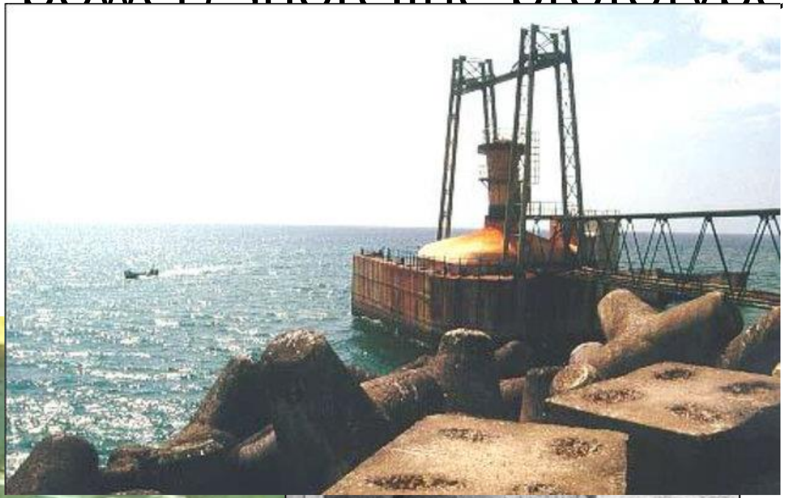
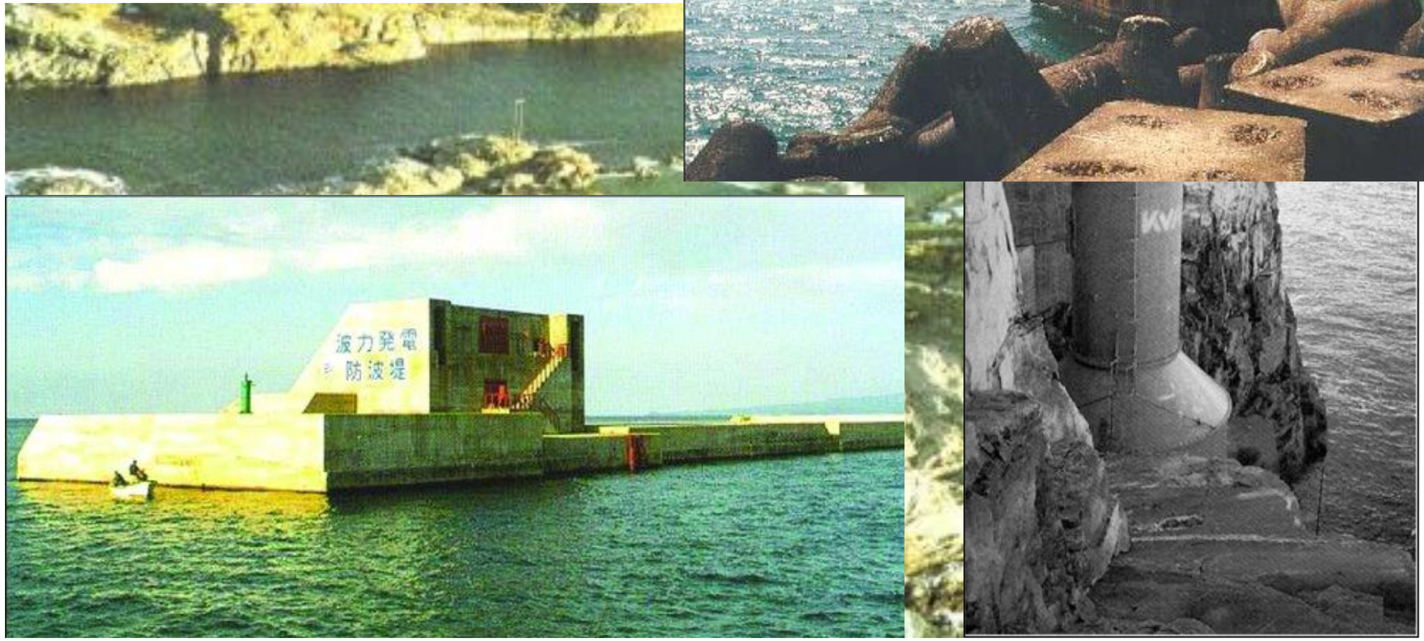
Evolution (1980-1990s)

1985: Two full-sized (350 and 500 kW rated power) shoreline prototypes installed at Toftestallen, Norway

1990: Asia and India

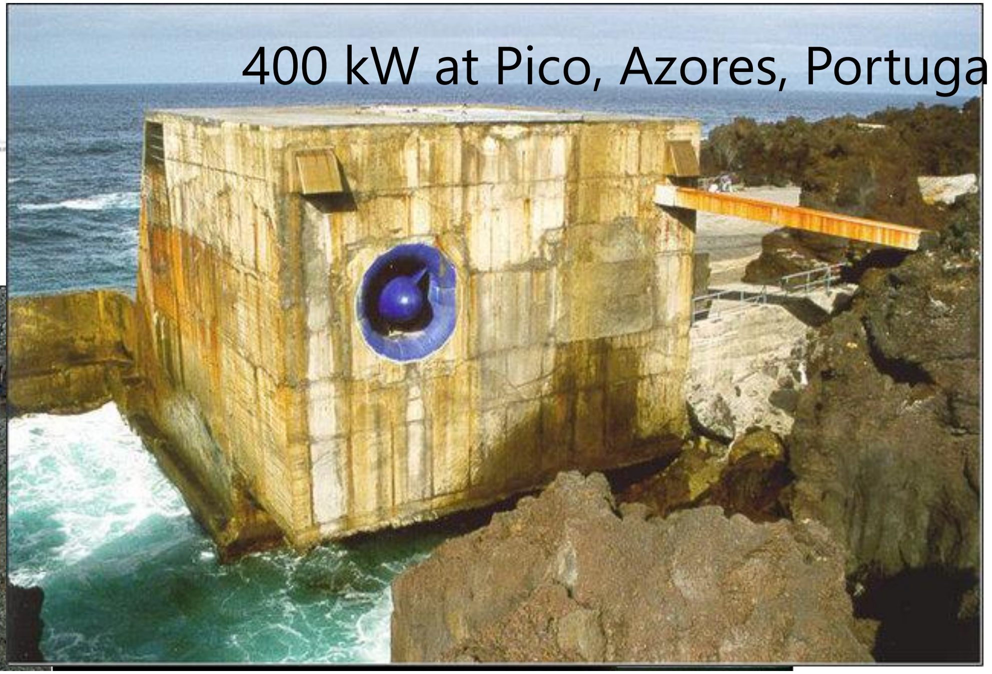




Evolution 1990s-2000s

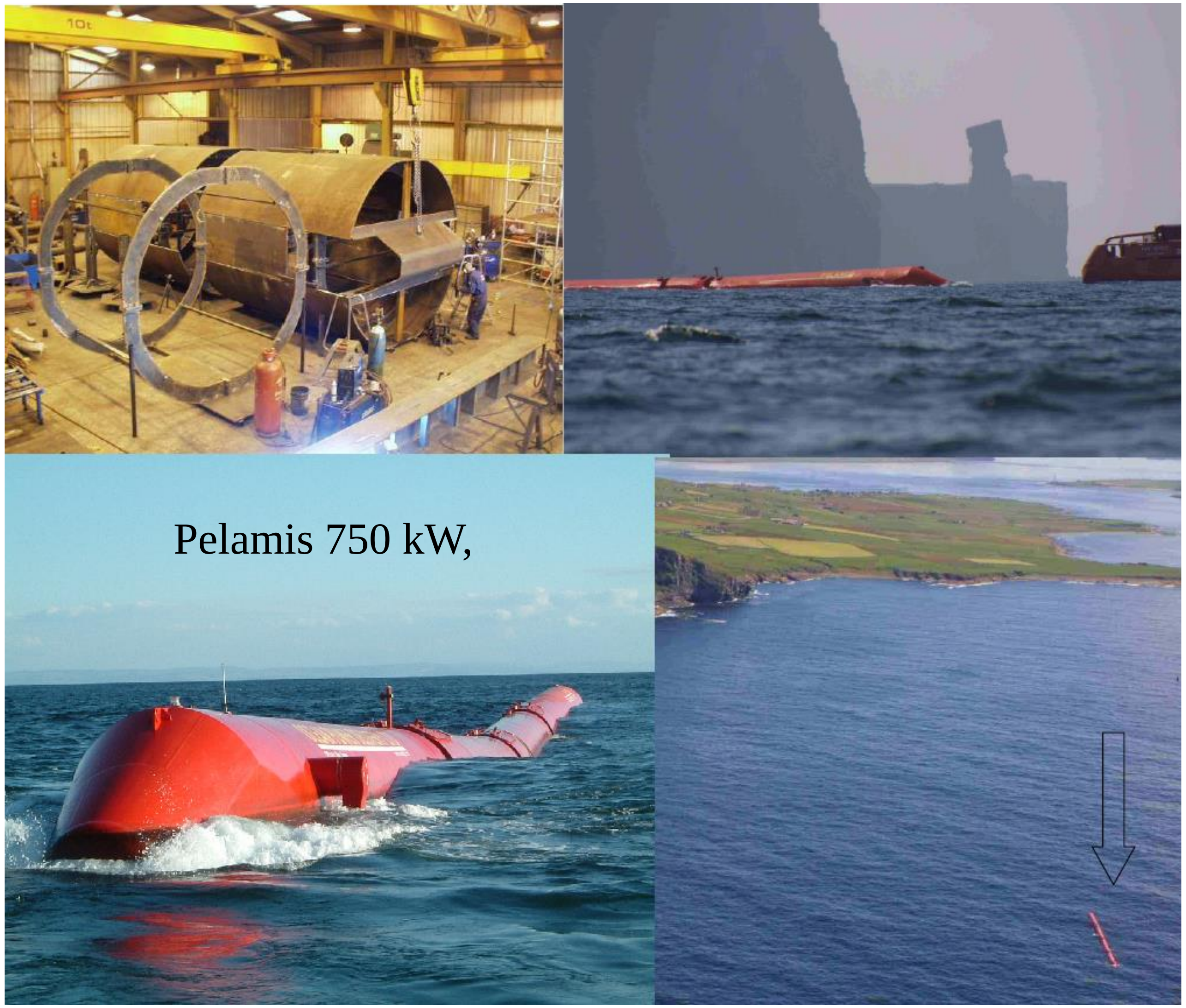
1991: LIMPET 500 kW, Scotland

1994: Waveroller, Sweden



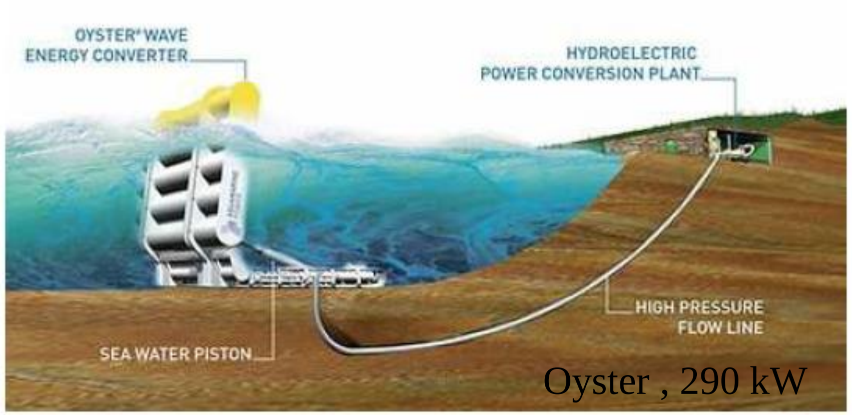
400 kW at Pico, Azores, Portugal

Evolution (2000s – 2010s)

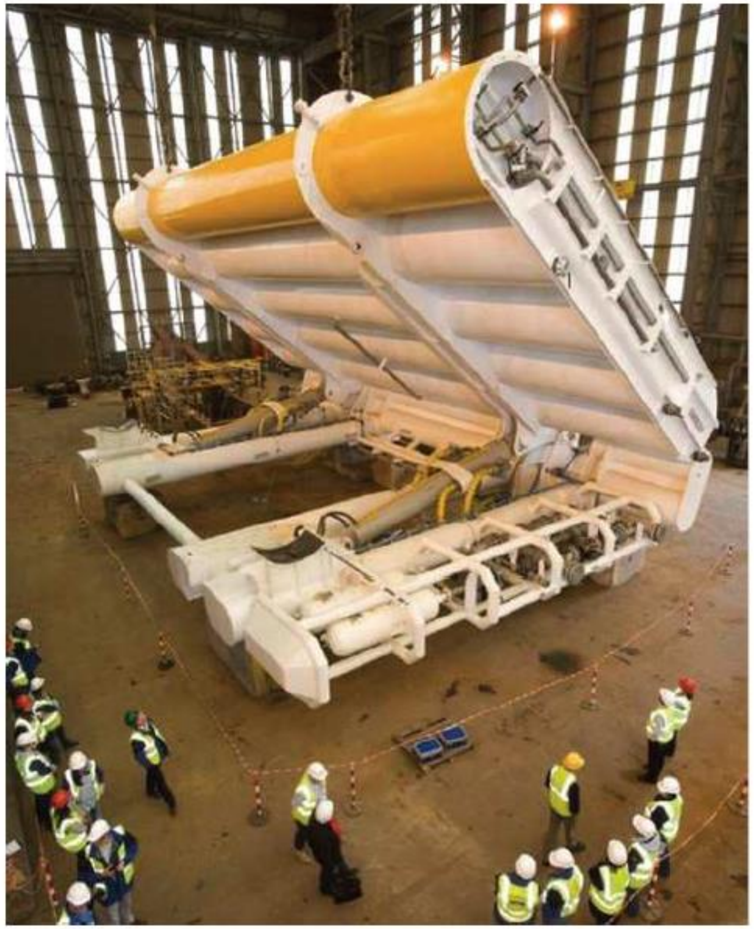


Evolution (2000s – 2010s)

Aquamarine Power Ltd



Oyster , 290 kW

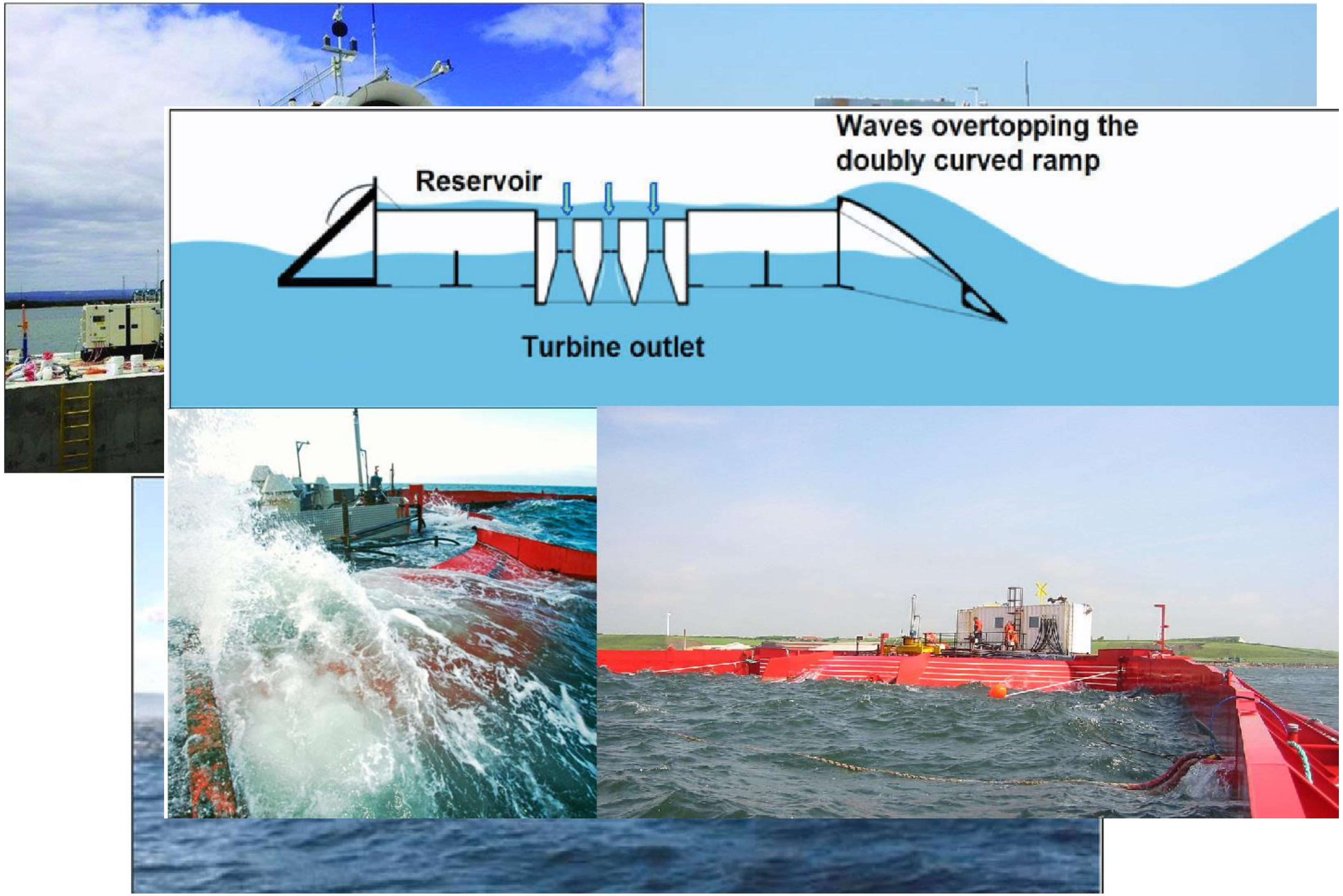


Evolution (2000s – Present)

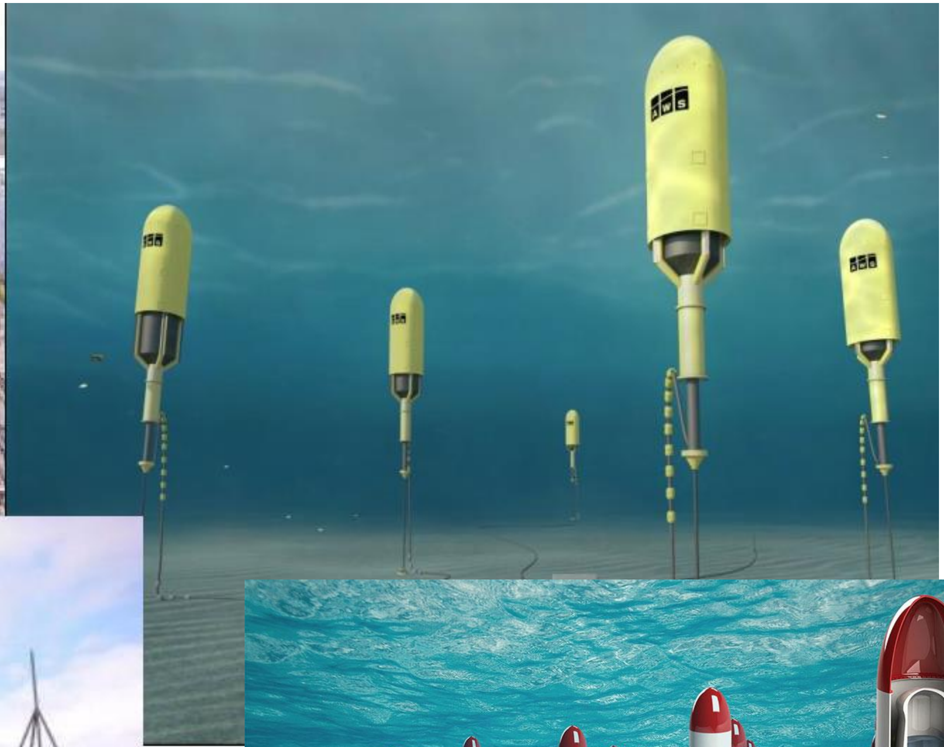
WaveStar 600 kW

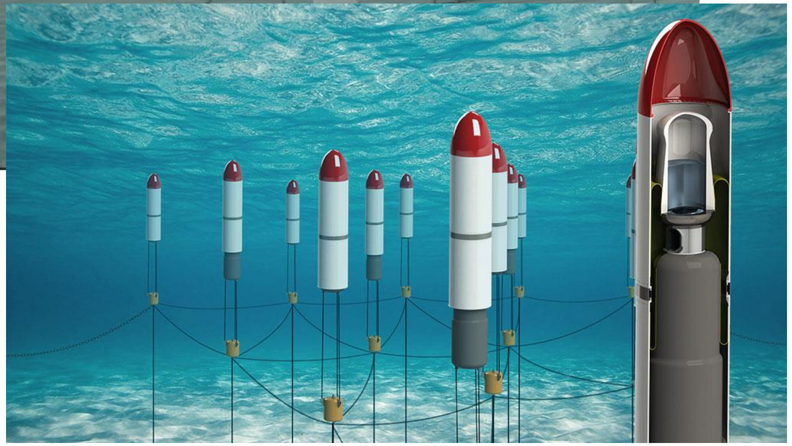
Eco Wave Power

Evolution (2000s – Present)



Evolution (2000s – Present)





Evolution (2000s – Present)

Mitriku, 300kW

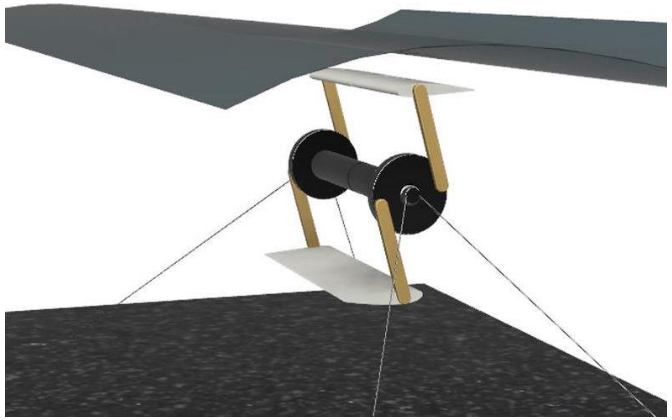
Still operating, almost 12 years

New devices (2015s-Present)

Current status

Corpower C4

Blue Star X



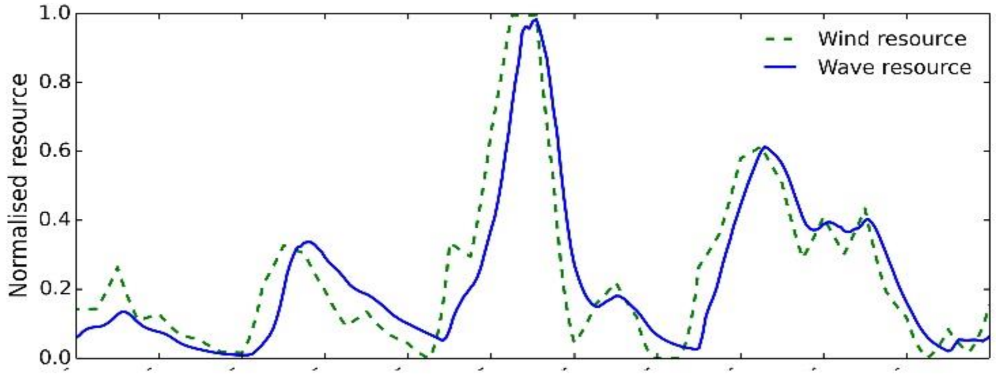
LiftWEC

Wave Energy Converters

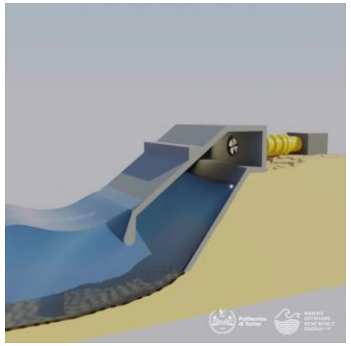
Why Waves ?

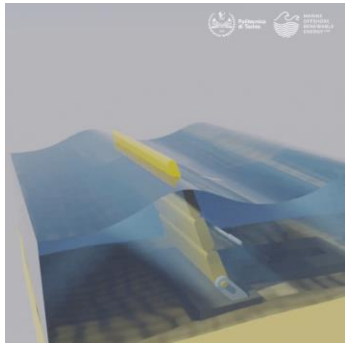
- **Waves are amongst the highest energy density renewables**
- Predictable (though not as solar)
- Persistence of resource
- Access to the resource
- Temporal Cross-Correlation
- Variability reduction
- Coastal protection
- Offshore hybrid systems
- Energy Benefits to isolated commu
- etc...

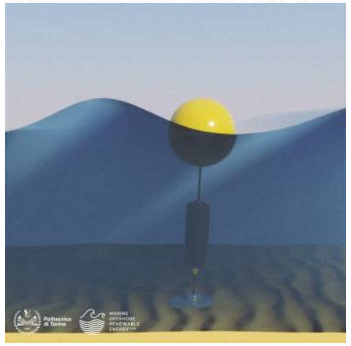
- ✓ Potential for variability reduction
- ✓ Accelerate the Energy Transition
- ✓ Increase utilization of indigenous resources
- ✓ Improve the environment
- ✓ Sustainable Development
- ✓ Renewable energies

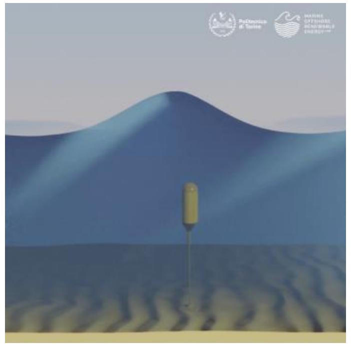


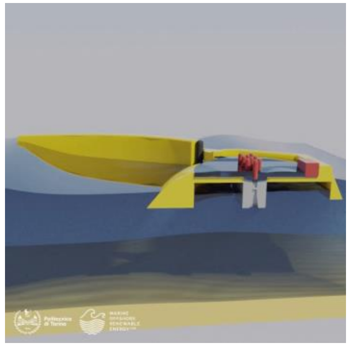
WEC concepts

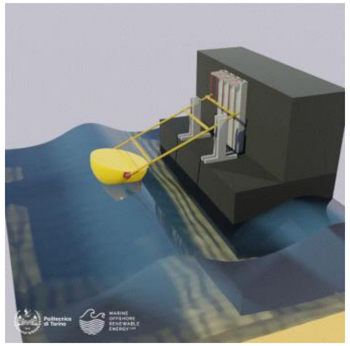


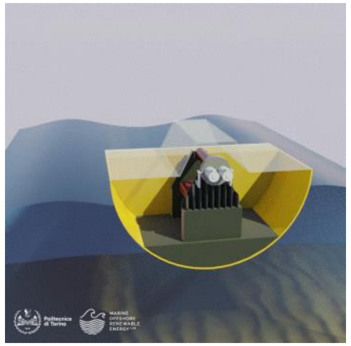












WEC concepts

Principles

1. **OWC**
   A. *Floating*
   B. *Fixed structure*
      i. *Isolated*
      ii. *Breakwater*
2. **OB**
   A. *Floating*
   B. *Submerged*
3. **Overtopping (OT)**
   A. *Floating*
   B. *Fixed structure*

Deployment (depths)

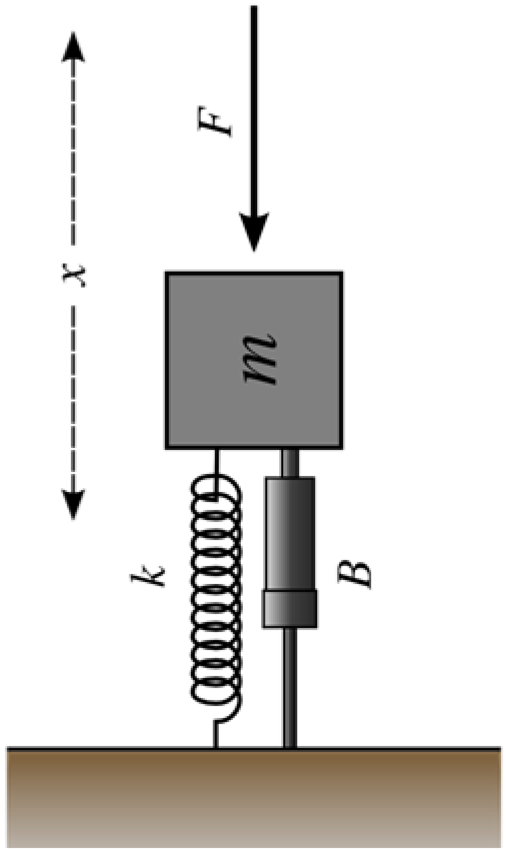
- Shoreline: $3m \geq d$
- Shallow: $3m \leq d \leq 25m$
- Intermediate $25m \leq d \leq 50m$
- Deep $50m \leq d \leq 100m$
- Very Deep $100m \leq d \leq 150m$
- Concept $d \leq 150m$

PTO

- Hydraulics
- Generators
- Turbines
- Etc..

Modelling a WEC

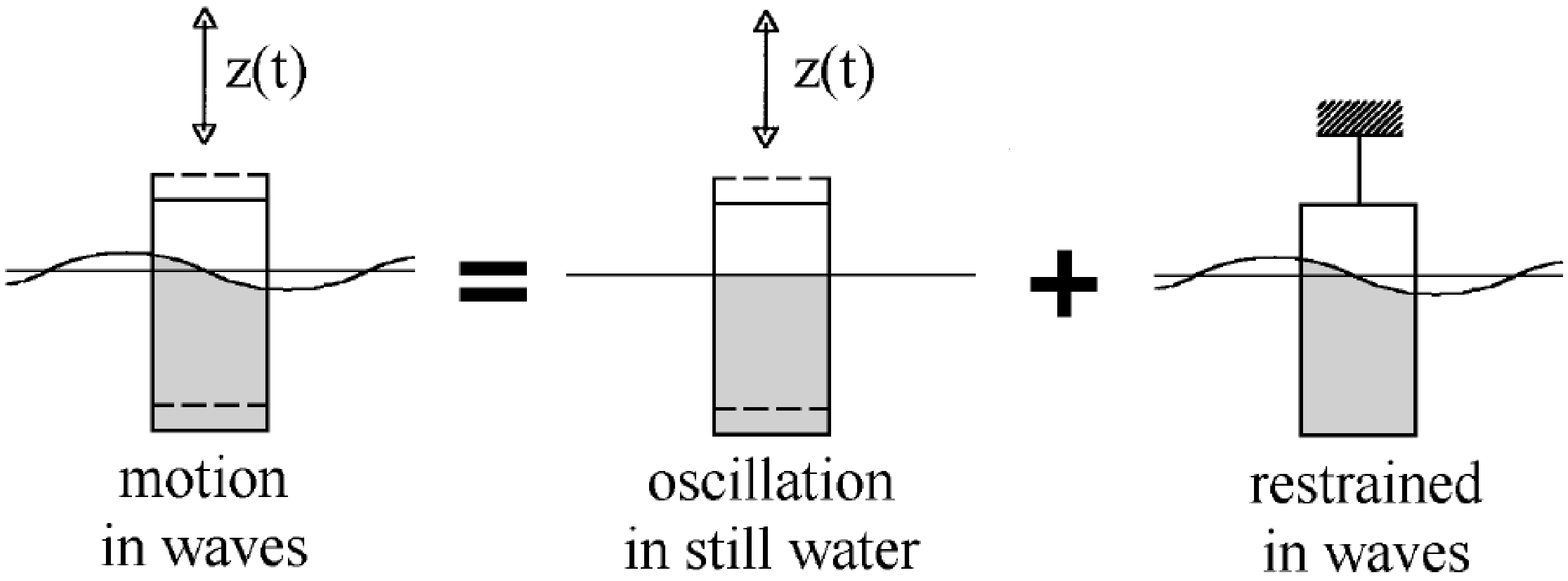
Analytical Linear mathematical model – Point absorber



Basic Assumptions:

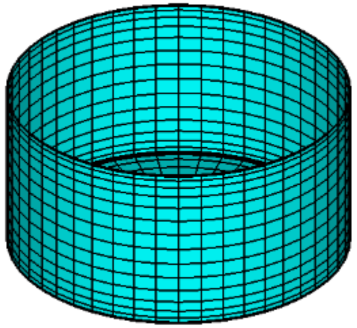
- Dimension (WEC) is small compared to the wave length
- PTO, mooring, control forces are linear
- WEC does radiate waves
- Over regular waves

Understanding the mathematical model – Heaving cylindrical PA



Hydrodynamic modelling of WECs – Numerical approaches

- Frequency domain methods – Boundary Element Method
  - *Linear potential flow*
  - *Boundary integral equations (Green's function approach)*
  - *Mixed source/dipole formulation*
  - *Least computational time*

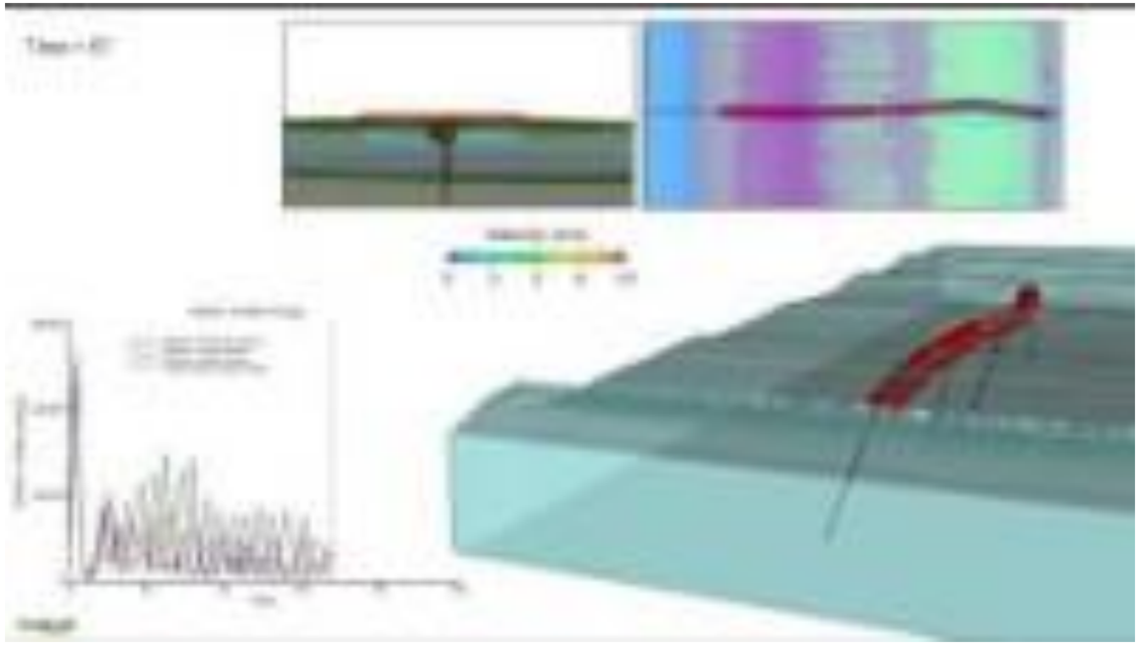


Liu et. al. 2019

- Time domain methods - Integro differential Cummin's equation method
  - *Modelling of non-linear forces such as viscous damping and inertia, PTO forces, mooring forces (more accurate)*
  - *Computationally expensive compared to frequency domain methods*
  - *Derive from frequency domain BEM method*

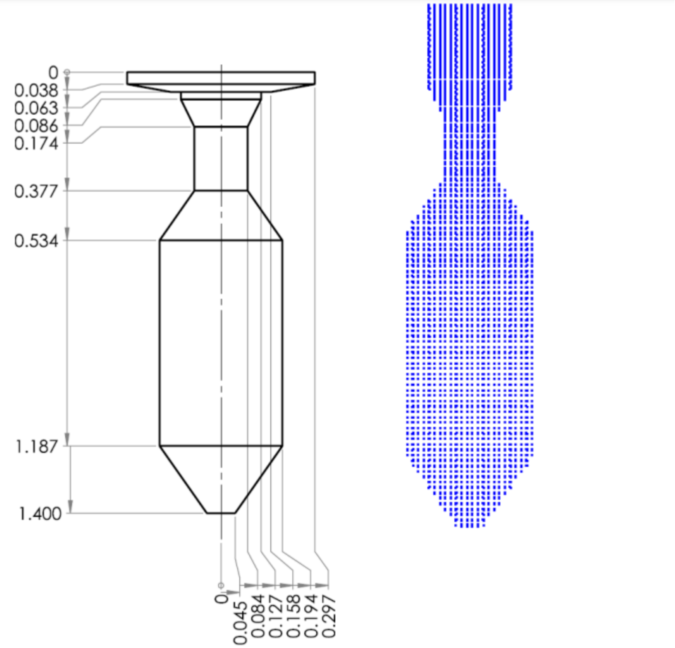
Hydrodynamic modelling of WECs – Numerical approaches

- CFD methods
  - *Derived from Navier Stokes equation, Eulerian method*
  - *Full non-linear modelling possible including turbulence effects*
  - *RANS formulation most common using Volume of fluid method (Free surface modelling)*
  - *Computationally expensive*



Hydrodynamic modelling of WECs – Numerical approaches

- Lagrangian methods – Smoothed particle Hydrodynamics
  - *Mesh free particle following*
  - *Computationally intensive but less compared to CFD*
  - *Commonly used: Dual SPHysics (Smoothed Particle Hydrodynamics)*



Estimating Power

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Non-linearities for detailed analysis

Detailed analysis based on BEM, non-linearities to be considered

Time domain simulation (e.g. Integro-differential Cummin's equation

$$(M+\mu_\infty)\ddot{X} = F_{ex} - \int_0^t K(t-\tau)\dot{X}(\tau)dt + F_H + F_{PTO} + F_V + F_{es}$$

PTO force – linear, hydraulic

Viscous forces

$$F_V = -\frac{1}{2}\rho C_D A_D |V - V_0|(V - V_0)$$

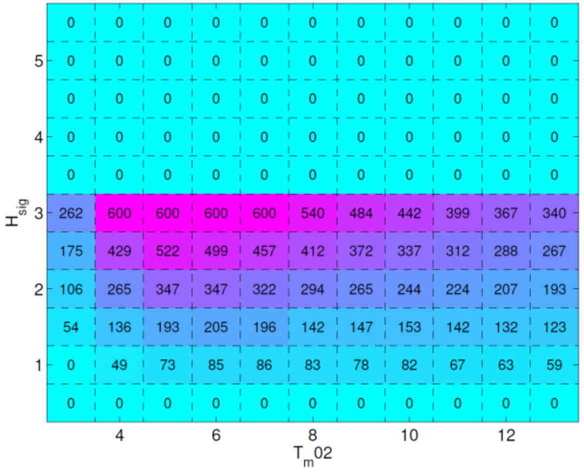
End Stop forces

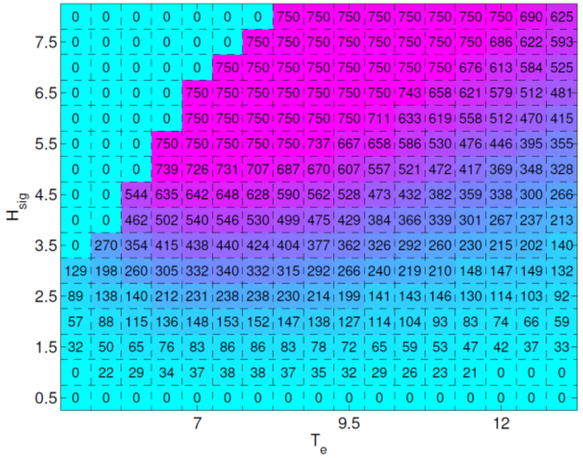
$$F_{es} = -K_{es}\mathrm{diag}(X + X_{es})u(-X - X_{es}) - K_{es}\mathrm{diag}(X - X_{es})u(X - X_{es})$$

Power Matrix (PM)

Models produces the responses according to excitation, operation, numerical estimation of sub-components, controls & PTO.

After some hydrodynamic analysis and conversions





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Producing Energy

Estimation of E_{el} production requires two main components:

- Power matrix (Bivariate or Trivariate)
- Joint/Bivariate (or Trivariate) of location (metocean)

Potential methods:

Non-advisable, is to use coefficients, i.e. η=90% and estimate the extractable energy

$$E_{el} = \int_{t=1}^{\infty} \eta \cdot P_{wave}(t) \cdot \Delta_{\omega}$$

Waves comprise a highly statistical multi-parameter process, hence matrices of directionality-occurrences-PM combined

$$E_{el} = \frac{1}{100} \cdot \sum_{i,j=1}^{n_T} \sum_{i,j=1}^{n_{H_{m0}}} \sum_{i,j=1}^{n_{PkDir}} p_{i,j} \cdot PM_{i,j} \cdot P_{kDir\ i,j}$$

Interpolation methods

$$E_{el}(t) = \int_{t=1}^{t=\infty} P_{PM_{i,j}(H_{m0_{i,j}};T_{m02\,|\,peak\,|m01_{i,j}};P_{kDir_{i,j}})}$$

Power production

Proper method is the combination of directionality-occurrences-P

$$E_{el} = \frac{1}{100} \cdot \sum_{i=1}^{n_T} \cdot \sum_{i=1}^{n_{H_{sig}}} \cdot \sum_{i=1}^{n_{Pk_{dir}}} \cdot p_{i,j} \cdot PM_{i,j} \cdot PkDir_{i,j}$$

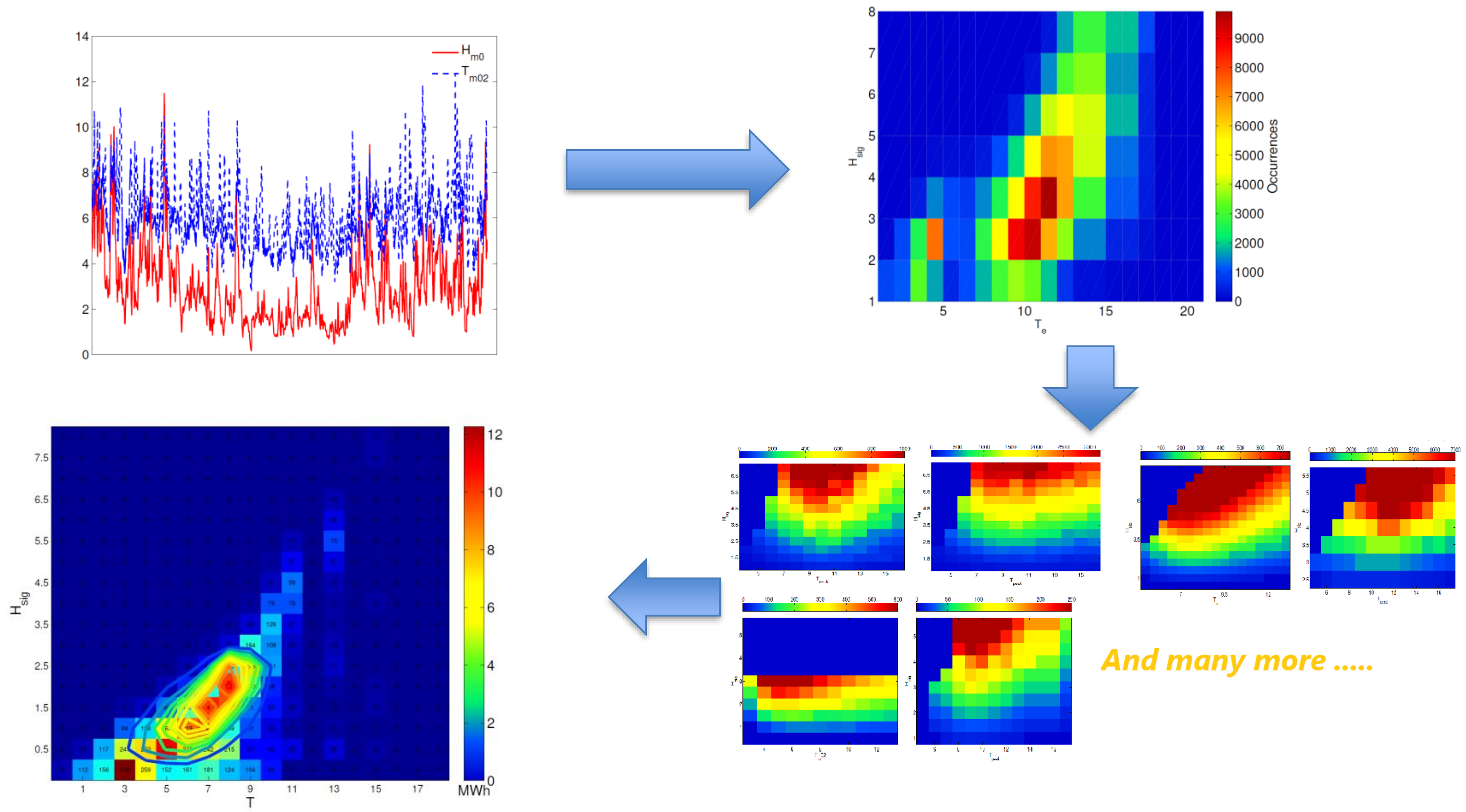
Do's

- ✓ Long-term dataset
- ✓ Trusted/validated sources
- ✓ Joint distributions
- ✓ Statistical Properties
- ✓ Consider depth
- ✓ Selecting device

Don't's

- ○ Data from non-viable depths
- ○ Lots of gaps in measurements
- ○ Un-validated/obscure sources
- ○ ≥3-hour intervals
- ○ Improper use of coefficients
- ○ Improper WEC applicability

Power production



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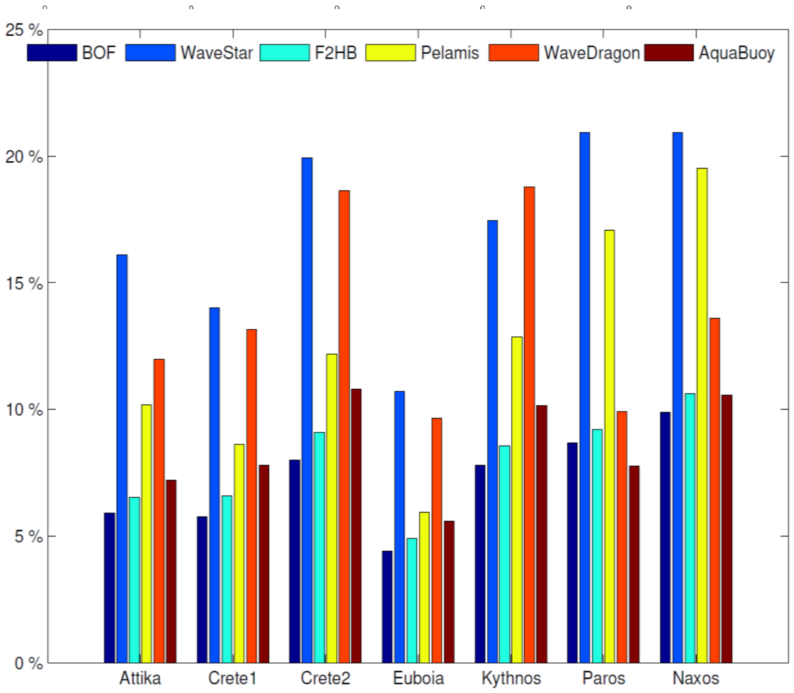
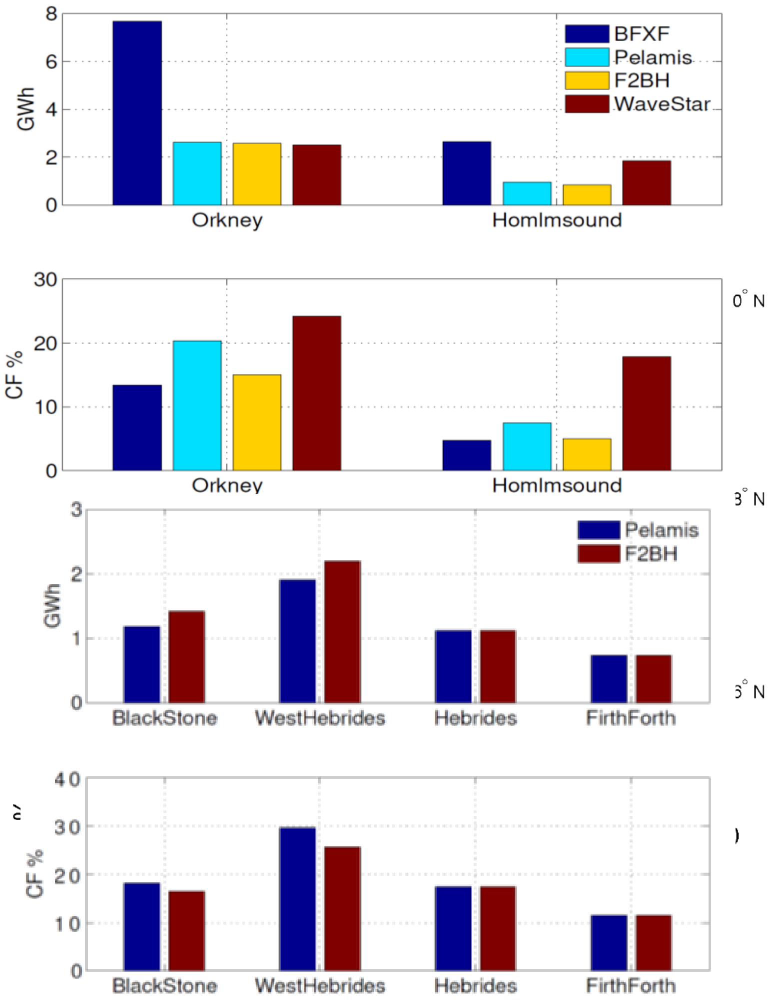
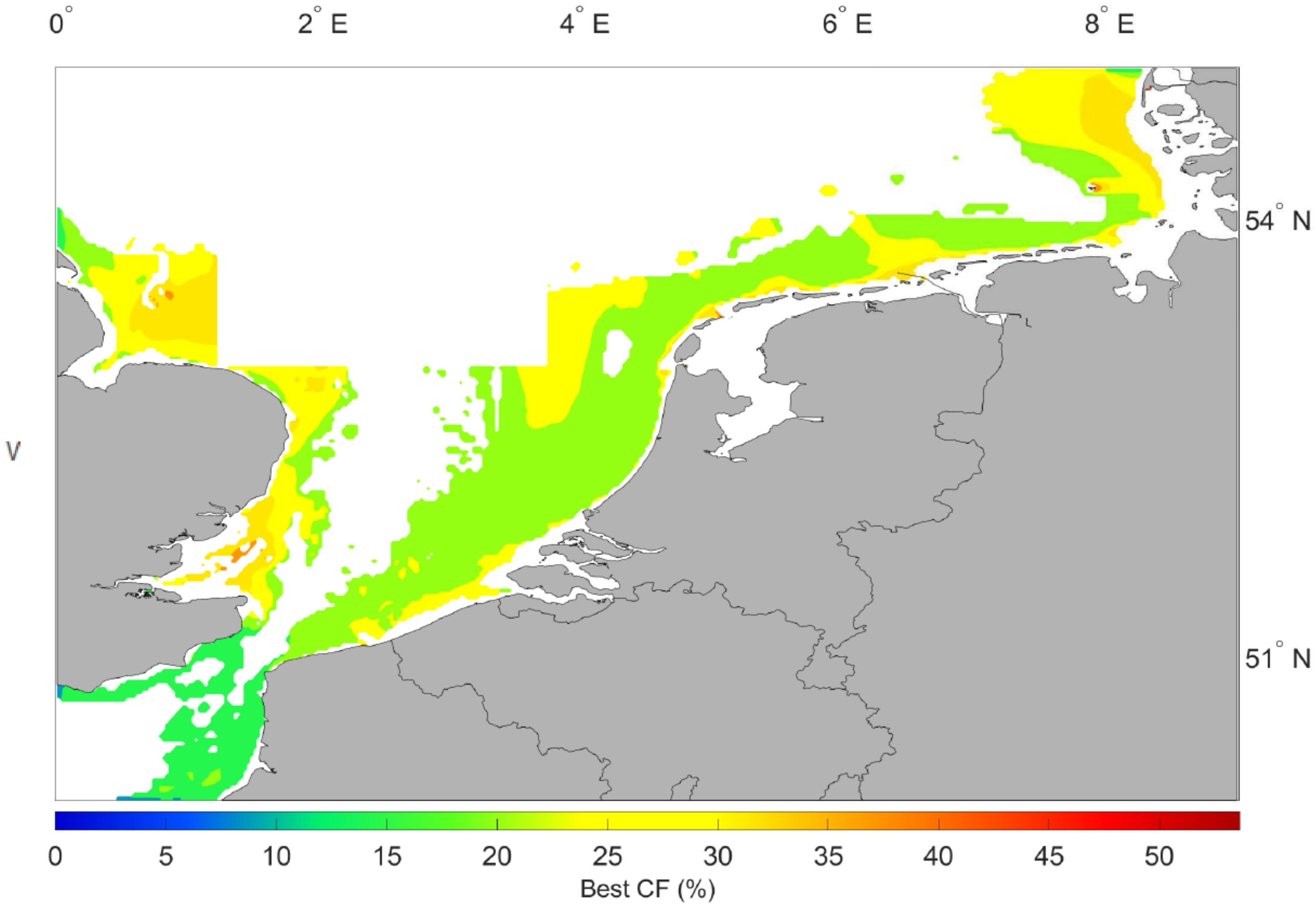
Utilisation rates





Wave energy in the Netherlands



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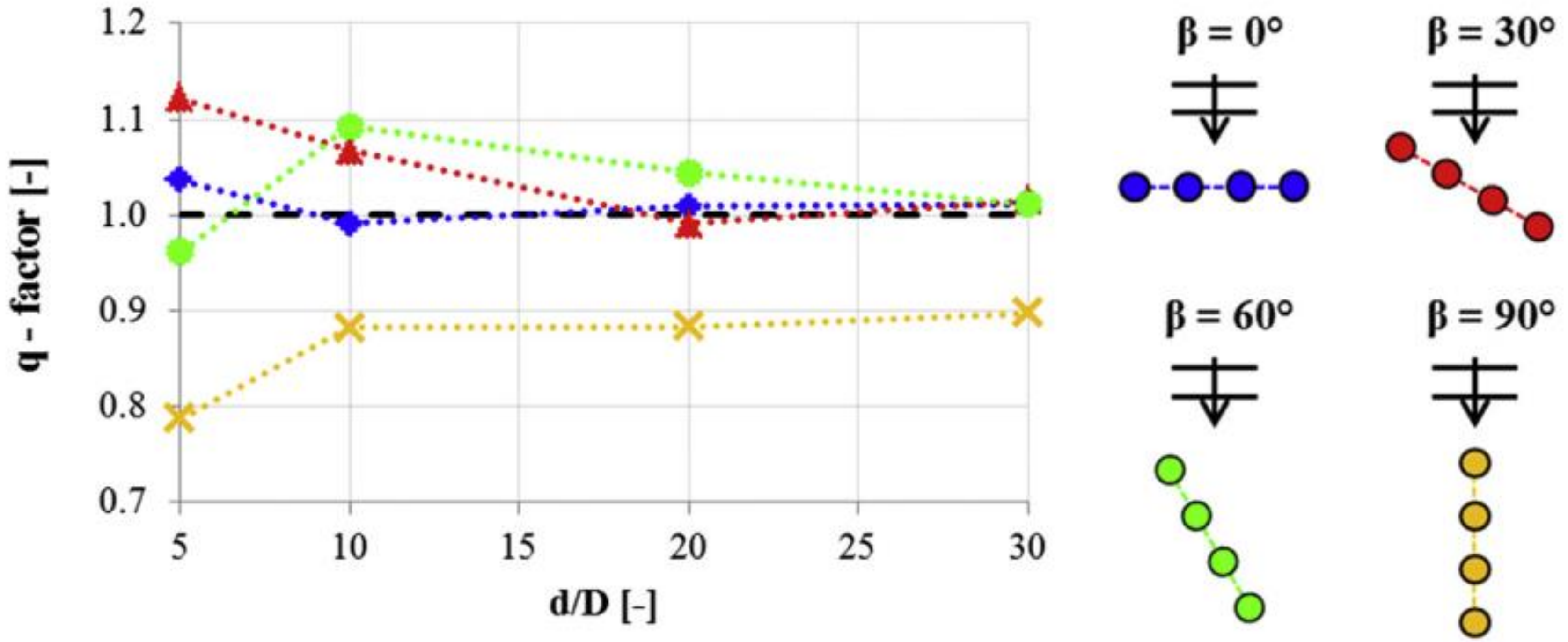
WEC arrays

WEC arrays

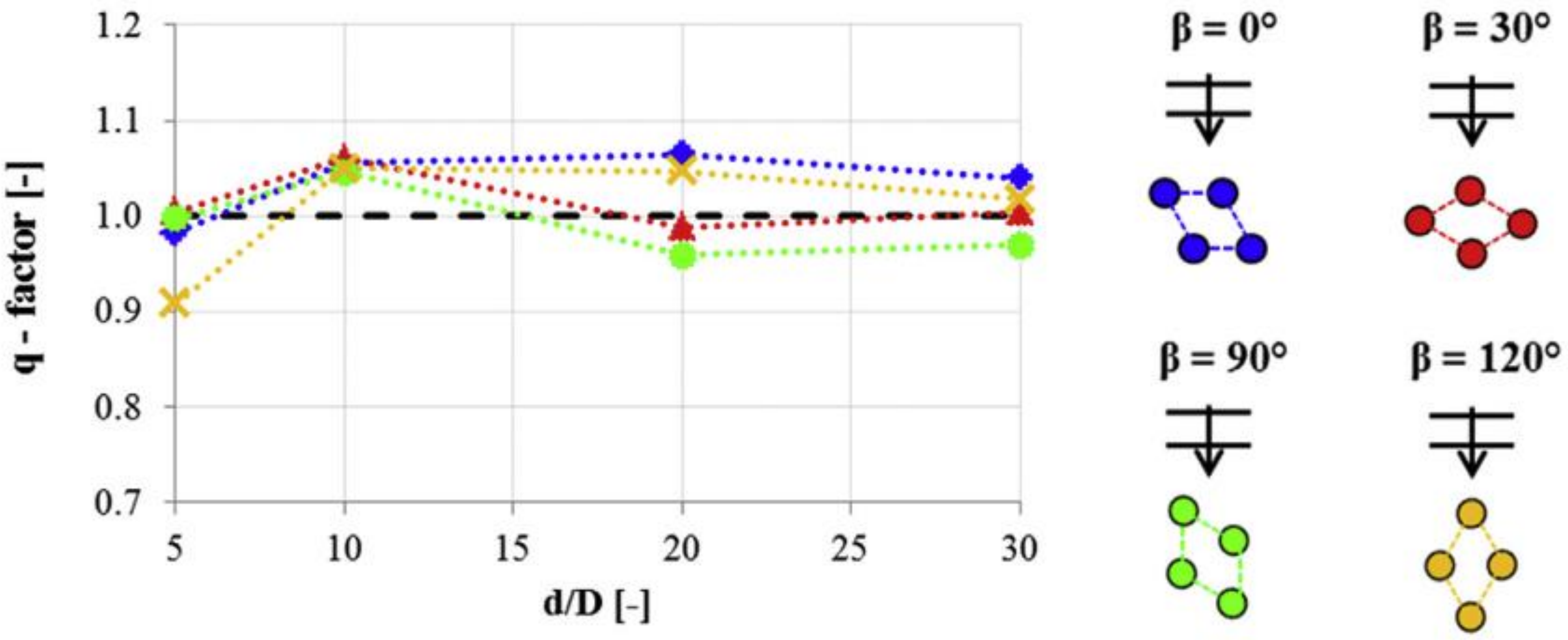
Why?

- Reduce costs
- WEC produce low power compared to wind
- Wake effects can be constructive

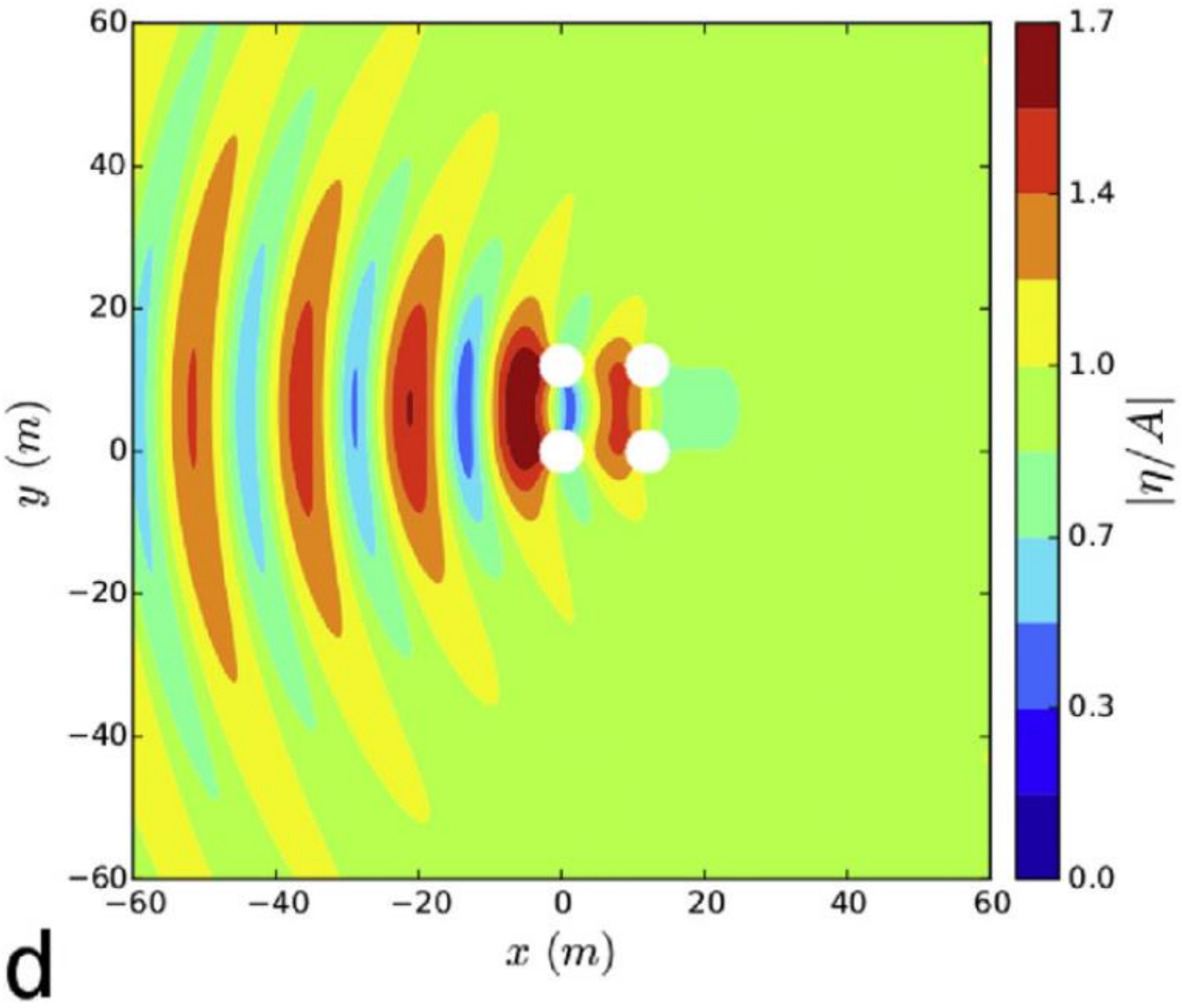
$$q(\omega) = \frac{\tilde{P}_{\text{array}}(\omega)}{N\tilde{P}_{\text{isolated}}(\omega)}$$



WEC arrays



WEC array interactions



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