U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

water

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

WATER POWER TECHNOLOGIES OFFICE

Innovating Distributed Embedded Energy Prize (InDEEP)

Introduction to Wave Energy

April 26, 2023

Webinar Logistics

- Everyone is joined in listen-only mode
- Audio Issues?—Try connecting over the phone
- If that doesn't work, visit the Zoom Help Center webpage
- Q&A—Submit your questions using the chat box

Agenda

1. Introductions
2. Ocean Waves
3. Wave Energy
4. Technology
5. Challenge & Motivation
6. Q&A

Introductions

Innovating Distributed Embedded Energy Prize

- **$2.3M prize pool**
- Three phases over two years
- Incentivize progress in early-stage research
- Help solve technical challenges that could be applied to wave energy

Contributing to Leaderboard Scoring

- For questions about the prize overall, view our recorded conversation on April 12
- Participation in this webinar contributes to your final leaderboard score
- **Make sure to complete the Leaderboard Eligibility Form to receive points for your participation**
- If you haven't done this yet, do so now: https://www.herox.com/indeep

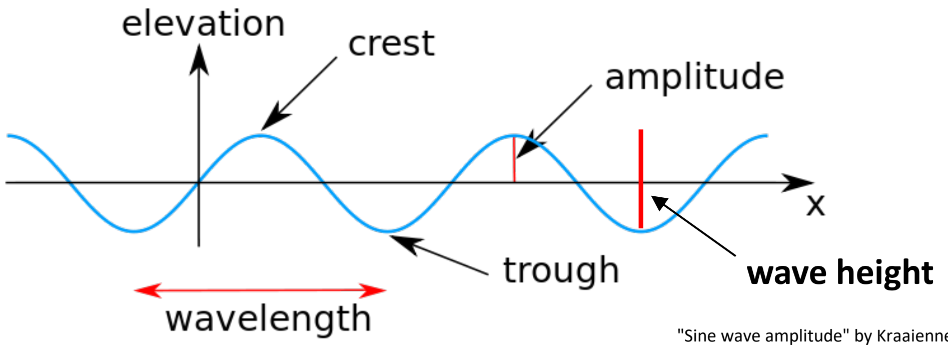
AMERICAN MADE WATER PRIZE

U.S. DEPARTMENT OF ENERGY

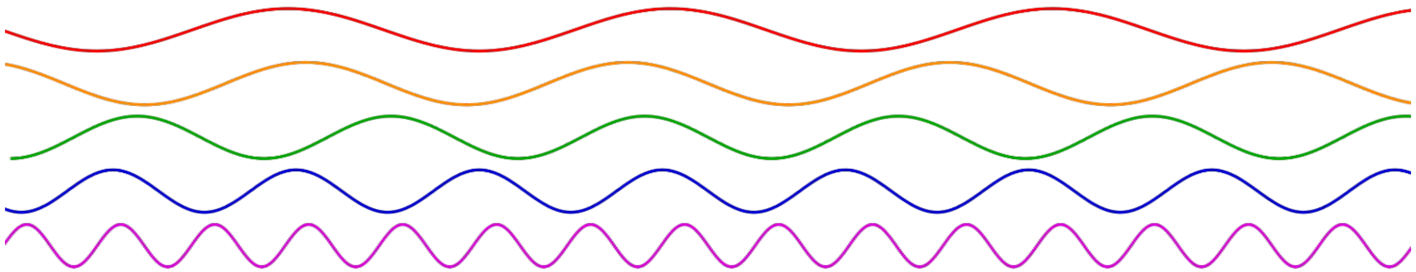
WPTO's desired outcome for InDEEP is an understanding of the landscape of innovators and potential DEEC-Tec solutions that could be applied to wave energy devices.

Ocean Waves

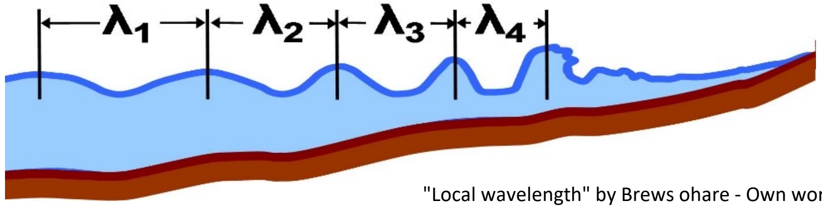
Ocean Waves – Key Geometric Parameters



"Sine wave amplitude" by Kraaiennest - Own work
Licensed under CC BY-SA 3.0 via Commons

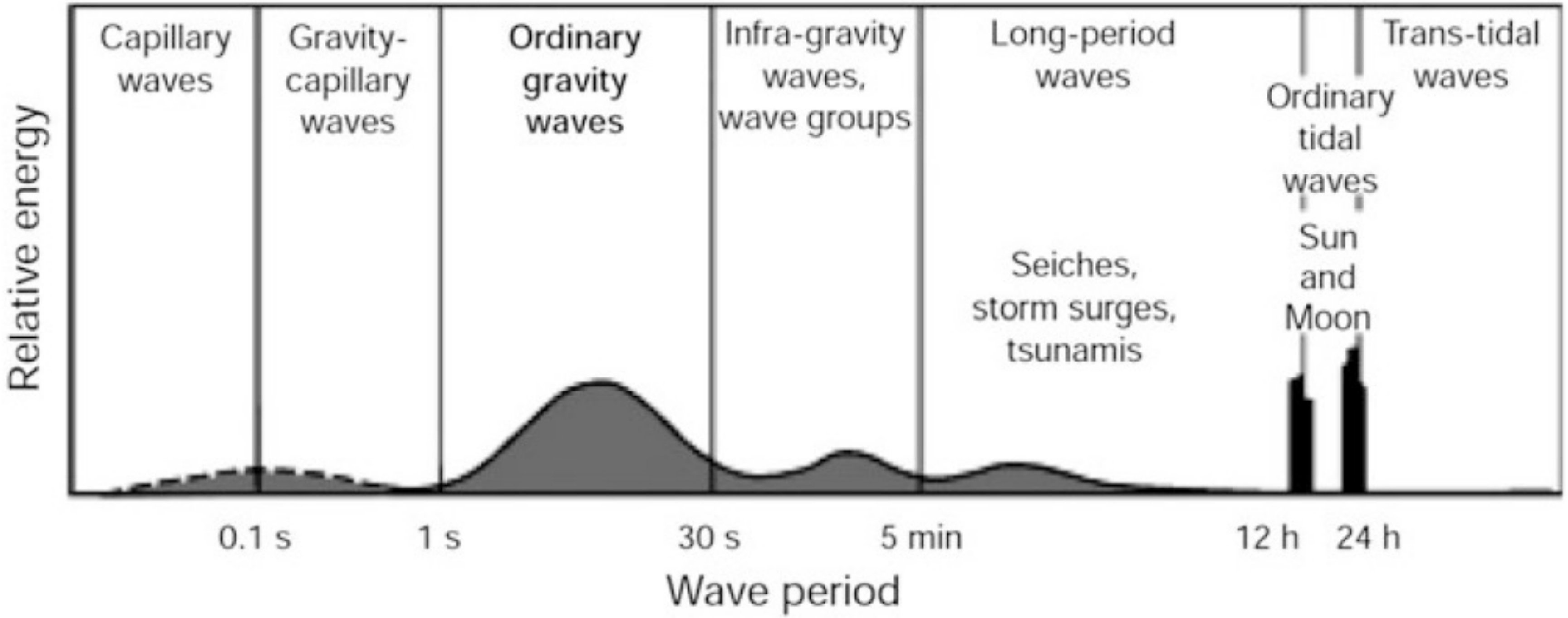


"Sine waves different frequencies" LucasVB. . Own work assumed
.. Licensed under Public Domain via Commons



"Local wavelength" by Brews ohare - Own work
Licensed under CC BY-SA 3.0 via Commons

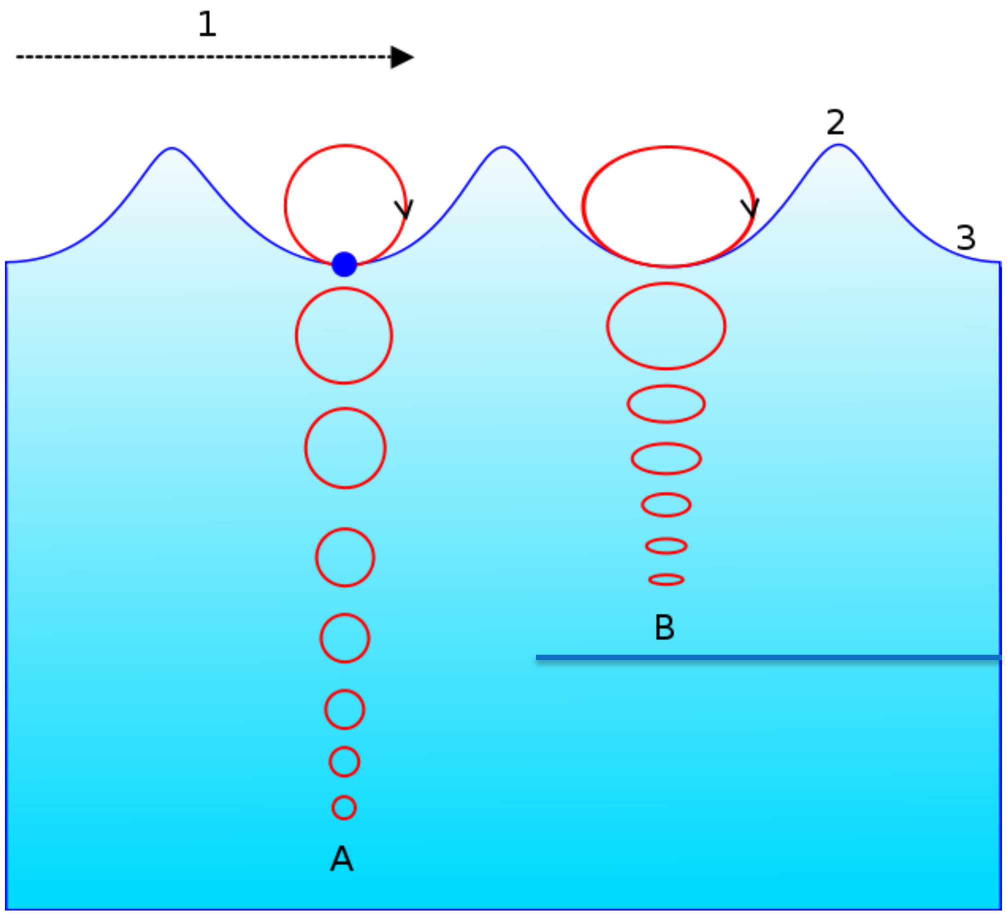
Ocean Waves – Key Temporal Parameter



Types of waves in the ocean by wave period

World Meteorological Organisation: Guide to wave analysis and forecasting (WMO 702), 2nd edn. WMO (1998)

Ocean Waves – Visualization of Dynamics



"Wave motion-i18n-mod" by Original uploader was Vargklo at en.Wikipedia
Licensed under CC BY-SA 3.0 via Commons

Motion of a particle in an ocean wave.

A = At deep water.

B = At shallow water

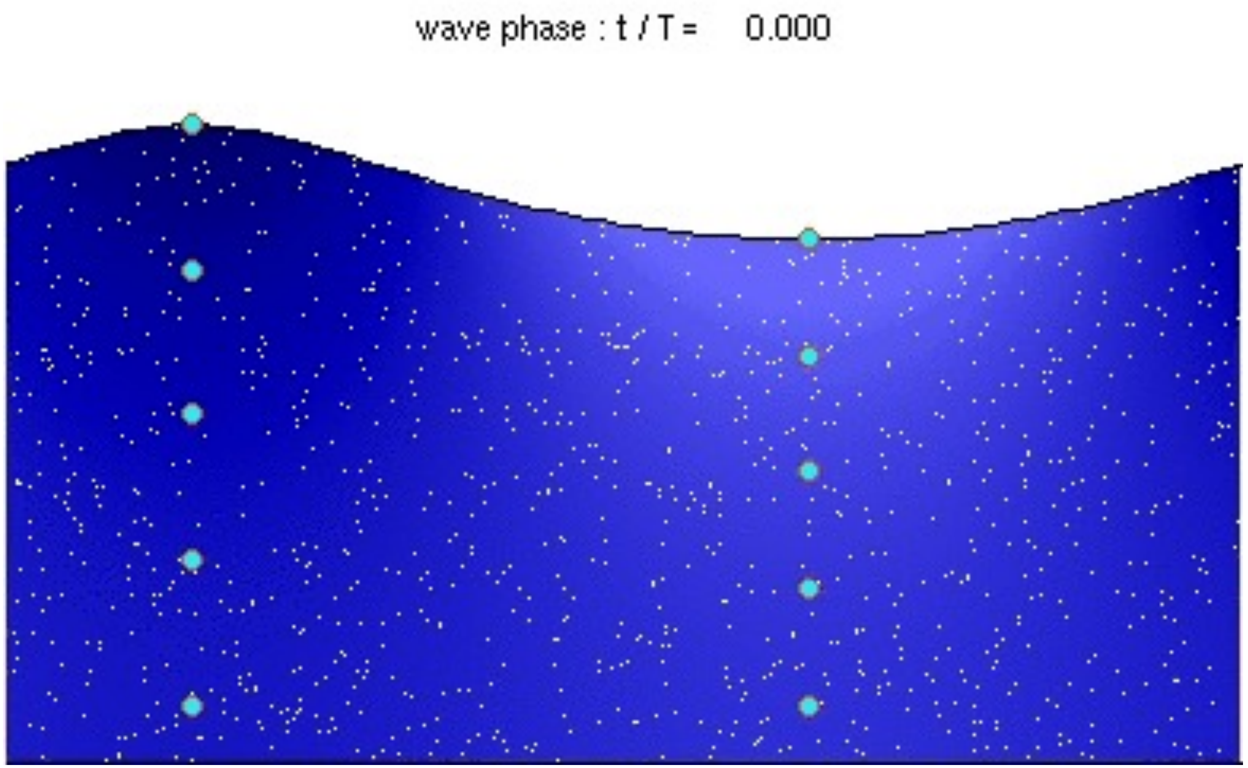
1 = Propagation direction.

2 = Wave crest.

3 = Wave trough.

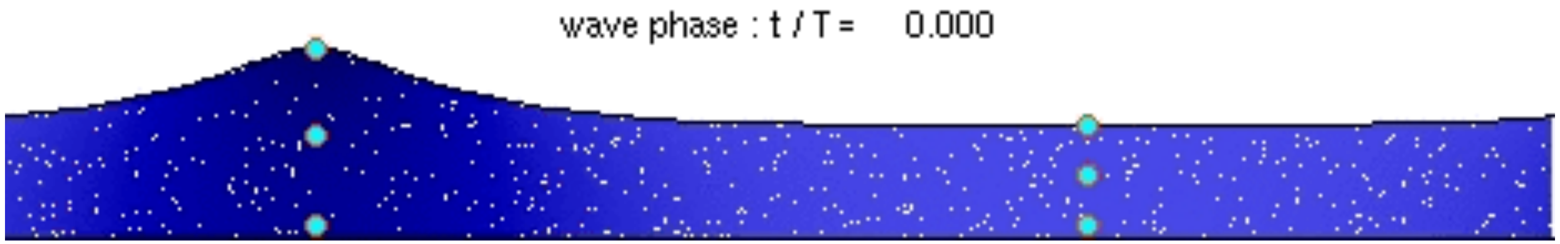
Wikipedia

Ocean Waves – Visualization of Dynamics



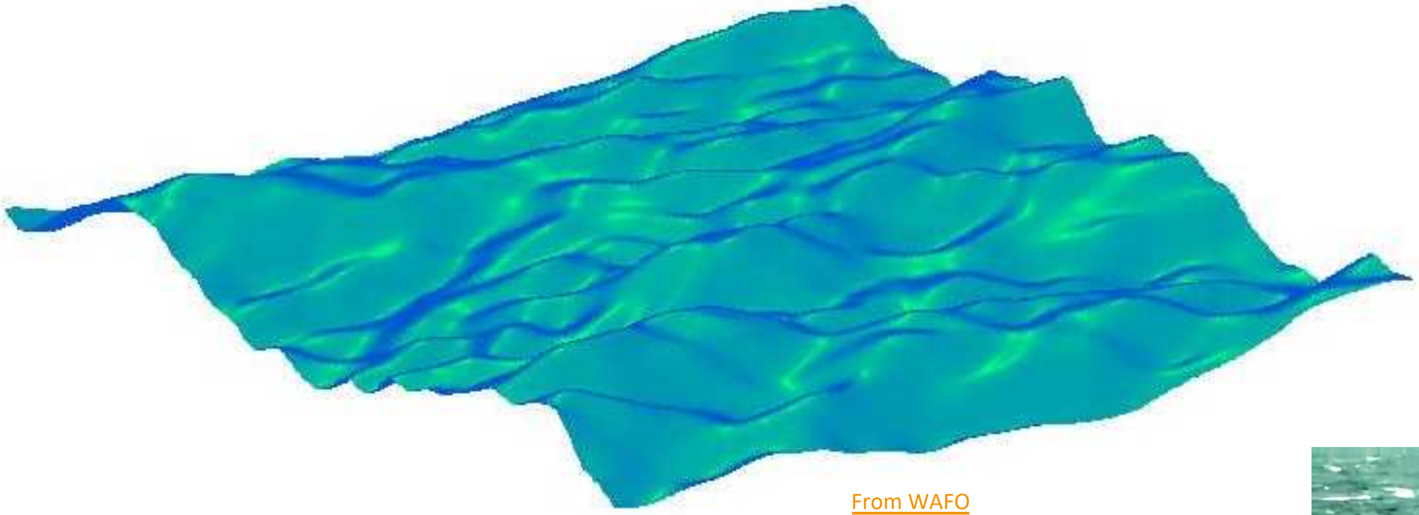
"Deep water wave" by Kraaiennest – Own work. Licensed under GFDL via Commons

Ocean Waves – Visualization of Dynamics



“Deep water wave” by Kraaiennest – Own work.
Licensed under GFDL via Commons

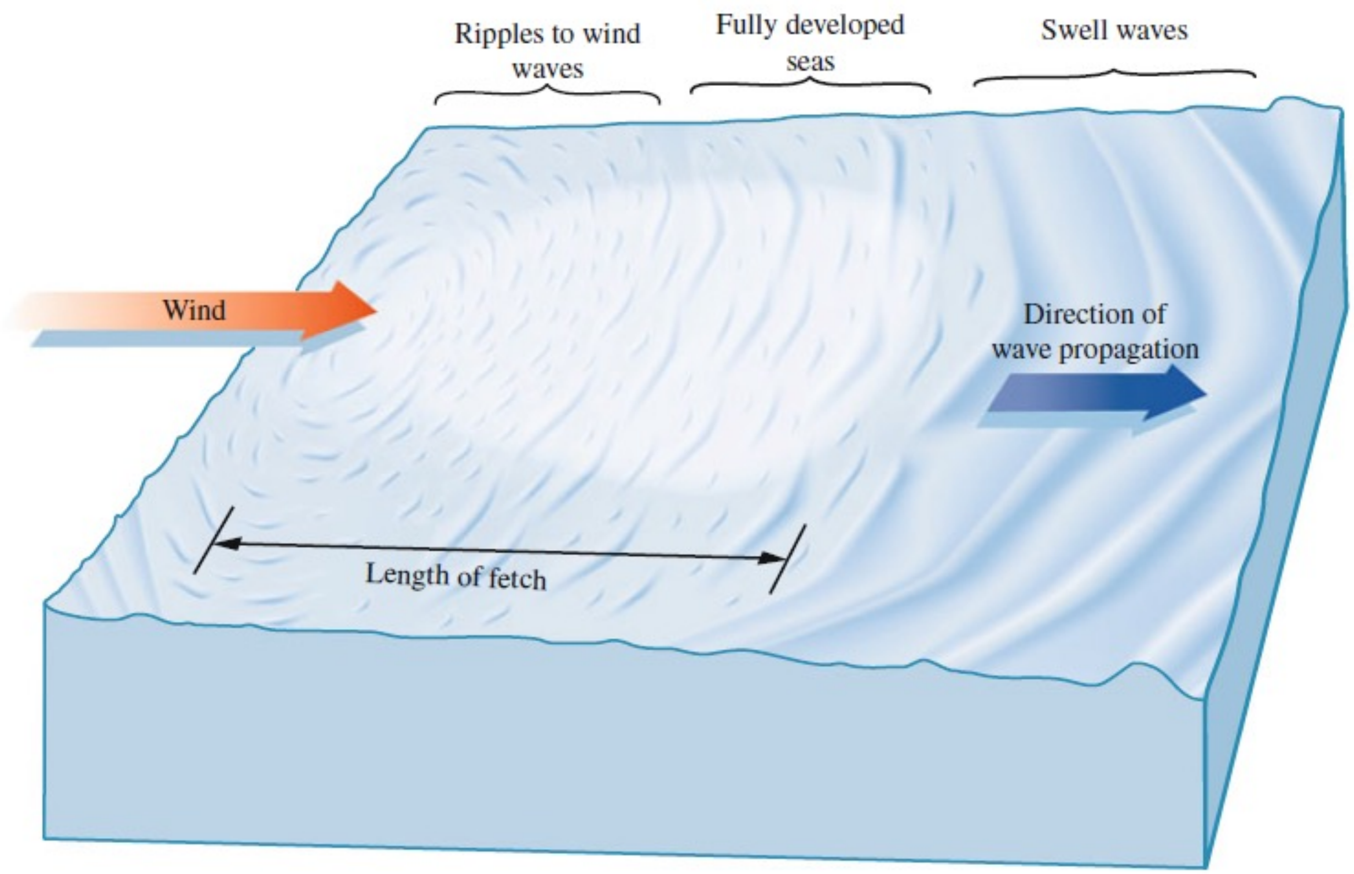
Ocean Waves – Three Dimensions



From WAFO

Wave Energy

Wave Energy – Propagation



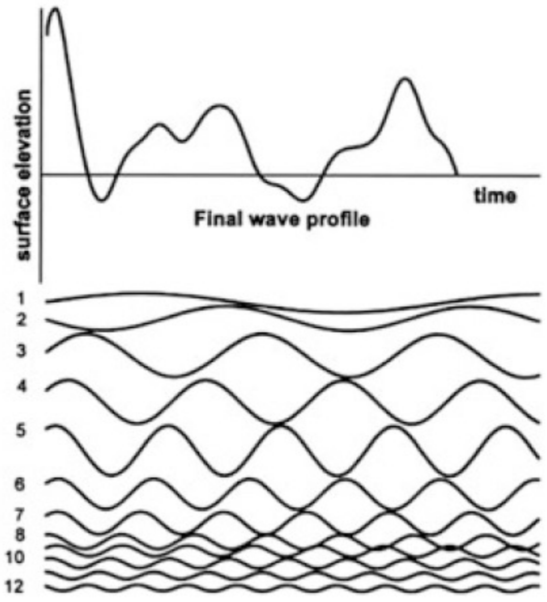
Garrison, T.S.: Oceanography: An Invitation to Marine Science, 7th edn. Brooks/Cole, Belmont, USA (2010)

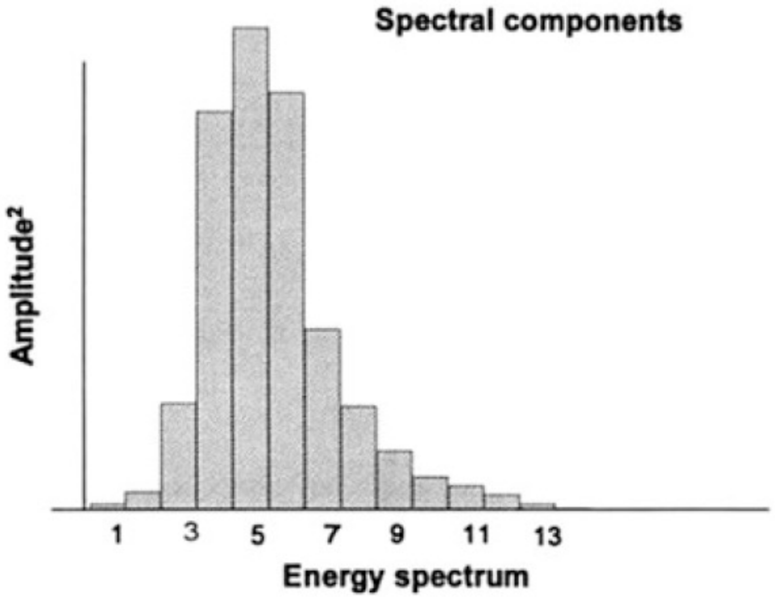
Energy Flux

[kW/m]

Incident Power

Wave Energy – Time and Frequency Domain

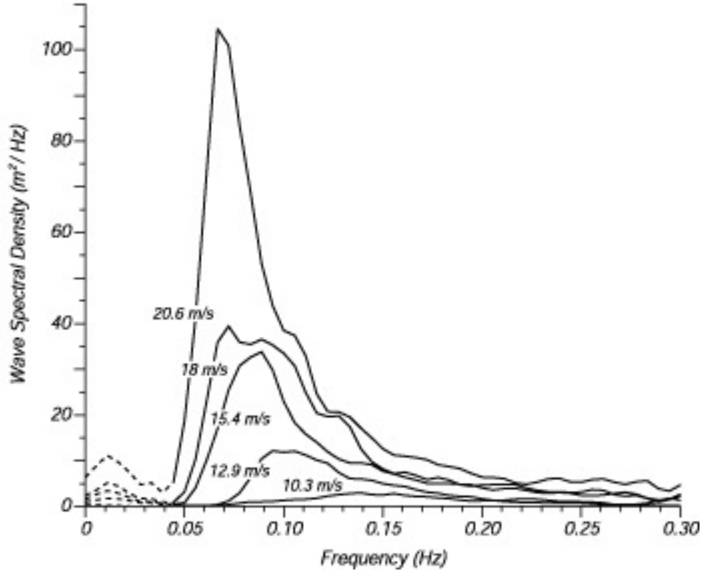


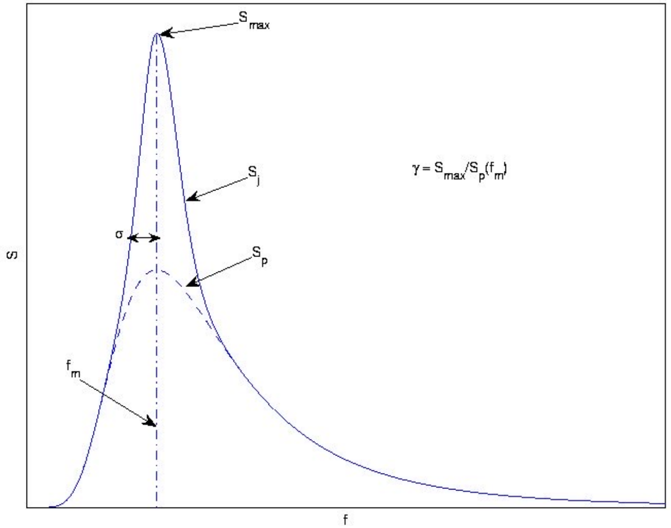


Super-positioning of waves (corresponding to spectral components) to create water surface elevation (left) and the resulting spectrum (right)

Massel, S.R.: Ocean Surface Waves: Their Physics and Prediction, 2nd edn. World Scientific Publishing, Singapore (2013)

Wave Energy – Spectral Representation





Real spectra (left) and parameterized (right) spectral representation (JONSWAP and Pierson-Moskowitz spectra) – defining sea states

https://wikiwaves.org/Ocean-Wave_Spectra

Scatter diagram

Hs \ Tz	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5
0.25	0.0066	0.0056	0.0030	0.0023	0.0011	0.0007	0.0003	0.00005				
1	0.0453	0.1650	0.0906	0.0347	0.0131	0.0047	0.0019	0.00069	0.0001	0.00004	0.00007	0.00005
2	0.0018	0.0368	0.1604	0.0650	0.0229	0.0099	0.0032	0.00121	0.00009	0.00005	0.00005	
3		0.0003	0.0187	0.1084	0.0335	0.0071	0.0033	0.00171	0.0004	0.00007		0.00002
4			0	0.01021	0.05565	0.01163	0.00209	0.00052	0.00034	0.00021	0.00005	
5				0.00002	0.00729	0.02391	0.00301	0.00069	0.00031	0.00014	0.00005	0.00005
6					0.00012	0.00603	0.00691	0.00052	0.00007			
7				0.00002	0.00009	0.00026	0.00352	0.00152	0.00016	0.00005		
8							0.00062	0.00288	0.00017			
9								0.00086	0.00073	0.00002		
10								0.00002	0.00043	0.00016		
11									0.00011	0.00014		
12										0.00004		

Matt Folley

Wave Energy – Distribution of Spectra

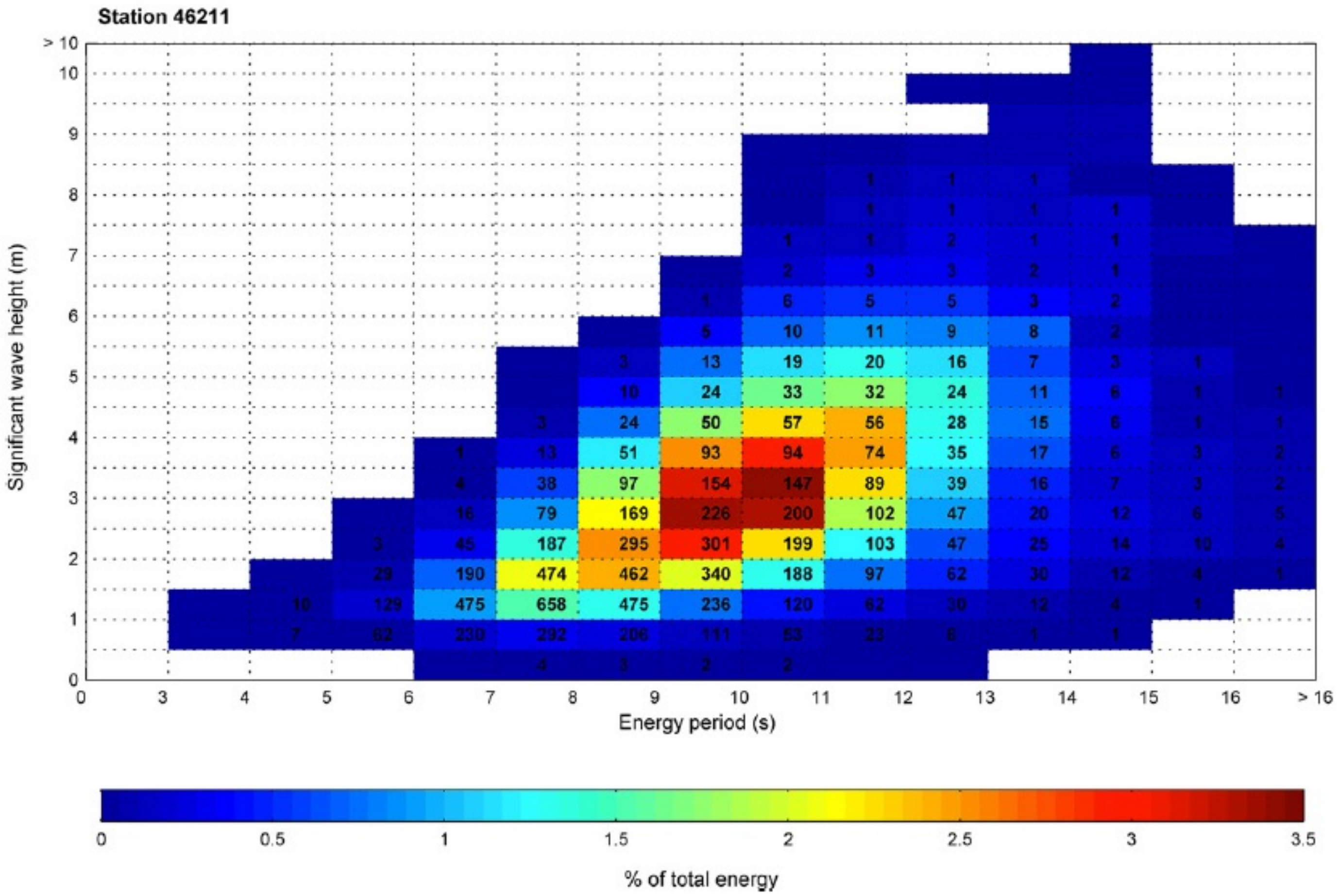
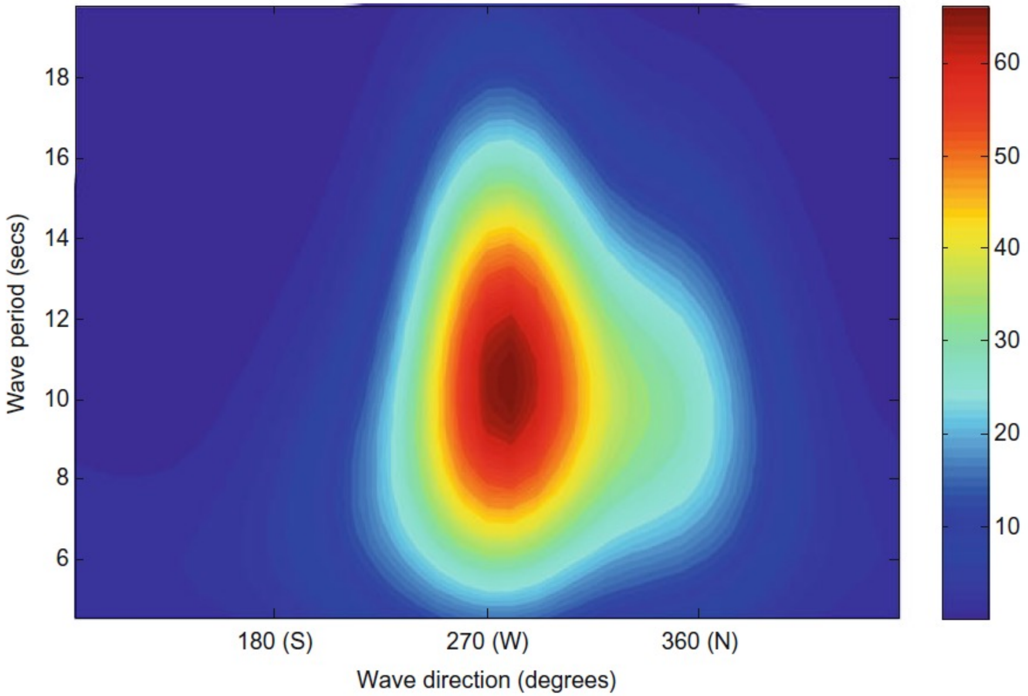


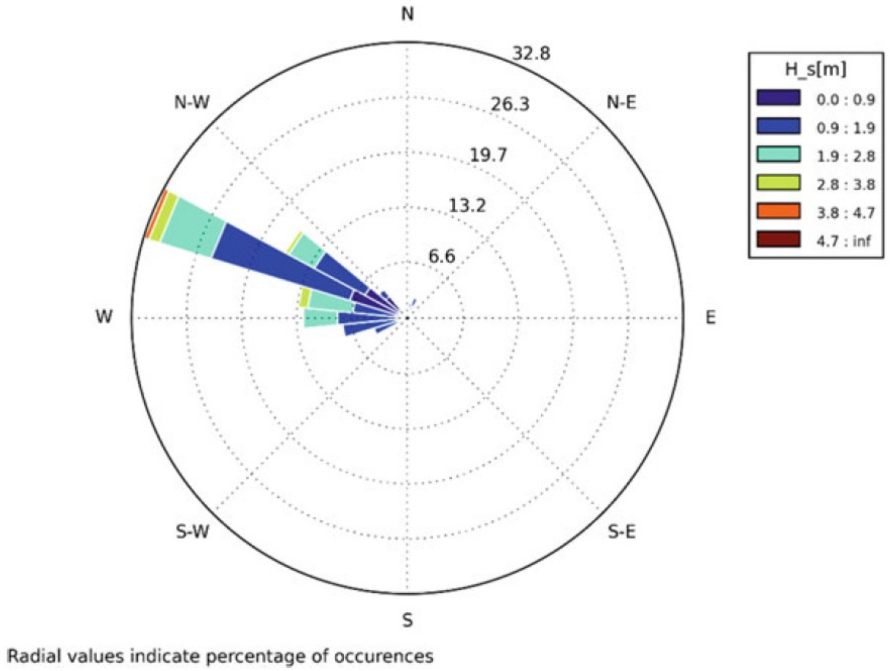
Fig. 8. Bivariate distributions of occurrence and energy, for sea states defined by significant wave height and energy period, at stations 46029 and 46211. The color scale is used to represent the contribution of the sea state to the total incident energy, as a percentage, while the number indicates the annual hours of occurrence for an average year.

Wave Energy – Distribution of Orientation/Direction



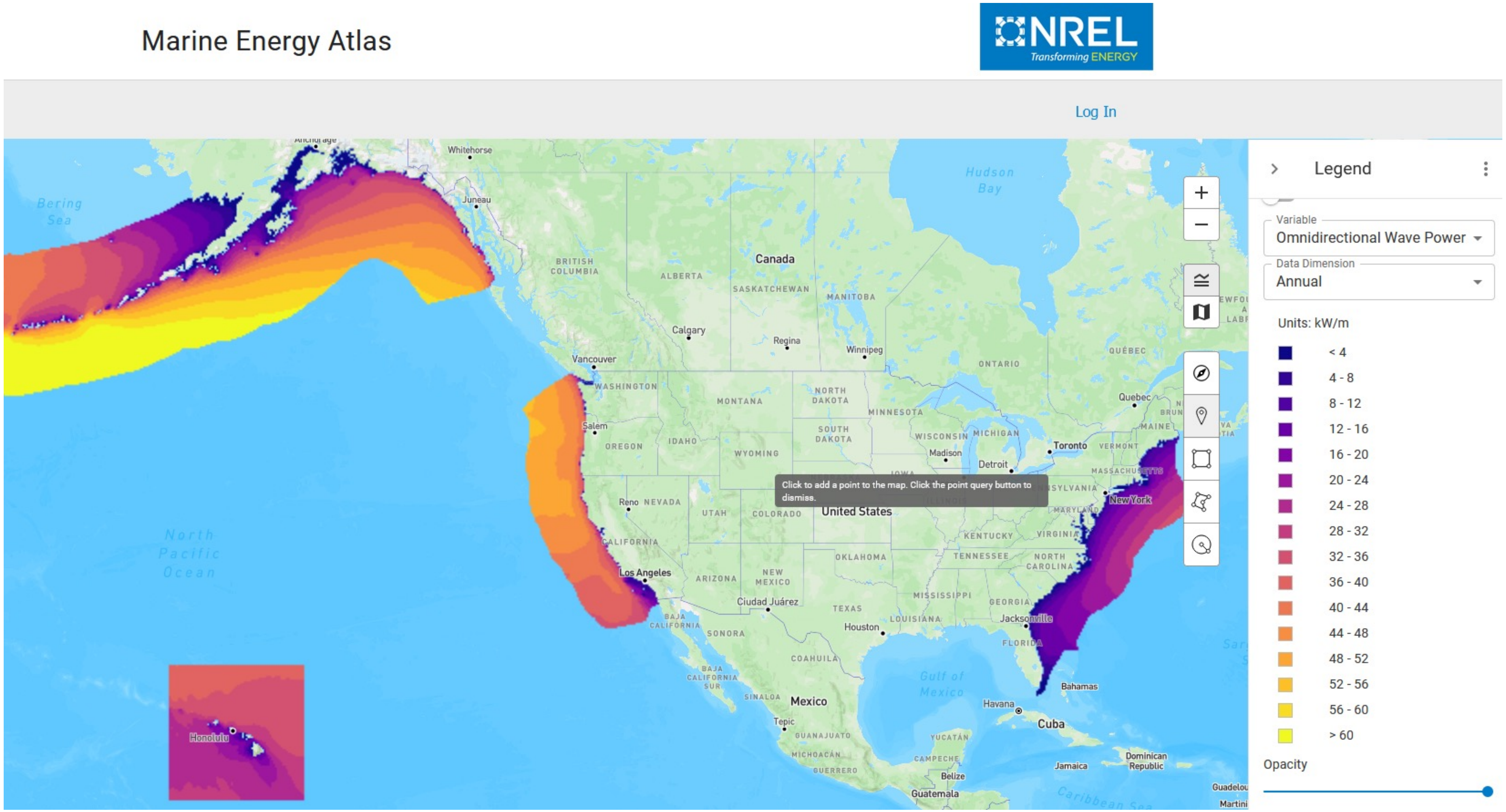
Average directional spectral variance density (m2/Hz/rad) at the European Marine Energy, Centre, Orkney, Scotland

Matt Folley



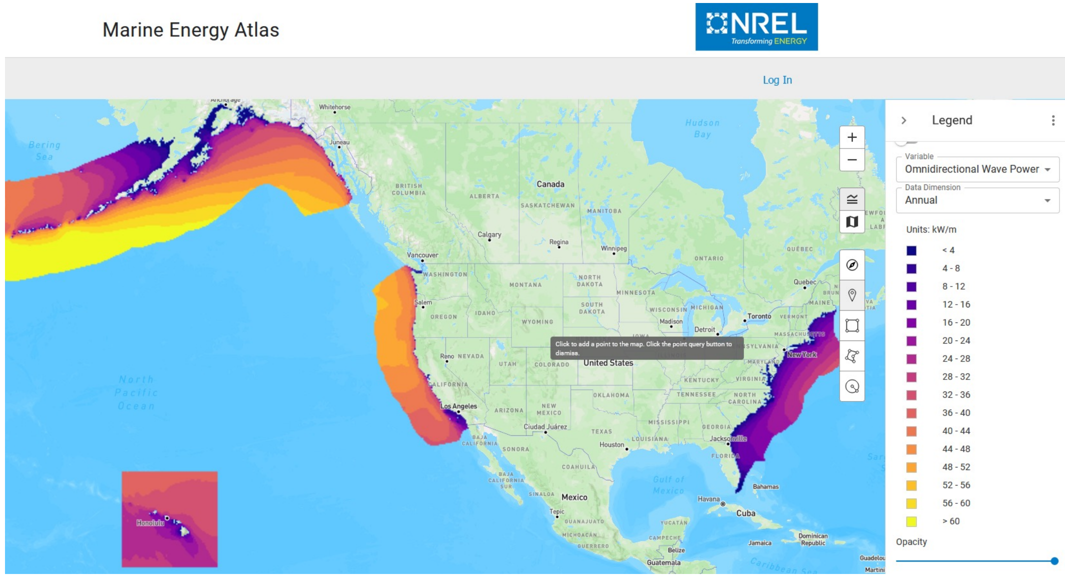
Matt Folley

Wave Energy – Resource



https://maps.nrel.gov/marine-energy-atlas/

Wave Energy – Resource



33 kW/m =  /(2 m)

- ***Theoretical resource potential***-annual average amount of physical energy that is hypothetically available
- ***Technical resource potential***-portion of a theoretical resource that can be captured using a specific technology
- ***Practical resource potential***-portion of the technical resource that is available when other constraints—(e.g., economic, environmental, and regulatory considerations)—are factored in.

U.S. MARINE ENERGY RESOURCES	THEORETICAL RESOURCE (TWH/YR)	TECHNICAL RESOURCE[B] (TWH/YR)	TECHNICAL RESOURCE AS POTENTIAL NUMBER OF HOMES POWERED	TECHNICAL RESOURCE AS PERCENT OF U.S. ELECTRICITY GENERATION (4126.7 TWH) (%)
WAVE (EEZ)	3,300	1,400	130,000,000	34
WAVE (TO 10 NMI)	1,800	770	72,000,000	19

https://maps.nrel.gov/marine-energy-atlas/

Technology

Technology – Concept Classification

Location

- *Onshore* Parts or all of the structure is fixed on the shore. The wave field is strongly influenced by the presence of the shoreline and the local bathymetry.
- *Near-shore* Plant is at some distance from the shore. The wave field is considerably influenced by the vicinity of the shoreline.
- *Offshore* Plant is a considerable distance away from the shore. The wave field is an open-sea wave field and the influence of the distant shoreline is negligible.

Orientation

- *Terminator* Transversal with respect to the predominant horizontal dimension.
- *Attenuator* Longitudinal with respect to the predominant horizontal dimension.
- *Point Absorber* Independent: No prevailing horizontal dimension.

Technology – Concept Classification

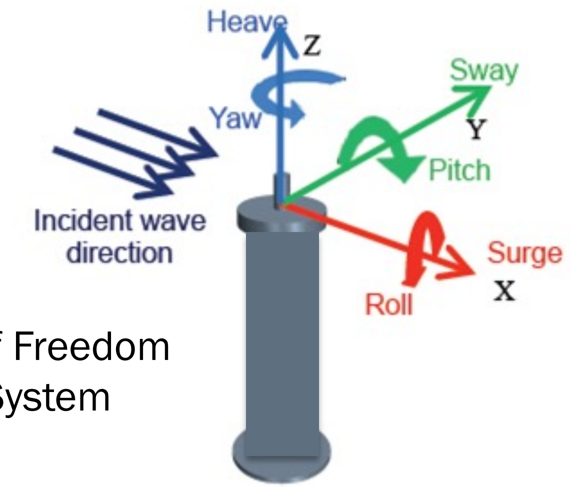
Mechanism of Extraction

- *Body motion* Fluid-body interaction causing body motion and power take-off extracts energy by damping the motion of one or more bodies. Hereby the body motion refers to the total motion of solid bodies and also to the local motion of deformable and elastic bodies.
- *Water surface motion* Fluid-gas-body interaction causing gas motion. Power take-off extracts energy by damping the motion of one or more gas volumes. The bodies involved are typically solid and the fluid-gas interaction is direct via a spatially limited free surface.
- *Fluid capture* Fluid-body interaction causing fluid separation with partition and capture of fluid in a spatially limited containment. Power take-off extracts energy by damping the flow of the separated fluid back into the outer, original fluid domain. The returning flow path is typically driven by a pressure difference and is different to the separating flow path.
- *Currents* Fluid-body interaction causing localised oscillating or changing currents due to waves. Power take-off extracts energy by dampening the flow of the currents.

Technology – Concept Classification

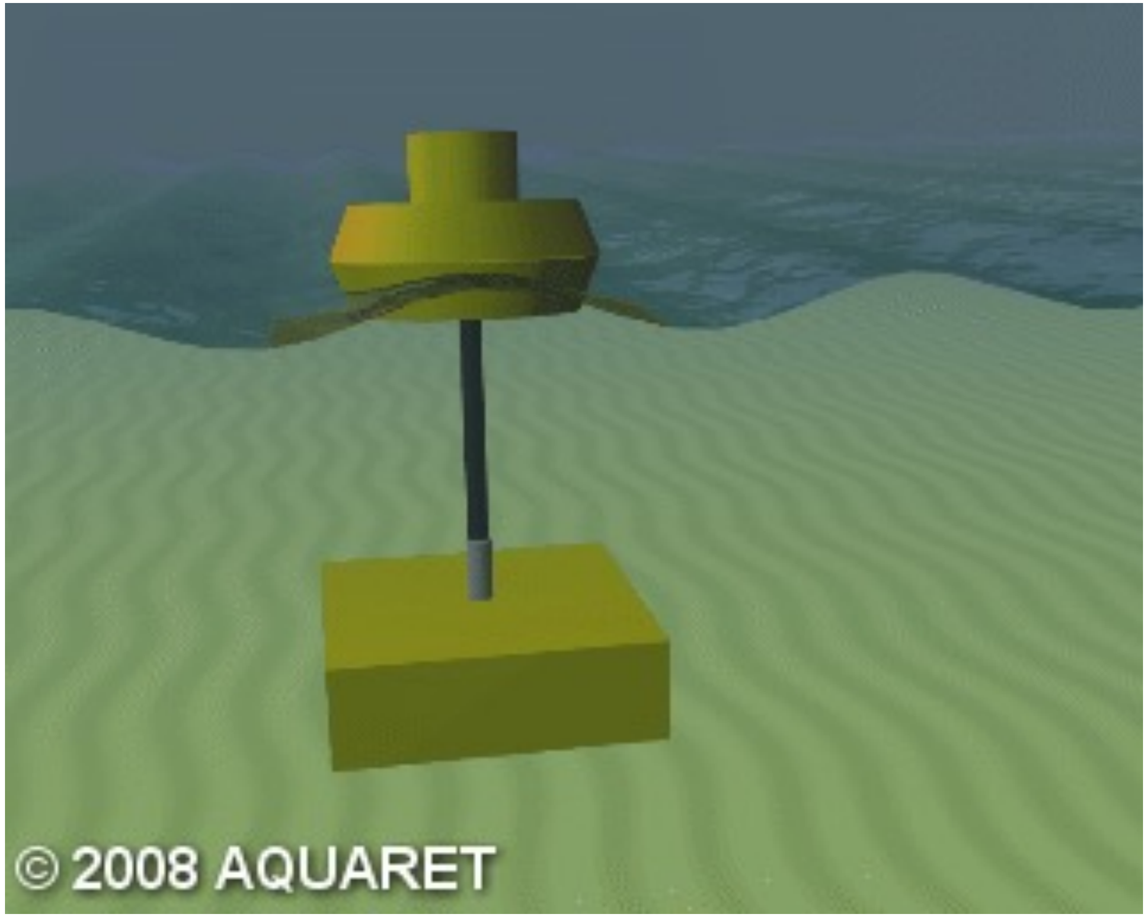
Reactional Reference

- *Absolute* Power take-off reacts in relation to the absolute reference frame and reactional forces are provided by the sea bed or the shoreline.
- *Relative* Power take-off reacts in relation to a relative reference frame and two further distinctions are made.
  - Relative reaction of two or more system components, of which all are directly exposed to the power extracting wave interaction.
  - Relative reaction of two or more system components, of which not all are directly exposed to the power extracting wave interaction. The reactional forces of the wave independent components are thus due to their inertia.

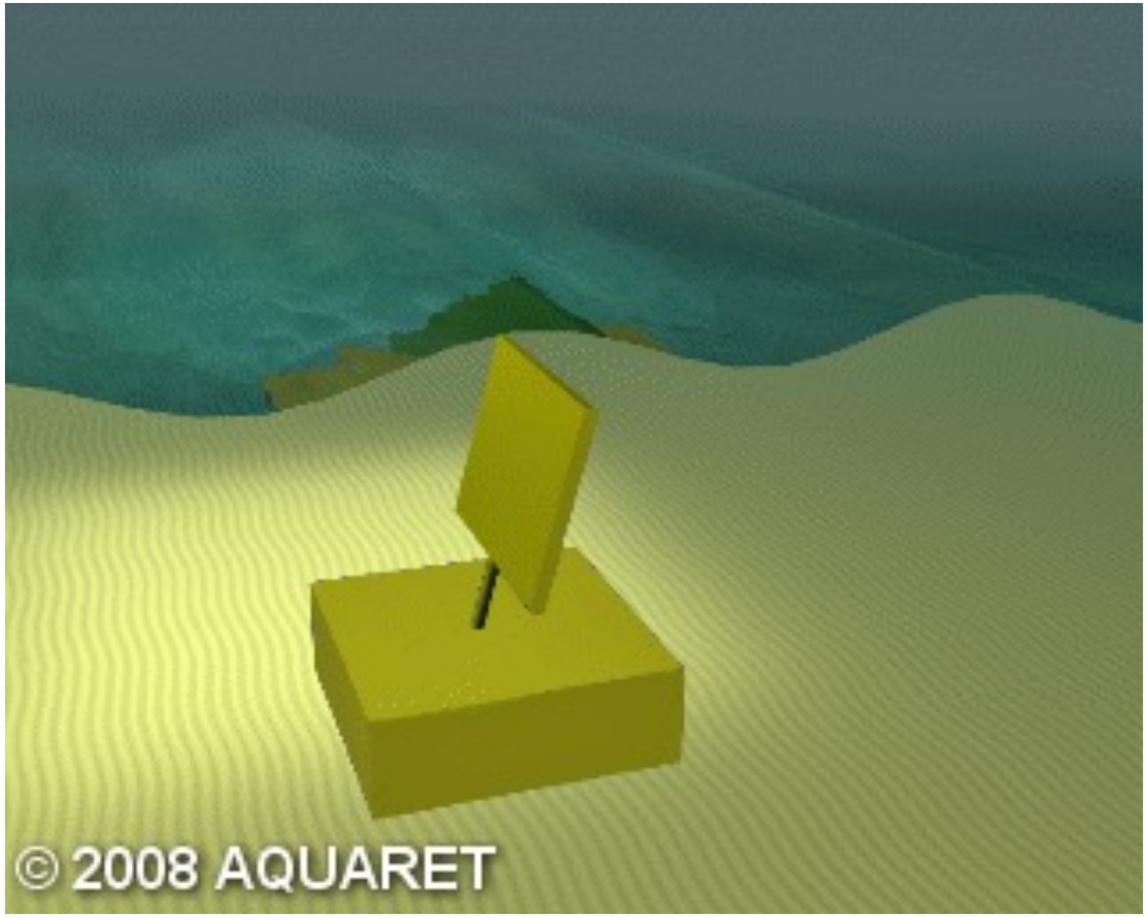


Motion Degrees of Freedom in Coordinate System

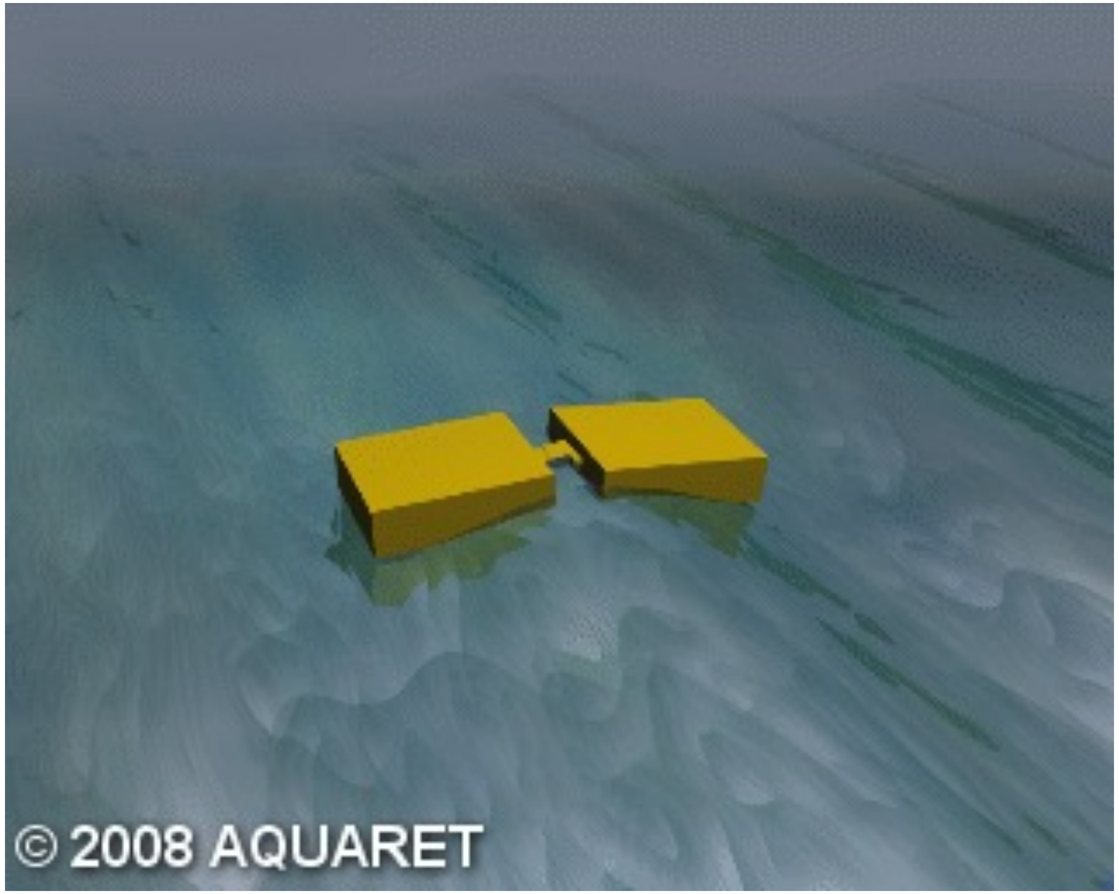
Technology – Concepts



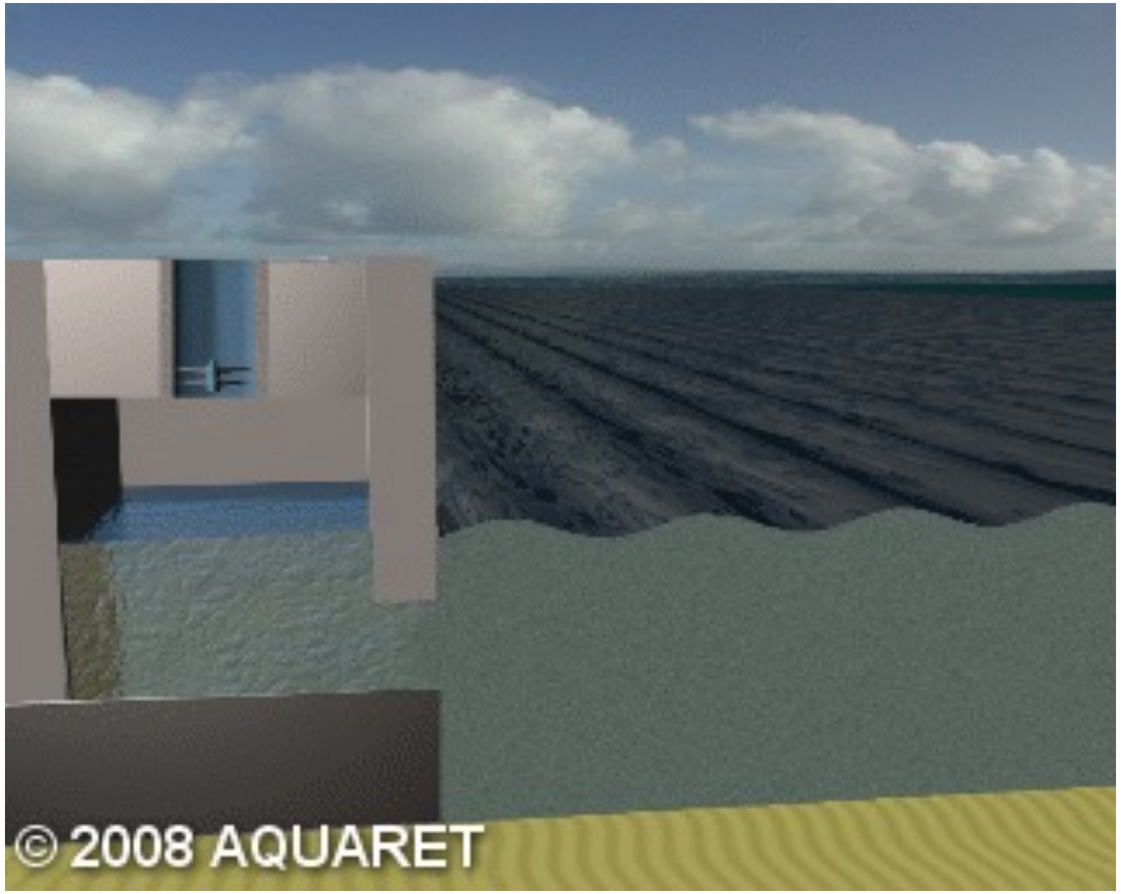
Technology – Concepts



Technology – Concepts

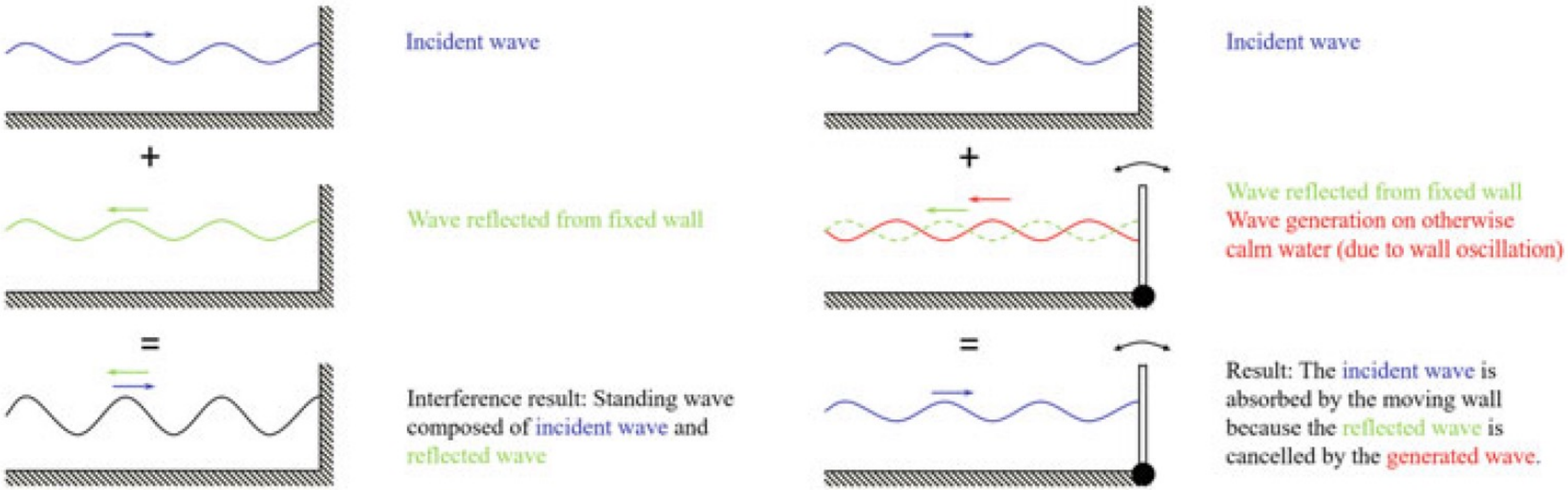


Technology – Concepts



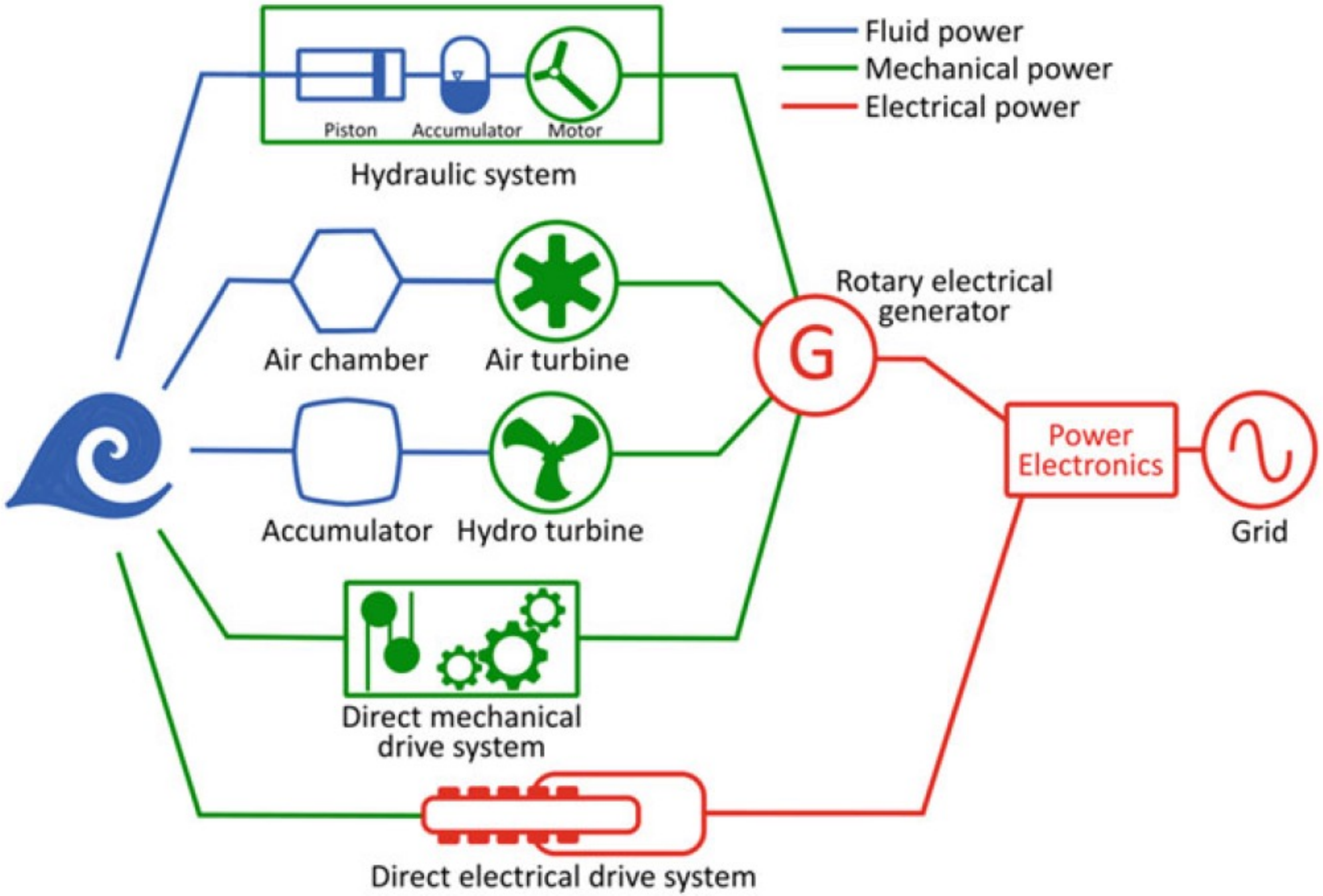
Technology – Concepts

Technology – Energy Absorption



Jorgen Hals

Technology – Energy Conversion



Different paths for wave energy to electricity conversion

A. Têtu

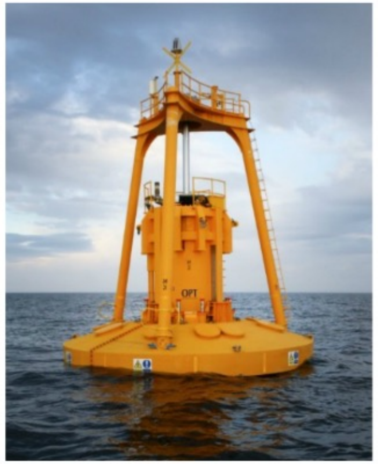
Technology – Development Challenges: Cost

Expensive

OPT
OCEAN POWER TECHNOLOGIES

Ocean Power Technologies

PB 150



"PB 7"

PowerBuoy System Specifications

Payload		
Voltage ranges		5 to 300 VDC
		100 - 240 VAC (50-60Hz)
Power*		
	Continuous	300 Watts
	Peak (1 hr/day)	7.2 kilowatts
Temperature		-18C to 35C
Available payload volume		
	External	0.25m dia x 0.60m
	Internal (upper)	0.25m x 0.35m x 1.60m
	Internal (lower)	0.60m x 0.60m x 1.50m
Max shock/accel.		5G

Buoy	
Overall Length	12.8m
Spar length	10.8m
Height above waterline	3.4m
Spar diameter (max)	1.1m
Float diameter	2.2m
Weight	10,000 kgs
Transport	Single 40' ISO container
Mooring	Single point
Deployment options	Buoy tender, tow-out, crane, A-frame vessel

Communications	
Serial	RS232
Ethernet	100 BASE-TX
WiFi (200 m)	802.11g/n
3G/4G (15 km)	3 mbps/500 kbps
Iridium/Satellite	2400 bps

* *Amount of power is dependent on site-specific wave conditions. Values shown are for a site 20 miles off the New Jersey coast.*

August 2013:
"Ocean Power Technologies Deploys Autonomous PowerBuoy …"

Annual Report 2012:
"As of April 30, 2012, we had an accumulated deficit of $126.0 million"

Technology – Development Challenges: Risk

High Risk

Aquamarine Power

Oyster 800

July 2013:
“Aquamarine Power releases performance data and details of planned improvements to Oyster 800”.
”Chief executive Martin McAdam said the results are “lower than they could be” but “encouraging” because Oyster has been operating on only one functioning power cylinder. … “It is a similar story with our hydraulic hoses, accumulators and control and instrumentation systems,” McAdam said.
-> Component failure during system testing

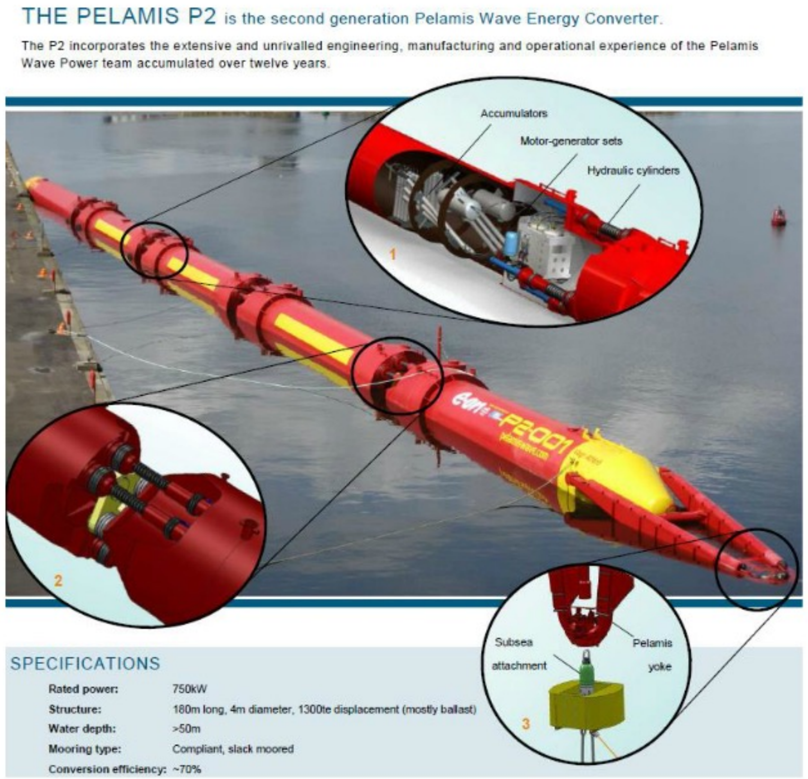
Technology – Development Challenges: Time

Slow

Pelamis wave power

Pelamis Wave Power

Pelamis P2



"Founded in 1998 by Pelamis inventor Dr Richard Yemm, alongside Dr David Pizer and Dr Chris Retzler, Pelamis Wave Power designs, manufactures and operates the Pelamis wave energy converter."

June 2013: "E.ON pulls out of Orkney Pelamis marine energy project"

Technology – Development Challenges: Innovation

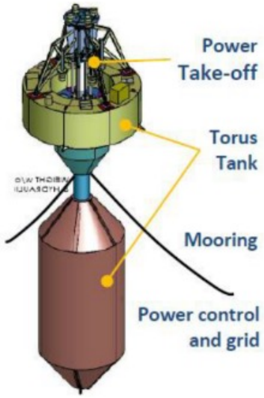
Rigid

Wavebob

Wavebob ADM 5

Wavebob ADM 2

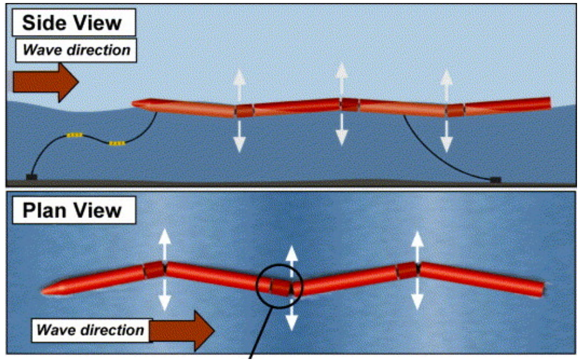
Wavebob concept

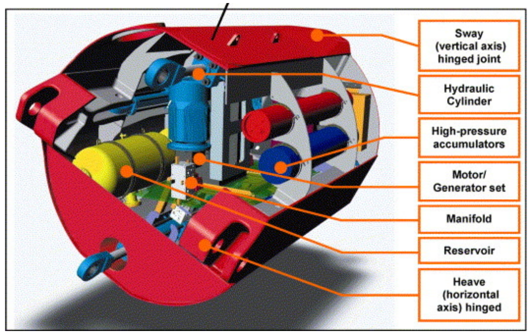


"Original patents filed in 1999."

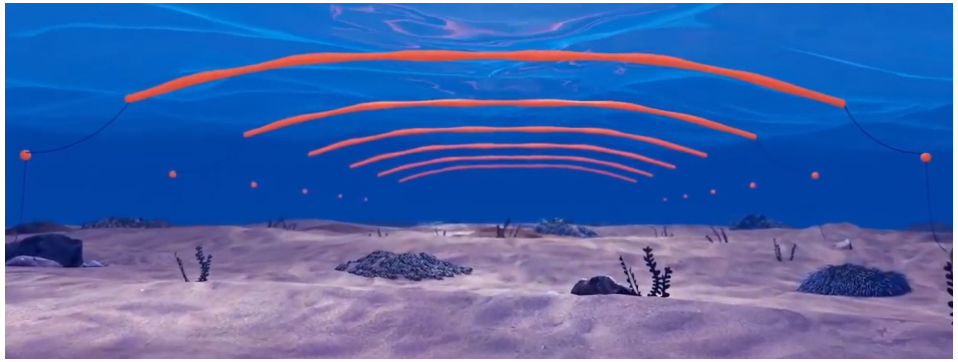
April 2013: "Ireland: Wavebob to go into Liquidation"

Technology – Possibility for Paradigm Shift?





Pelamis

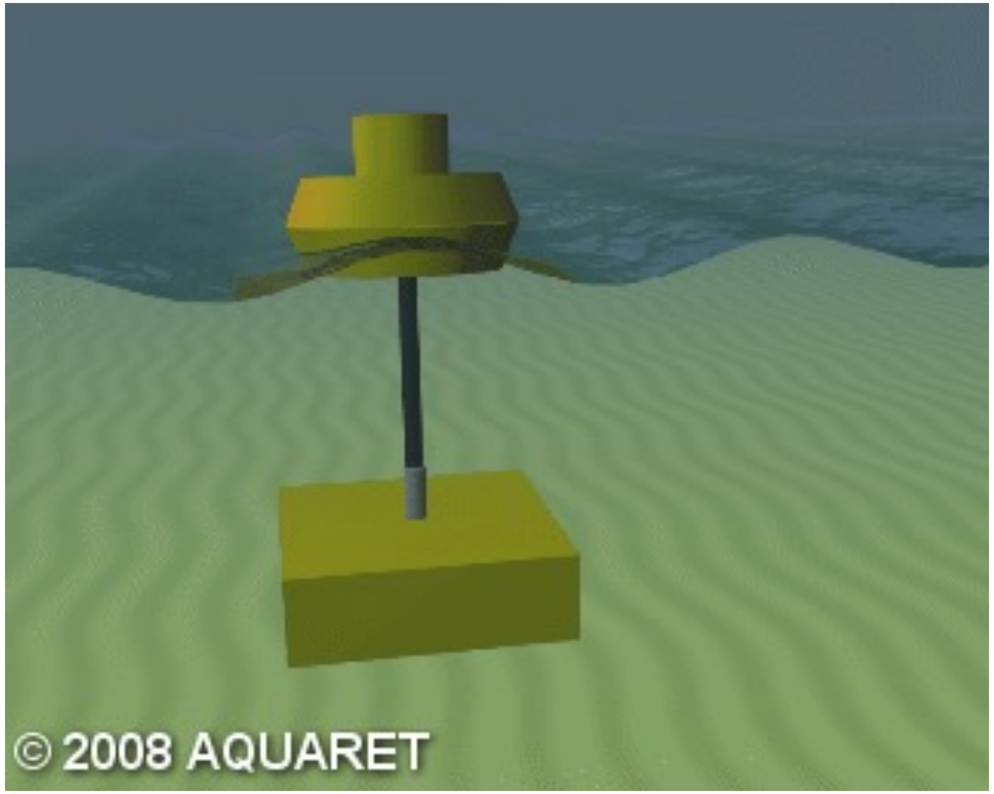


SBM Offshore

Questions

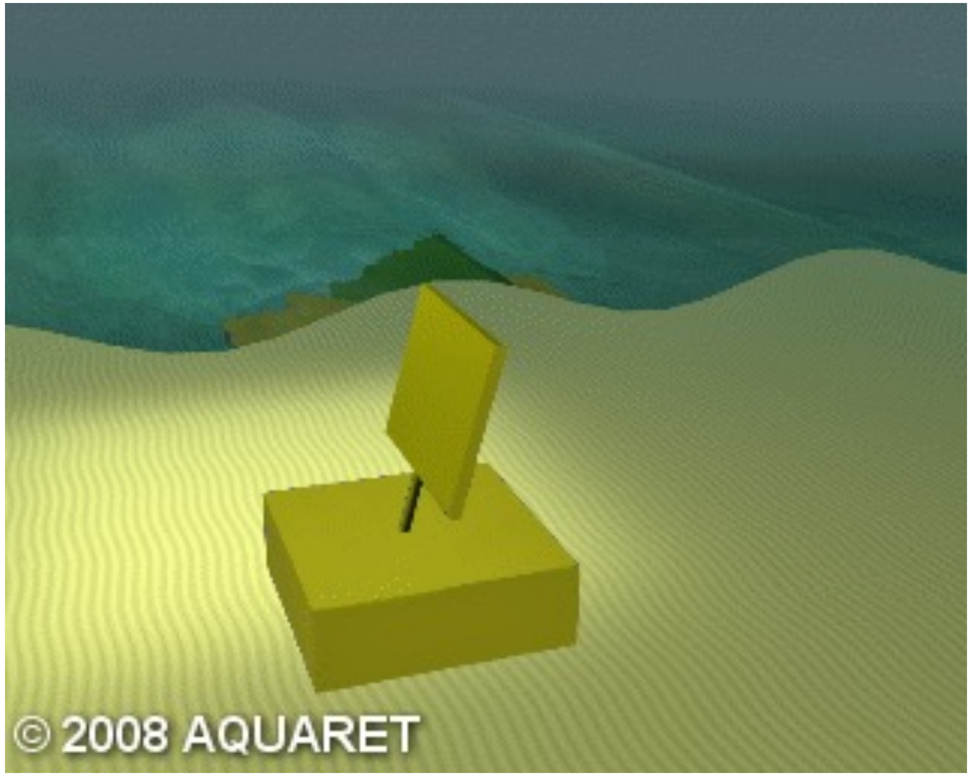
Example WEC: point absorbers

- **Point absorbers** are small in comparison to the incident wavelength. They are typically axisymmetric. Point-absorbers typically extract energy through a heaving or pitching motion, or a combination of both.



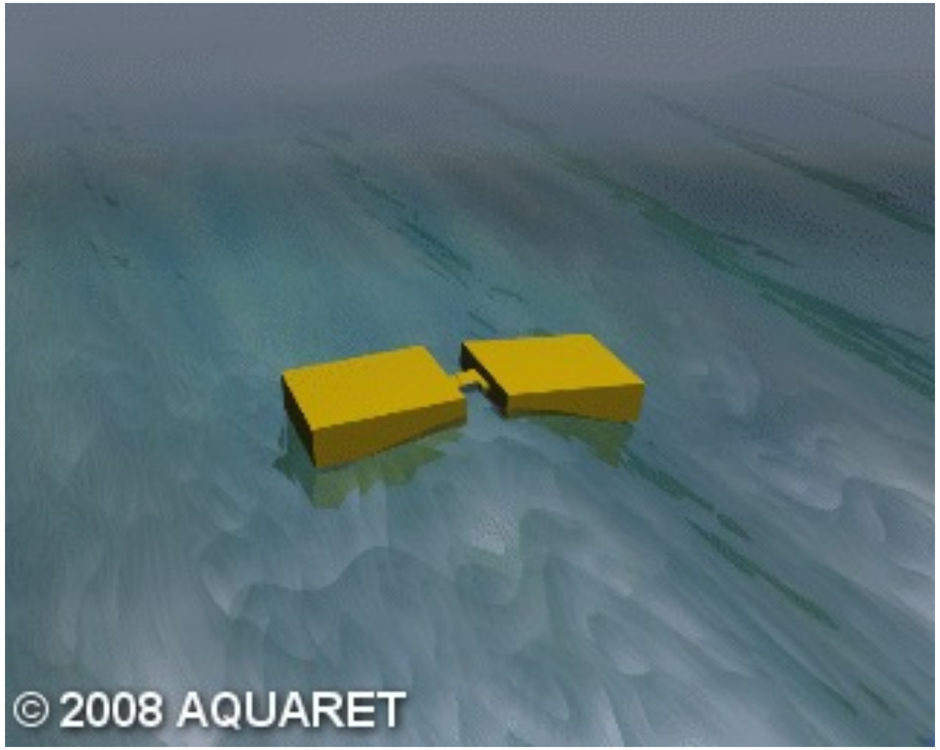
Example WEC: Oscillating Wave Surge Converters

- **Oscillating Wave Surge Converters** are fixed on the seafloor and the waves move a flap back and forth
- Energy from wave movement is captured with an inverted pendulum



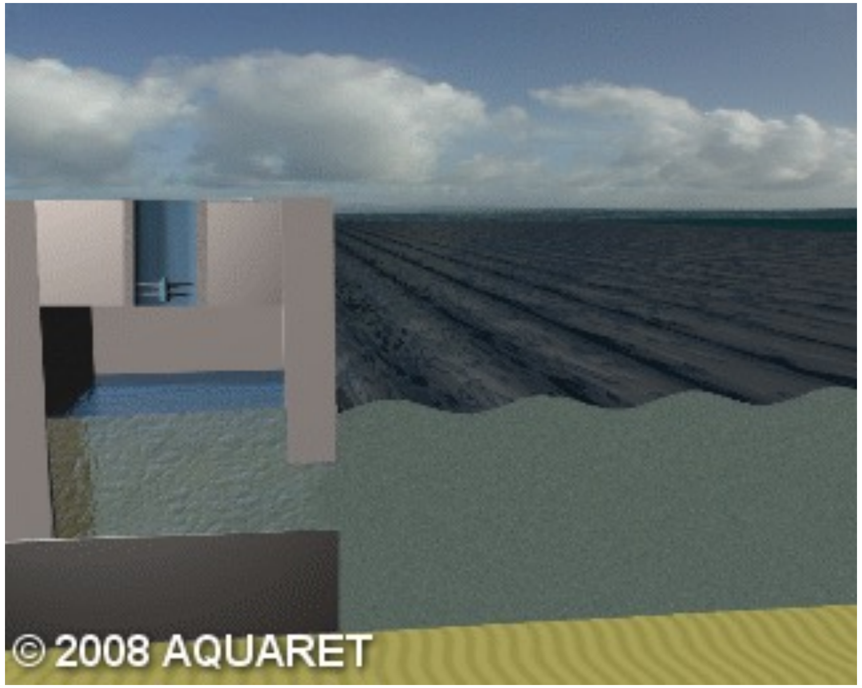
Example WEC: attenuators

- **Attenuators** have their principal dimension parallel to the dominant wave direction and progressively absorb energy as the wave passes along the device.
- An attenuator captures wave energy along its length from a large wave front length



Example WEC: oscillating water columns

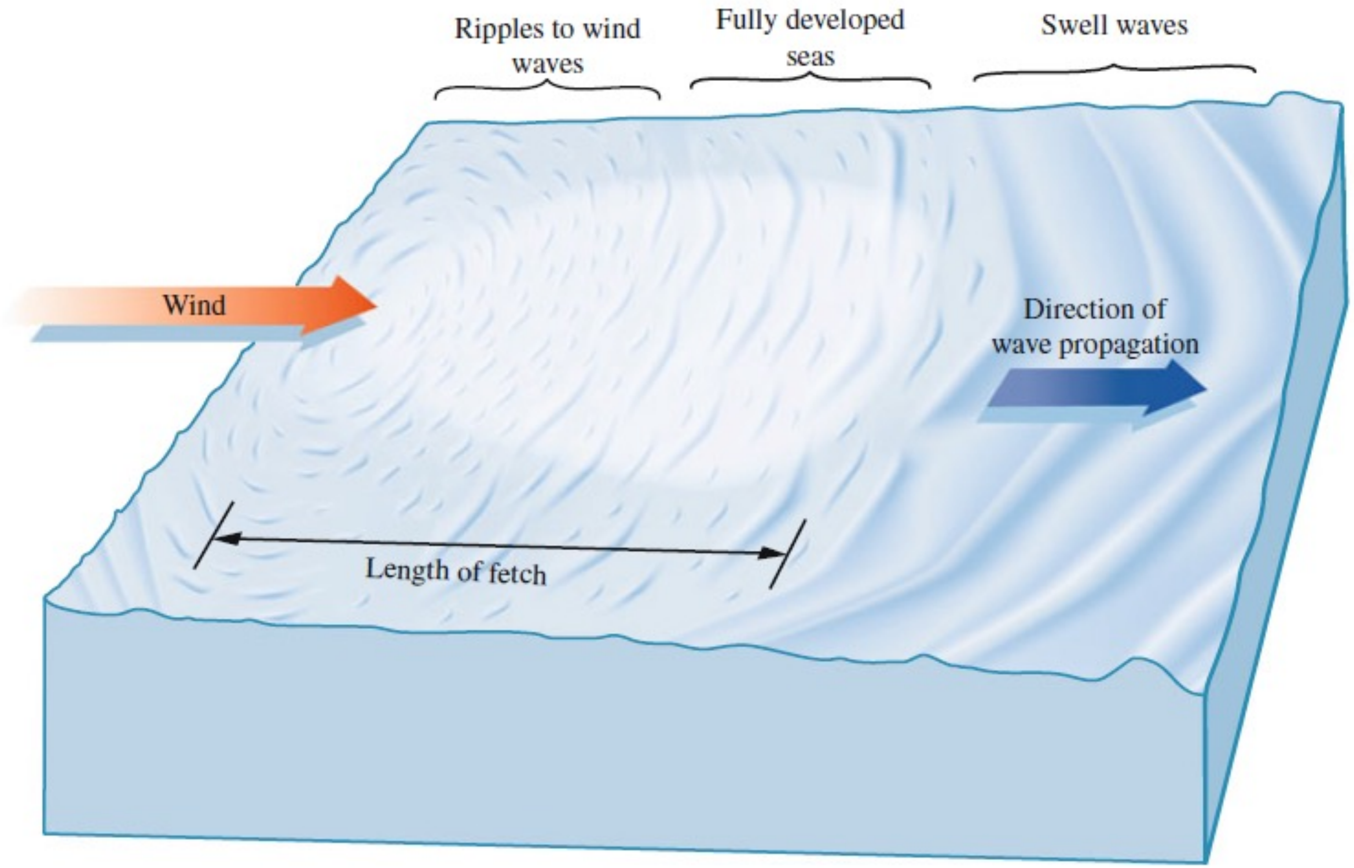
- **Oscillating water columns** are comprised of a partly submerged collector, open to the sea below the water surface.
- The collector contains air trapped above a column of water.
- This column of water will move up and down as waves enter and exit the collector, behaving like a piston, compressing and de-compressing the air.
- This is then channeled through an air turbine, which generates power in both air flow directions.



Example WEC: overtopping devices

- **Overtopping devices** operate similar to dams.
- They gather water in a reservoir at a height higher than the mean free surface as waves pass over the top of the device. The resulting hydrostatic pressure difference that is created between the reservoir and the open ocean is used to drive a turbine, just like a dam.
- Waves run up a ramp into a raised reservoir from which the water falls back to sea level through salt-water hydro turbines.

Wave Energy – Propagation



Garrison, T.S.: Oceanography: An Invitation to Marine Science, 7th edn. Brooks/Cole, Belmont, USA (2010)

Wave Energy Flux

[kW/m]

Incident Wave Power

An outline of what you're about to learn

- What fluid motions can energy be extracted from?
- Wave energy
  - What is a wave?
  - Key properties of waves
  - Visualizing wave motion
  - How is a wind/ocean wave generated?
  - Types of waves
  - Classification of waves and wave resources
  - What do sea states look like?
  - Understanding direction
  - How much power is there is waves?
  - How do devices move in an ocean wave?
  - Examples of WECs
  - Tools and approaches to design WECs
  - Understanding WEC performance
  - WEC parts, components, and systems
  - Challenges faces WECs
- Current and tidal energy
  - Understanding current flow
- Understanding the resource
- Environmental considerations for all marine energy technologies
- The techno-economics of marine energy technologies
  - Thinking about technological development
  - Technology readiness levels
  - Technology performance levels
- Some definitions and learning resources

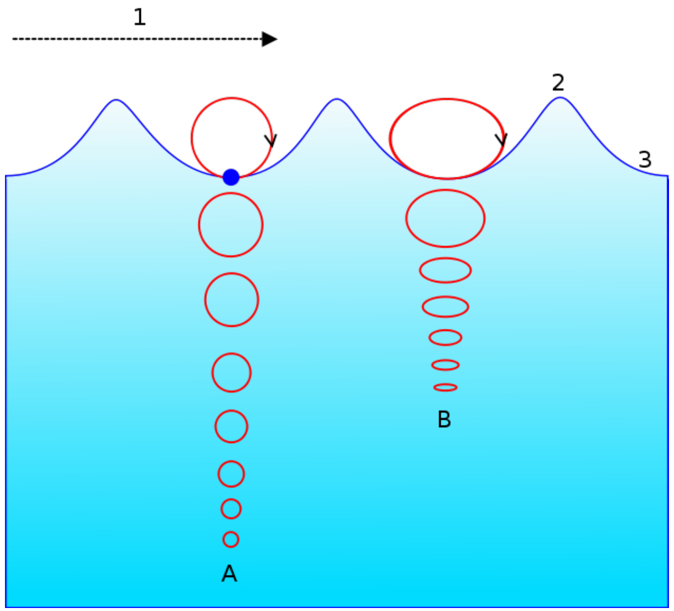
Wave Energy

What is a wave?

A wave is a phenomenon that moves energy through particle motion

- Sound waves transfer energy through pressure waves that move air
- Wind waves, or wind-generated waves, like you see on the beach, transfer energy through the motion of liquid particles.
  - They are also called surface waves, and they occur on the free surface of oceans, seas, lakes, rivers, and canals or even on small puddles and ponds.
  - The sun heats up air at different places and causes winds to blow over the a water surface.
    - Wave energy is a concentrated form of solar energy!
  - Wind waves range in size from small ripples (Capillary waves), to waves over 100 ft (30 m) high. These winds create ripples and then swells.
    - The distance traveled by wind or waves across open water is called fetch. Longer fetch creates more energetic waves.
  - Waves can travel *thousands* of miles before they reach land with virtually no loss of energy!

Visualizing wave motion



"Wave motion-i18n-mod" by Original uploader was Vargklo at en.Wikipedia
Licensed under CC BY-SA 3.0 via Commons

Motion of a particle in an ocean wave.

A = At deep water. The elliptical motion of fluid particles decreases rapidly with increasing depth below the surface.

B = At shallow water (ocean floor is now at B).

The elliptical movement of a fluid particle flattens with decreasing depth.

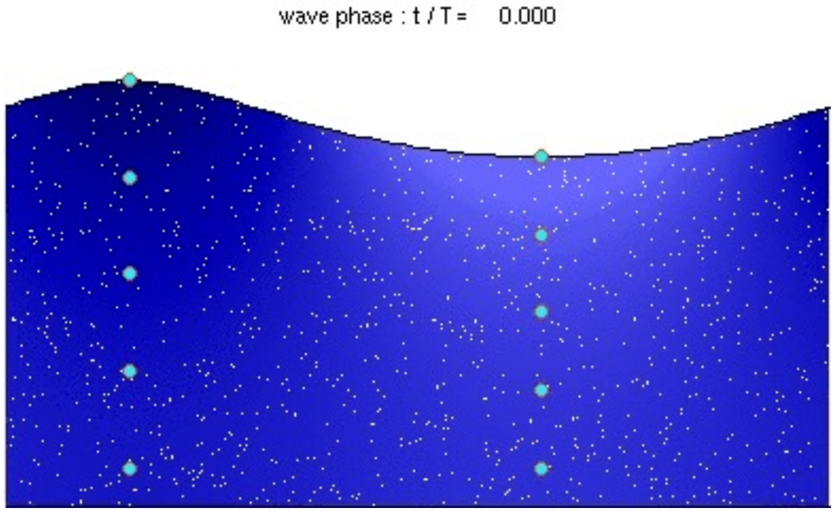
1 = Propagation direction.

2 = Wave crest.

3 = Wave trough.

Wikipedia

"Deep water wave" by Kraaiennest – Own work.
Licensed under GFDL via Commons

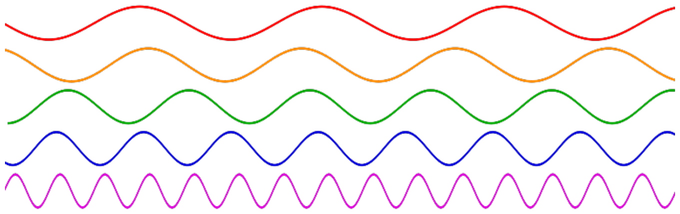


How is a wind/ocean wave generated?

- Ocean waves are generated by winds blowing over the surface of water
- Real ocean waves are complex, dynamic, and cannot be precisely predicted.
- Over the deep ocean, winds blowing over many hundreds of kilometers lead to the creation of *sea states*, which when broken down by defining characteristics like frequency, amplitude, and phase (*spectral analysis*), show the summation (*superposition*) of waves of varying frequency, amplitude, and phase.
  - In fact, the spectral distribution almost shows the history of the winds experienced by the sea over the entire journey of the wave!
- Ultimately the waves crest and break as they approach the shoreline.
  - In this case you see a changing wavelength as shown in the previous slide…

Types of waves

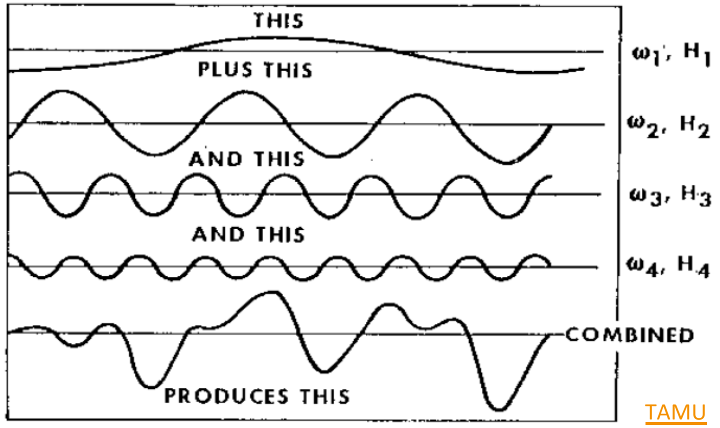
- Regular waves look like the sine waves below. They have a constant period/frequency and amplitude and a homogenous distribution of energy.



"Sine waves different frequencies" LucasVB. . Own work assumed .. Licensed under Public Domain via Commons

- Irregular waves are a combination of a multiple regular waves. Said differently, irregular waves that you'll see on the ocean surface can be broken down into a bunch of regular waves!
  - Here you see a combination of four regular waves to give one irregular wave…

The oceans are full of these irregular waves!



TAMU

Classifications of waves and wave resources

- At a given site in the ocean, the sea state changes over a time span of thirty minutes to one hour. Over the course of a year, a site's wave energy resource has about 1,000 sea states. Each sea state has different spectral distributions with unique probabilities of occurring – this is the *wave scatter diagram*.
- It is in the deep water where the wave energy resource is strongest. By the time the waves reach the shore, all the wave energy has dissipated due to friction with the sea bed, resulting in the waves' energy equaling zero at the shoreline.
  - What does that mean for where it is best to extract wave energy?

What do sea states look like?

You now know what the wave height and what the period of a wave are. When you take one point in the ocean and map out all the waves in terms of their wave heights and periods and plot them out, you get a diagram as you see below - this maps out a sea state.

This shows that a large fraction of the waves at this point in the ocean have a wave height of 3 meters and a period of 10 seconds…or, in other words, waves that have a wave height of 3 meters and that pass by every 10 seconds are the most common waves at this point in the ocean.

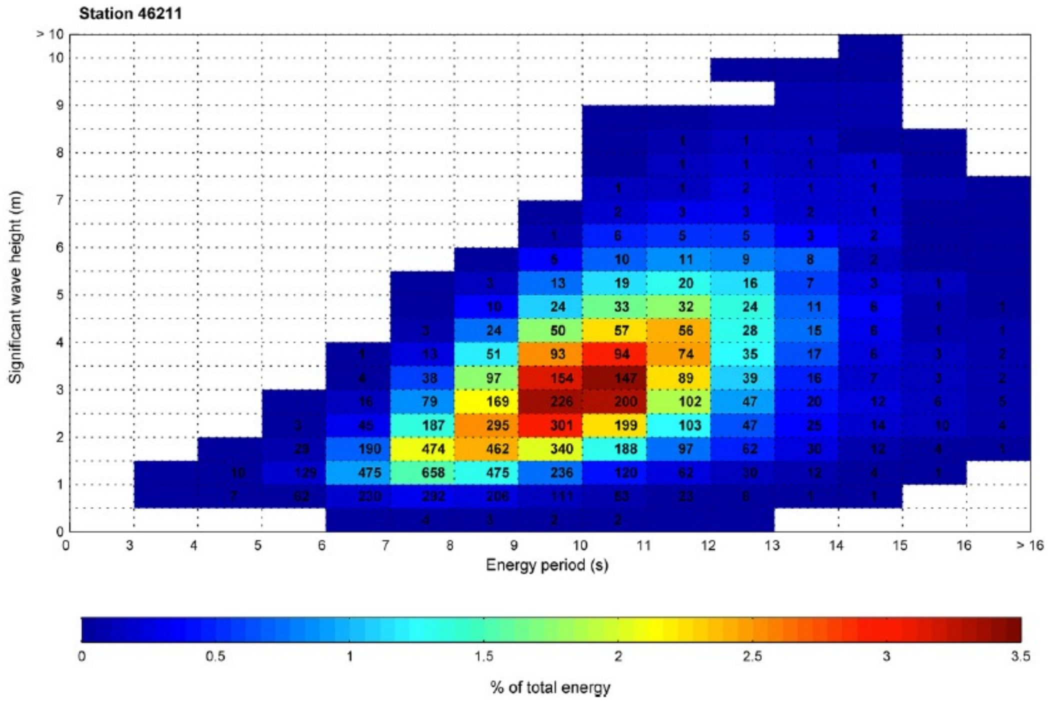


Fig. 8. Bivariate distributions of occurrence and energy, for sea states defined by significant wave height and energy period, at stations 46029 and 46211. The color scale is used to represent the contribution of the sea state to the total incident energy, as a percentage, while the number indicates the annual hours of occurrence for an average year.

How much power is there in waves?

- Potential wave power sites off the West Coast of the United States have annual average wave energy fluxes in the region of 20-30 kW/m of wave crest length
- In severe winter storms, the peak power can be multiple times higher than this, perhaps as high as 1MW/m, an increase by a factor of 30-50 over the average wave power flux!
  - This provides significant challenges to the structural design and consequent capital cost, or requires survival strategies, such as diving, submersion, or perhaps even removal to shore.
  - And these typical winter storms are not even as strong as the survival conditions to be met for the “100 year wave” or rogue waves, which will be even more demanding!
- Context and scale…
  - An incandescent bulb draws 60 Watts of power
  - A typical hairdryer runs on about 1 kW of power

Physical interactions of waves

- possible interactions between physical bodies/systems and ocean waves. E.g., slamming, overtopping, snatch loads, shock loads, anchoring, mooring, foiling effects, wave impacts, et al.

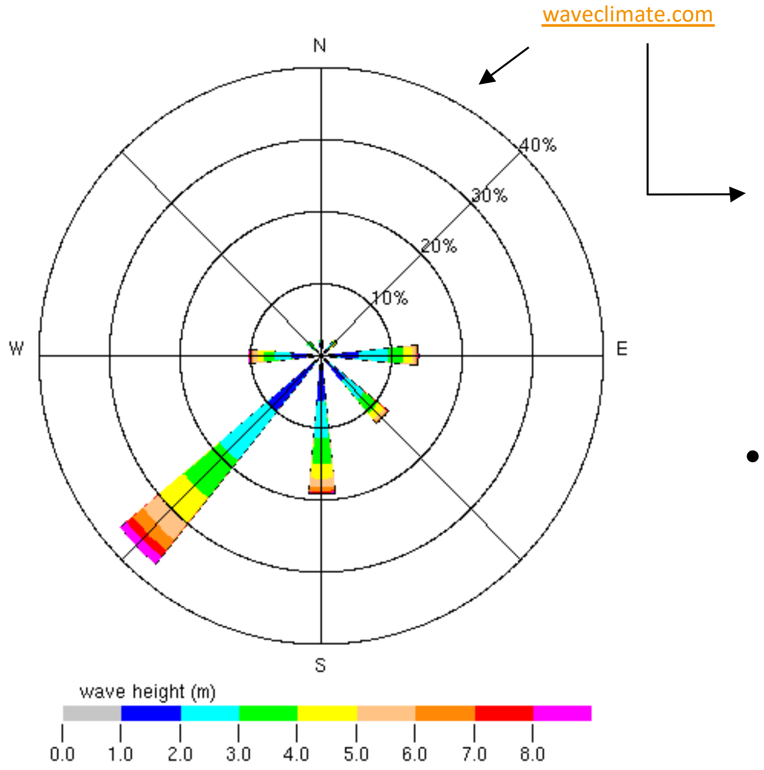
Some notes on wave power resource

- The sun throws a lot of power onto the Earth's surface…on average 350 W/m^2.
- The rate of energy input into waves is a small fraction of that--0.01 to 0.1 W/m^2. Remember, this is the conversion of solar energy → wind energy → wave energy!
- But over a long distance, power is continuously added to a wave, giving waves powers of 50 kW/m (50,000 W/m) or more! (Note the change in units! Once the energy is input in the waves, the waves transport that energy, and as we noted earlier, the power in waves is measured per unit crest width!)
- "Because of its origin from oceanic winds, the highest levels of wave power are found on the lee side [sheltered side] of temperate zone oceans."
- More on how wave energy resource is calculated later…

All notes and quotes above from Ocean Wave Energy *edited by* João Cruz

Understanding direction

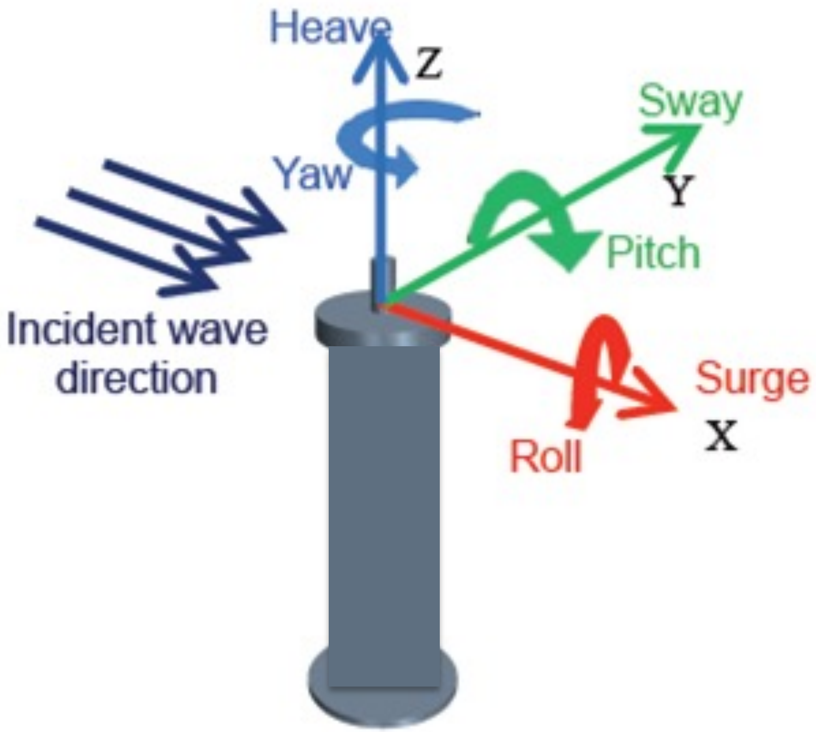
- As you now know, there are dominant directions that waves travel in, along with waves traveling in other directions.
- At the same time, you've also learned that there are dominant wave heights at certain locations.
- A *directional wave rose* provides an understanding of both direction and dominant wave height



- "The length of each colored spoke in the directional wave rose is related to the percentage of time that the waves arrive from that particular direction. Each concentric circle represents a different frequency, with zero at the center to increasing frequencies at the outer circles. Each spoke is broken down into color-coded bands that show wave height ranges. Directions follow the nautical convention.
- "In example here, most waves (more than 35%) arrive from the southwest, almost 20% of the time waves come from the south and about 10% of the waves come from the west. About 30% of the time, waves come from the southwest and are below 5m."

How do devices move in an ocean wave?

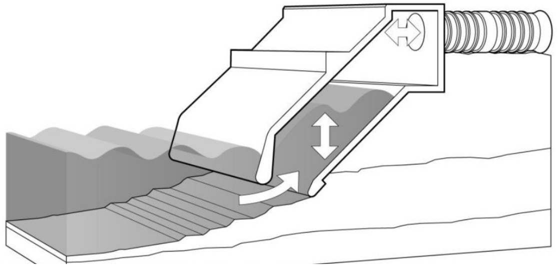
- WECs need to extract the energy from circular, elliptical, or linear fluid flow created by waves passing through water, waves that have a large number of spectral distributions as described above, and convert this energy into other usable forms of energy.
- Here, you see that
  - The movement of a device in the direction of the propagation of a wave is called *surge*
  - The movement of a device to the side of the direction of the propagation of a wave is called *sway*
  - The movement of a device up and down is called *heave*
  - And the rotations about the surge, sway, and heave directions are *roll* (imagine a corkscrew motion), *pitch* (imagine a somersault), and *yaw* (imagine an ice skater spinning like a top)



Classification of WECs by location

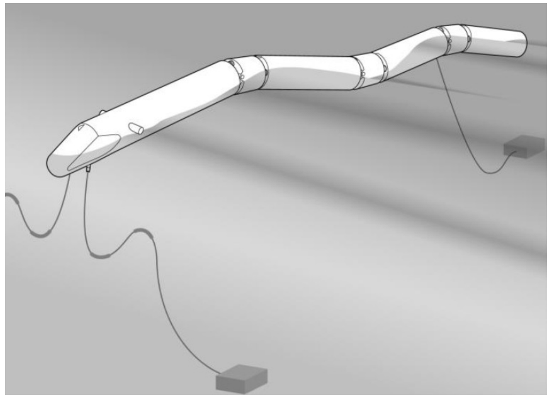
- **Shoreline** devices tend to rely on natural gullies to channel and focus the wave energy as it reaches the shore, such as the LIMPET device in Islay, Scotland, shown below
- **Near-shore** devices are located near to the shore. For instance, devices whose form of usable power is high pressure sea-water, have to be located relatively close to the shore due to the high losses associated with pumping sea water as a function of distance.
- **Offshore** devices get access to the most powerful wave climate in deep water. However, this is partly compensated by larger grid connection costs, greater electrical losses, potentially greater O&M costs.

LIMPET shoreline device
Figure from Ricardo AEA



Near-shore device
AquaMarine Oyster (a hinged flap)

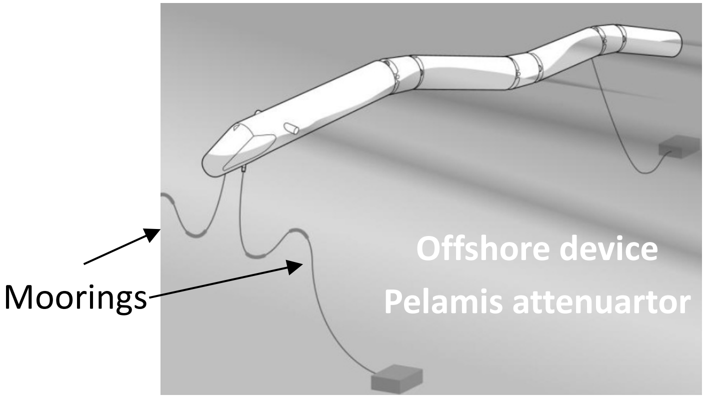
Offshore device
Pelamis attenuator



Classification of WECs by fixing

Offshore and near-shore devices can be moored or fixed to the seabed

- **Moored** devices are buoyant, but they do not necessarily need to float on the surface.
- Buoyant devices stationed beneath the surface will experience a lower wave power than floating devices, but to counter this, can be expected to experience less harsh storm conditions.
  – An example of a moored, buoyant, submerged device is the old concept the Bristol Cylinder, though this is not actively under development today.
- Devices fixed to the seabed will require some foundations, which can be gravity based.
  – An example of a rigidly fixed device is the Aquamarine Oyster.
  – Note, as it is fixed to the seabed, this means that it can only operate in shallow water, where the wave climate is again greatly reduced; at the seabed, the power in the waves is zero. Also, shallow water near the shore, means it is more vulnerable breaking waves.



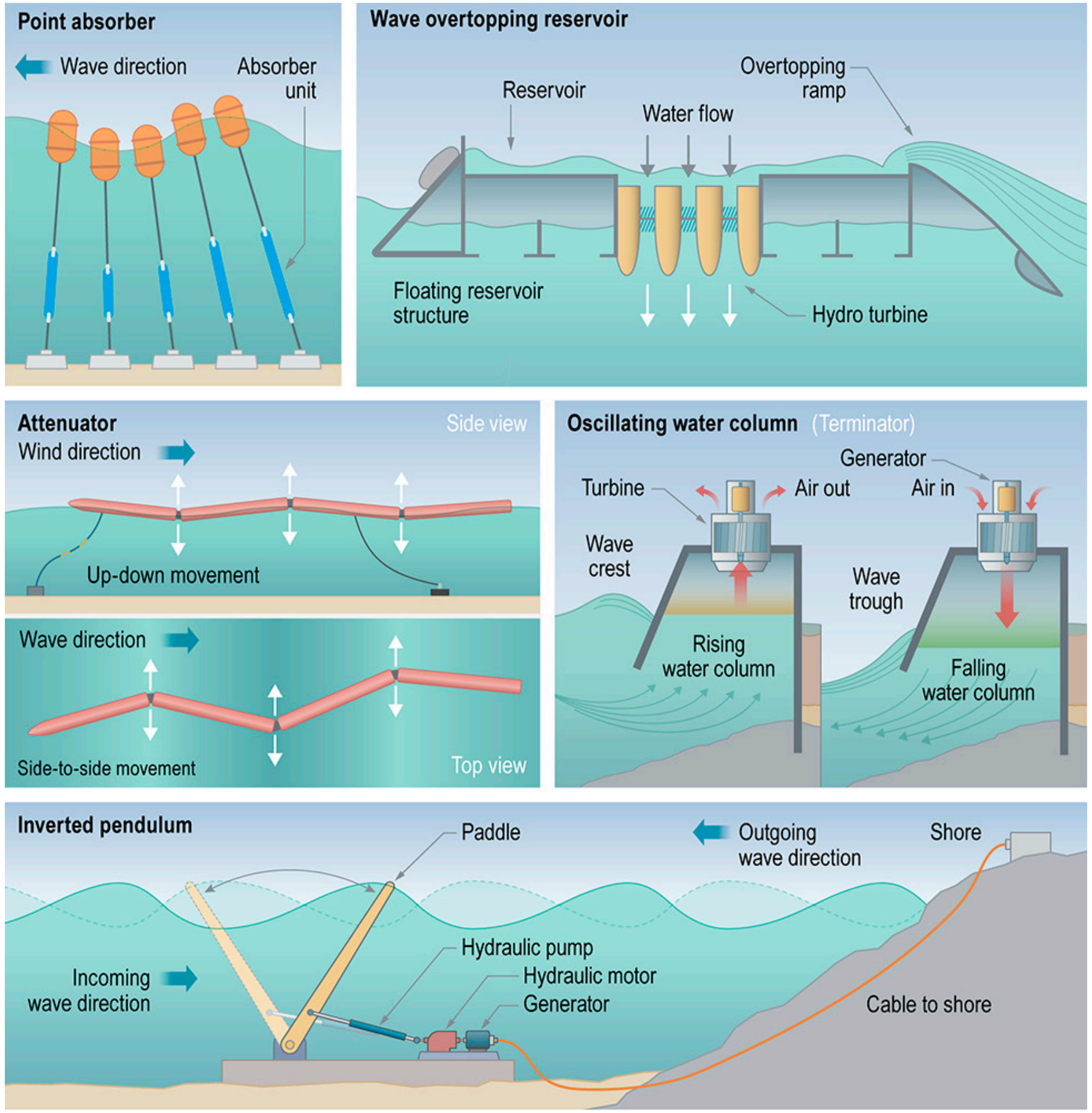
Classification of WECs by reaction force

- A refresher on Newton's First and Third Laws of Motion can be found here.
- While a WEC initially at rest is absorbing energy when it is moved by a wave, we want WECs to not only absorb energy, but also convert that energy into usable electricity. This is done through *power take-off* (PTO) systems, which are described later.
- For now, it is sufficient to say that we want the body of the WEC to *resist* being moved around by a wave, or to produce a *reaction force* such that the device doesn't move. In that case, the energy being absorbed by the WEC is transferred to the PTO.
- The body of the WEC and the PTO exert *equal and opposite forces* on each other—the reaction force. The reaction force performs work on the power take off mechanism as the PTO moves in response to it.
- The reaction force may be provided by the Earth, in the form of the seabed or a cliff face. The OPT PowerBuoy is moored to the sea-bed, which provides the reaction force.
  - Note that lift and drag are other possible reaction forces that can be leveraged by a WEC.

Examples of WEC designs

WECs can extract energy by heaving, swaying, surging, pitching, yawing, and rolling. WECs take on different shapes and have different sizes depending on how the device extracts energy from a passing wave.

We'll go through these configurations next



From the 2013 marine energy Techno-economic Assessment

Examples of WEC designs

Use Jochem Categorire

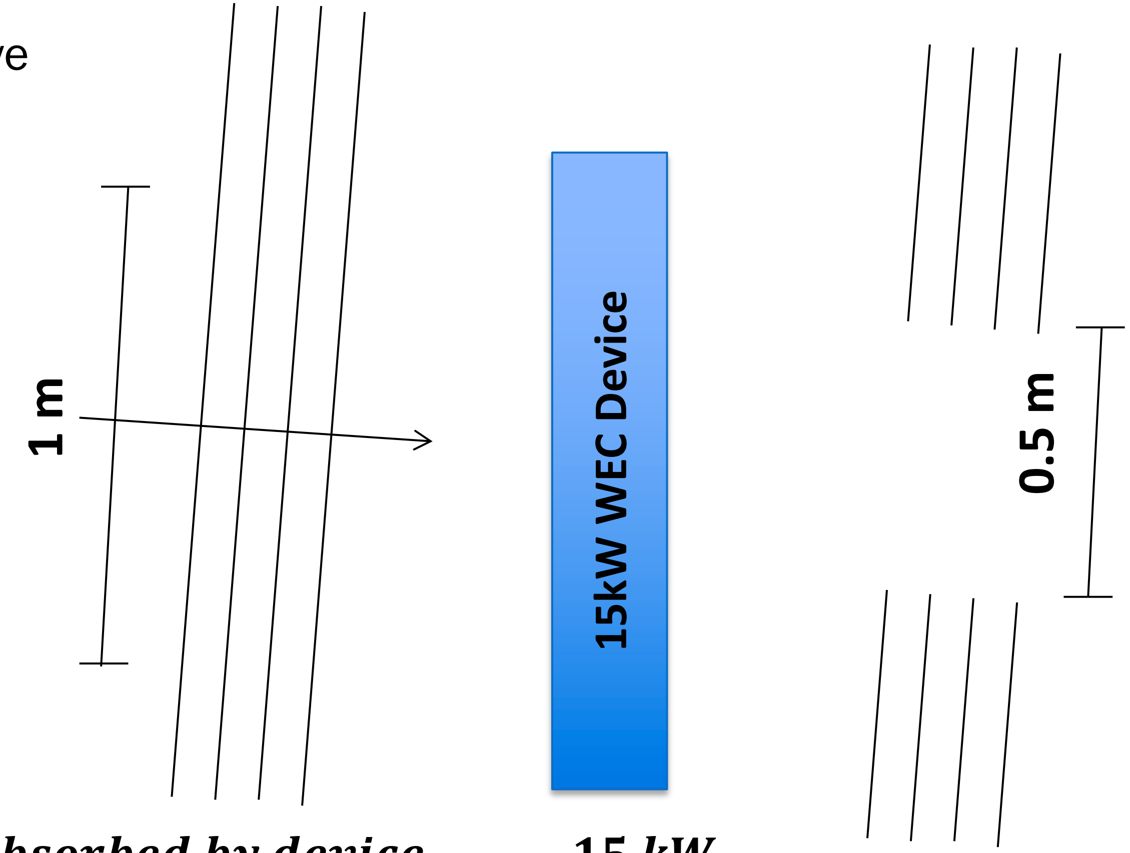
From the 2013
marine energy
Techno-economic
Assessment

How is WEC performance measured?

- There are various factors that speak to the performance of WECs
- You might ask a WEC designer questions like
  - What is the *capture width* of your device?
    - Capture width is the ratio of the total mean power absorbed by the body to the mean power per unit crest width for regular waves or per period for irregular waves. The higher the capture width, the better the performance.
  - What is the *bandwidth* of your device?
    - The bandwidth represents the spectrum of waves that a WEC can extract energy from. The higher the bandwidth, the more kinds of waves a WEC can extract energy from. The higher the bandwidth, the more versatile the WEC.
  - What are the survivability characteristics of your WEC?
    - As mentioned earlier, WECs need to withstand really high loads sometimes. Different WECs have different *survival* mechanisms. In storms, some WECs might be pulled below the water surface.
  - A good reference for understanding WEC performance is *Ocean Wave Energy* by João Cruz.

An example of how capture width is calculated

Power across 1 m of wave front = 30kW/m



$$CW = \frac{Power\ absorbed\ by\ device}{Power\ flux\ across\ wavefront} = \frac{15\ kW}{30\ kW/m} = 0.5\ m$$

CW is the effective width of the of wave front energy that the device absorbs and is therefore removed from the environment

WEC parts, components, and systems

- **Power conversion chain**: A single power conversion chain is defined as the entire absorption, transmission and conversion system between and including the absorbing element and the generator.
  - A device with multiple conversion chains will have more than one PTO, each operating in parallel with the others. For example, consider a flap type terminator with two flaps with separate PTOs per flap, then the device has two power conversion chains.
  - A range of power conversion steps are possible, to convert the power in the sea to usable power including hydraulic, pneumatic and even direct electrical. Furthermore, the form of usable power can also vary, as some applications could directly utilize hydraulic power.
- **Power take-offs** are the components that convert the mechanical energy absorbed by a WEC into electrical energy
  - Air turbines, which technically should include the air column as well.
  - Water turbines, include the low head hydro turbines used on overtopping devices, as well as other types used on devices which pump seawater, although in such cases the water pumping system also forms part of the PTO.
  - Hydraulic PTOs are used in a wide variety of designs, due to their ability to convert irregular reciprocating motion into unidirectional fluid flow that can be used to drive a hydraulic motor.
  - Linear generators have many of the advantages of hydraulic systems but are not efficient at the low speeds commonly encountered in wave energy collectors.

WEC parts, components, and systems

- Controls: Software that allows makes the device react to or prepare for an oncoming event.
  - Example is cruise control: when you drive up a hill and your car slows down, a computer senses this deceleration and tells the engine to throttle up to maintain the set cruise speed!
  - Similarly WECs can employ controls to adjust orientation to waves or even change shape, PTO reaction force, condition the power produced by the PTO, etc.
  - In terms of time and reaction, there are two kinds of controls: *causal* (or *reactive*) and *acausal* (or *proactive*).
    - Reactive controls tell the device to do something once an event is experienced
    - Proactive controls tell the device to do something in anticipation of an event
  - There is so much to know about controls! Tuning; and P, PI, and PID approaches; error estimation and optimization, and on and on!

Challenges facing WECs

- **Structural stability**: This is straightforward for onshore and relatively straightforward for shallow-water offshore wind turbines. Tidal stream is more challenging, due to the high-speed water currents in commercial sites, but still relatively close to shore, and not at very significant water depths. For WECs in deep water, this requires multiple mooring systems, potentially remotely operated vehicles and divers, possibly operating many miles from the shore base for marine operations..
- **Directionality:** WECs can extract energy from multiple motions. Some WEC concepts are intrinsically directional in their approach to exploiting wave power, whereas wind turbines and potentially tidal stream turbines have easy strategies for orienting the system towards optimum flow conditions for energy extraction.
- **Marine debris and biofouling:** With many wave energy concepts located at the surface of the sea where the wave energy is greatest, they are potentially more vulnerable to damage caused by marine debris, such as shipping containers, ropes and fishing nets. Biofouling is also far more prevalent at the surface or near the surface, as this is where the biological activity is greatest.
- **Other uses of the sea:** WECs potentially have greater impacts on other users of the sea, such as those in shipping, fishing and recreation. Many wave energy concepts have some freedom to move, but tidal or wind turbines are essentially static devices that are constrained by moorings. This uses up a large surface of the sea, and increases the potential for collisions.
- **Non-linearity:** Wave energy theory is linear, which is an approximation that holds only for small waves. In practice, the waves themselves and the interaction of the device with them is likely to be non-linear, potentially requiring very significant computer power to even understand how the device might react to the waves, or accepting uncertainty in performance and maybe life-time of the device.
- **Breaking waves:** This is not really a great concern for deep-water WECs, with the possible exception of rogue waves or in survival conditions. However, breaking waves impart huge slamming forces on structures and their moorings, leading to potentially catastrophic failure.

Understanding the Resource

Energy flux …

Energy flow from the sun

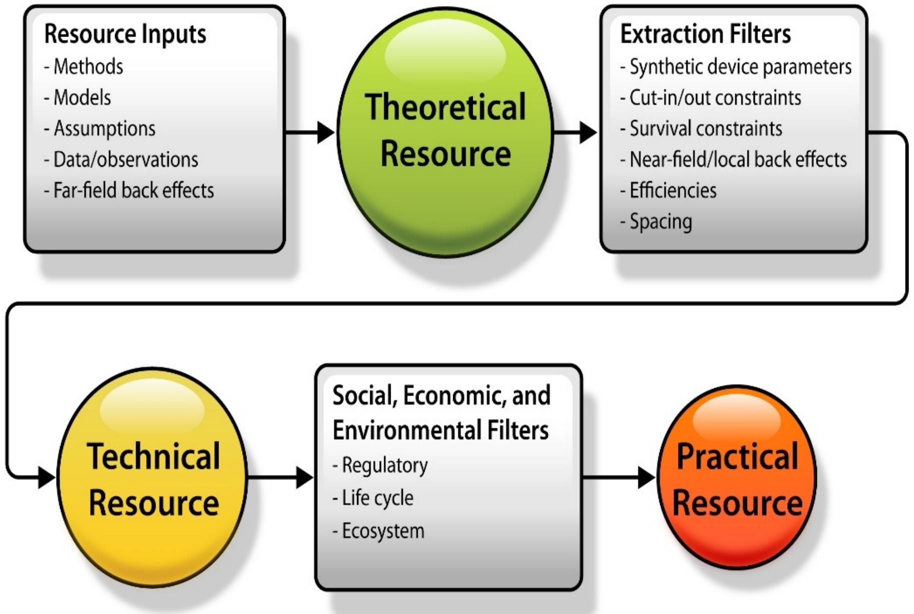
- The Earth receives an immense amount of energy from the sun
- For example, in 2002, the Earth received more energy from the sun in one hour than was used by the whole world in the entire year! (Nature, Powering the Planet)
- In one year, the Earth receives *twice as much energy from the sun as will be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and uranium combined*. (Energy Flow Charts)
- This solar energy is converted into wind energy and marine and hydrokinetic energy

Resource definitions

Here's how we work through how much energy we can extract and how we can do so:

- There is a whole lot to tap into = ***theoretical resource***
- But things aren't technologically straightforward. Technologies aren't perfectly efficient and there are improvements to be made = The theoretical resource gets boiled down to the ***technical resource***
- After including political considerations and other social and regulatory considerations = The technical resource gets boiled down to the ***practical resource***

Marine Resource Assessment Terminology



The breakdown

- Here's what the numbers look like

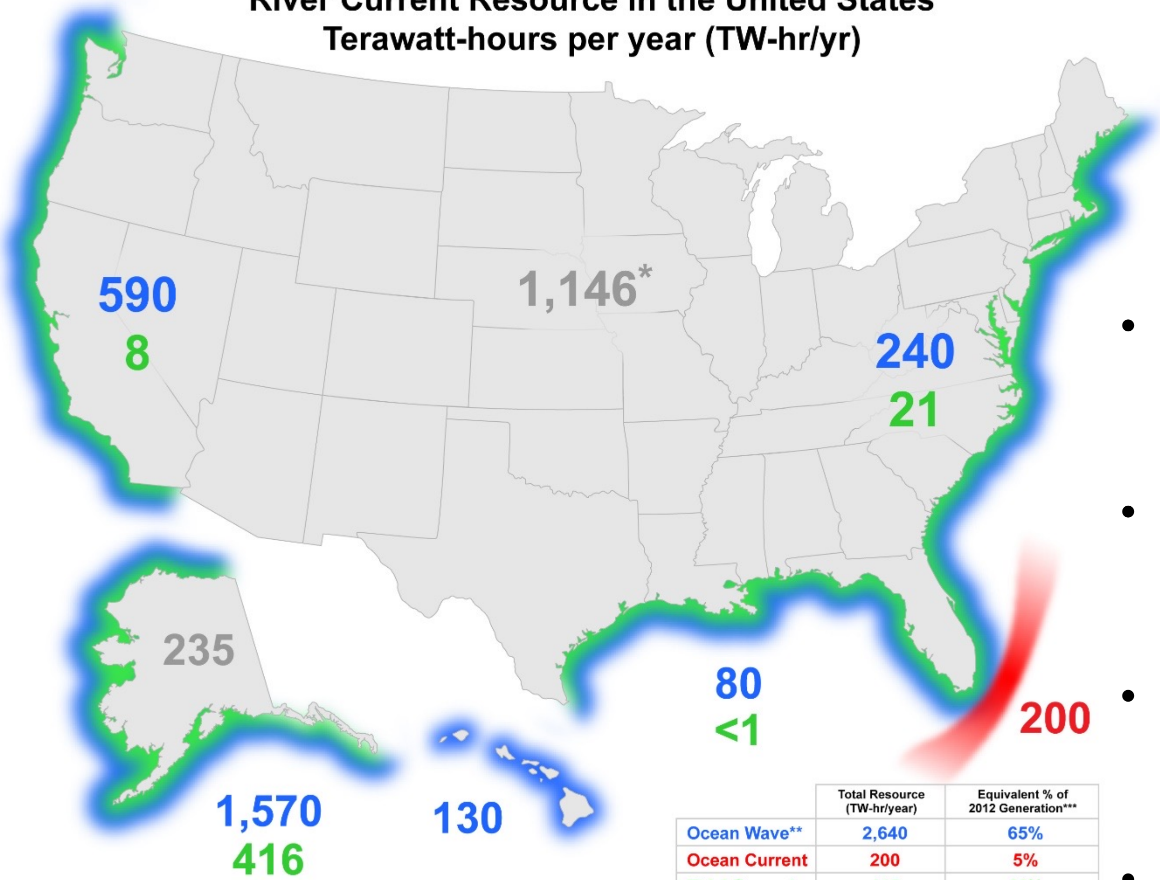
Marine Energy Potential by Resource						
Resource	Theoretical Resource		Technical Resource		Practical Resource	
	TOT US		TOT US		CONUS	
	TWh/yr	%US AEP	TWh/yr	%US AEP[2]	TWh/yr	%US AEP[2]
Wave Energy	1594-2640	39-65%	898-1229	22-30%	378-472	9-12%
Tidal Current Energy	445	11.0%	334-222	5.5-8.2%	15-22	0.4-0.5%
Ocean Current Energy	200	4.9%	45-163	1.1-4.0%	45-163	1.1-4.0%
River Current Energy	1381	34.1%	120	3.0%	100	2.5%
Total:	3620-4666	89-115%	1285-1846	31.6-45.2%	538-757	13-19%

- In short, marine energy technologies can supply about a sixth of the total amount of energy used in the contiguous US

From *Techno-economic Assessment of Marine and Hydrokinetic Technologies, Report to Congress, September 2013*

Understanding the resource

The Ocean Wave, Ocean Current, Tidal Current, and River Current Resource in the United States Terawatt-hours per year (TW-hr/yr)



	Total Resource (TW-hr/year)	Equivalent % of 2012 Generation***
Ocean Wave**	2,640	65%
Ocean Current	200	5%
Tidal Current	445	11%
River Current	1,381	34%

Ocean Wave: P. Jacobson, G. Hagerman, and G. Scott, "Mapping and Assessment of the United States Ocean Wave Energy Resource," Electric Power Research Institute, Report Number 1024637, 2011.
Ocean Current: K. Haas, H. Fritz, S. French, and V. Neary, "Assessment of Energy Production Potential from Ocean Currents Along the United States Coastlines," Georgia Tech Research Corporation, 2013.
Tidal Current: K. Haas, H. Fritz, S. French, B. Smith, and V. Neary, "Assessment of Energy Production Potential from Tidal Streams in the United States," Georgia Tech Research Corporation, 2011.
River Current: T. Ravens, K. Cunningham, and G. Scott, "Assessment and Mapping of the Riverine Hydrokinetic Resource in the Continental United States," Electrical Power Research Institute, Report Number 1026880, 2012.

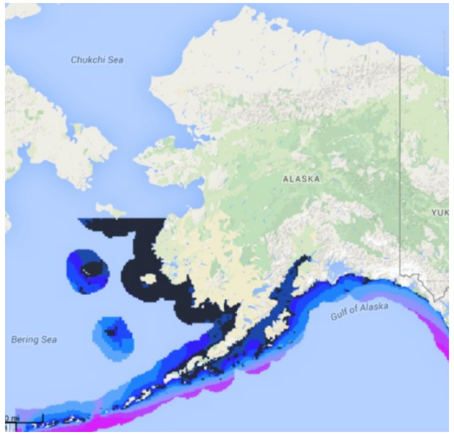
*Resource distributed throughout the river systems in the United States.
**Resource data for the 200-m depth contour.
***The size of the resource with respect to total U.S. electricity generation in 2012, which was 4,054 TW-hr (U.S. Energy Information Administration, "Electric Power Monthly," May 2013).

From *Techno-economic Assessment of Marine and Hydrokinetic Technologies, Report to Congress, September 2013*

- Wave energy is the most abundant marine energy resource and can supply quite a bit of energy to the coast
- In 2010, 123 million people, or 39 % of the American population lived in counties directly on the shoreline. (NOAA)
- Globally, more than 44% of people lives within 150 kilometers of the sea (UN Ocean Atlas)
- The possibilities of using ocean-based marine energy technologies are huge.

Annual wave power density across the US

- The resource is the highest along the West Coast and off Alaska…



NREL marine energy Atlas

Wrap Up & Next Steps

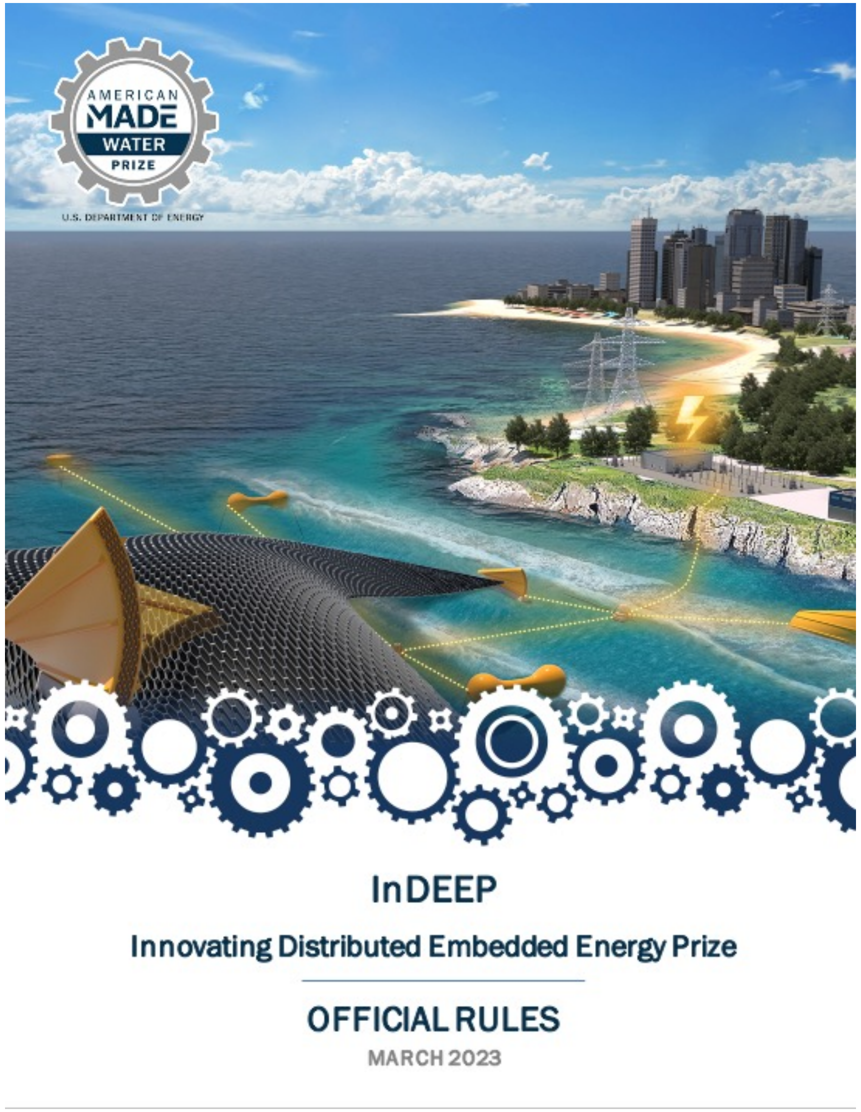
Competitor Support Mechanisms

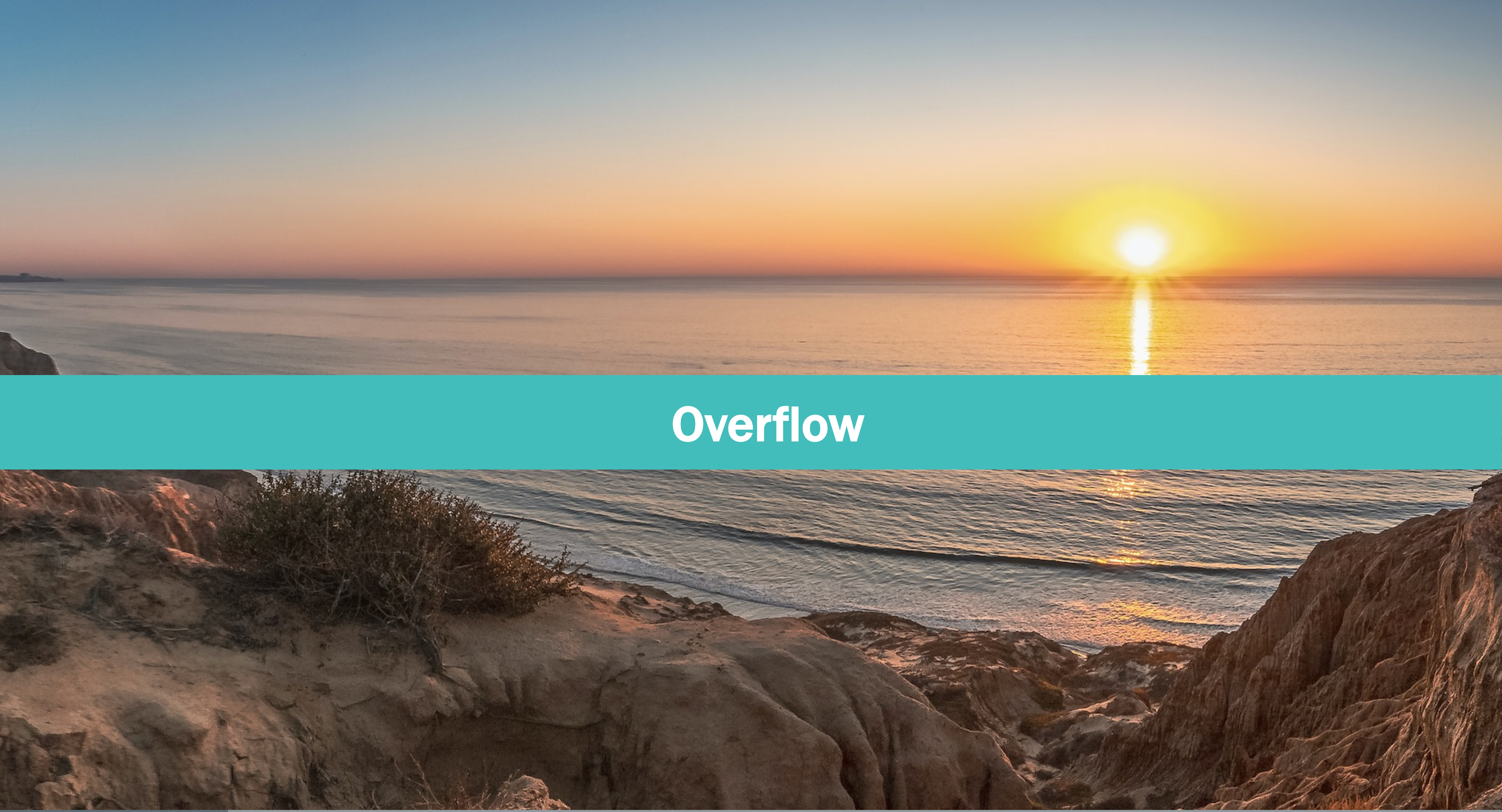
- Save the Dates!
  Upcoming Training Sessions:
  - May 10: Innovation methods
  - July 5: TPL assessment
- Teaming Platform
- Submission Feedback
- Mentorship in Innovation Methods and TPL Assessment
- *Resources linked in Appendix C of the Rules Document*

Read the Rules

For a more in-depth look at the prize overall where these topics will be applied, please read the rules document, available here:

https://americanmadechallenges.org/challenges/indeep/docs/InDEEP-Prize-Rules.pdf





Overflow

Wave Energy Extraction

- ...
  - ...

Technologies

- ...
  - ...

Challenges

- …
    - …

Motivation for InDEEP

- …
  - …

Webinar Questions to be answered

- What is a ocean wave?
- What is energy in ocean waves
- Wave Interaction and extraction of waves
  - Principles: scatter, diffraction , radiation, canceling + others, overtopping, blow whole,
  - Technology concepts
- Technology development history
- Challenges
- Motivation

Purpose of this Webinar