University of Victoria
Institute for Integrated Energy Systems

Cleaning BC: The role of Wave Supplied Power in a Low-Carbon Energy System

Dr. Brad Buckham

Professor, Department Mechanical Eng.

WCWI Director

29 February 2019

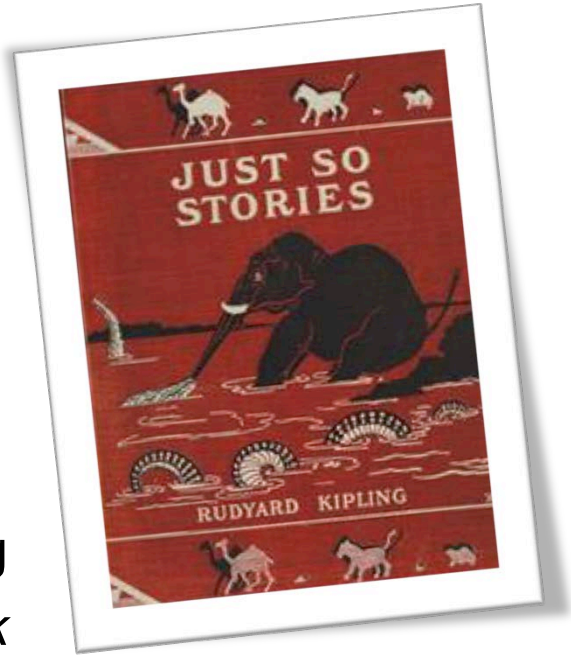
WCWI WEST COAST WAVE INITIATIVE

Presentation Overview

Following the maxim of the “5 Ws and the 1 H”

I keep six honest serving-men
(They taught me all I knew);
*Their names are **What** and **Why** and **When** and*
***How** and **Where** and **Who**.*

Rudyard Kipling
How the Elephant Got His Trunk



Presentation Overview

Following the maxim of the “5 Ws and the 1 H”

Who am I?

What is wave energy?

What is a Wave Energy Converter (WEC)?

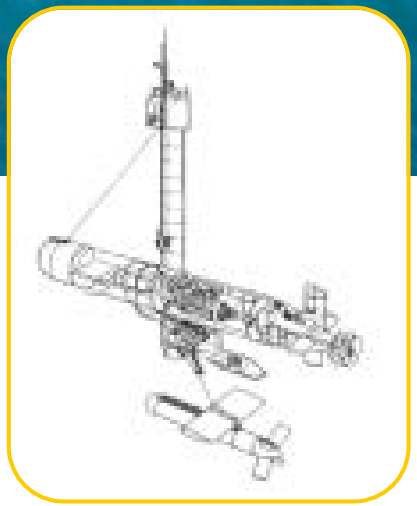
How is WEC technology development being supported?

Where will WECs be deployed in BC – and to what benefit?

How are researchers making WECs perform better?

Who will lead WEC development in BC / Canada?

Who am I?



< 2003: cabled/towed ocean vehicles

- cable dynamics, vehicle dynamics.

2003 – 2012: Remotely operated vehicle manipulators (ROVMs)

- Articulated body dynamics, control, navigation.

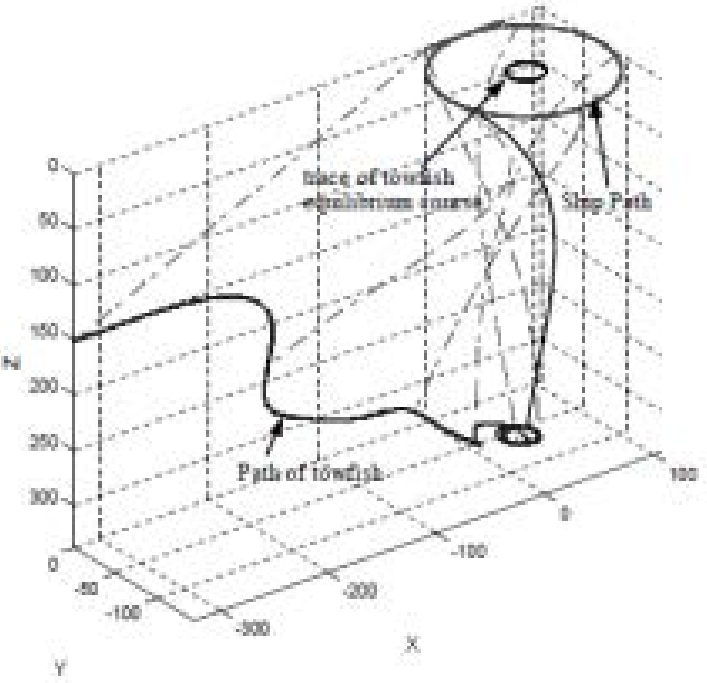
2006 – 2010: SyncWave Energy Systems

- Point absorber WEC dynamics, moorings

2012 – present: West Coast Wave Initiative

- Wave resource assessment, WEC performance, community integration.

2017 – present: Co-director of PRIMED



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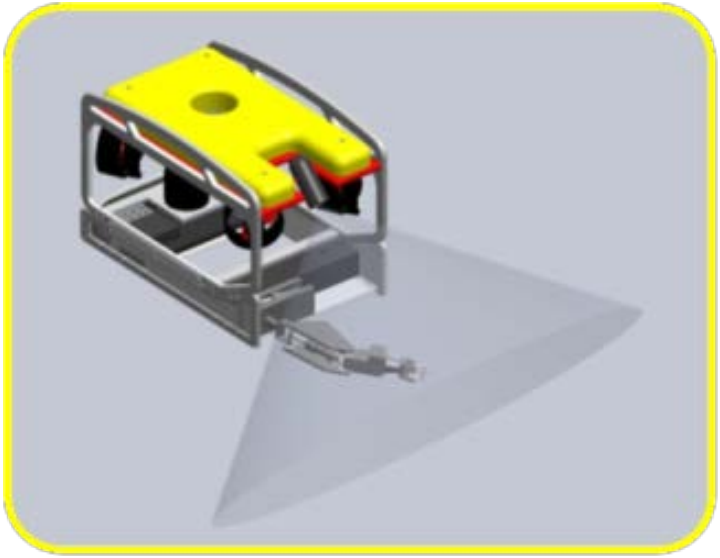

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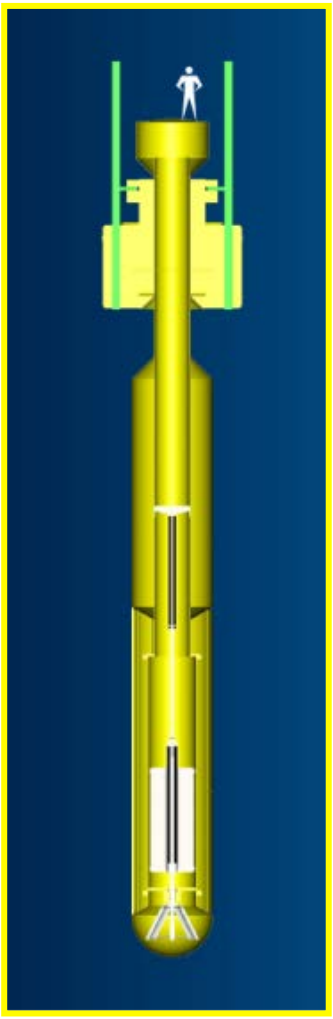

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PRIMED

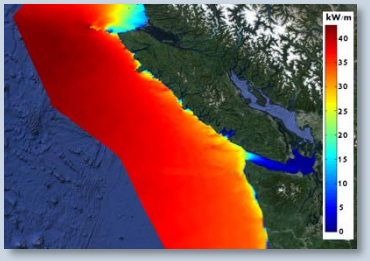
The West Coast Wave Initiative (WCWI)

WCWI

Comprehensive Wave-to-Wire Modeling Study

Resource Assessment

- Nearshore SWAN wave models
- Fully directional models
- 5 Measurement Buoys
- WEC site investigations



GROSS RESOURCE

Technology Modeling

- Time domain simulations
- Complete spatial motion
- Fully coupled PTO, mooring and device models
- WEC control

NET RESOURCE

Grid Integration

- KW: Hesquiaht Sound
- MW: Vancouver Island
- GW: BC-Alberta

USABLE RESOURCE

Goal: Use field measurements and advanced numerical tools to define the benefits to be realized in BC through wave energy technology.

PRIMED: Pacific Regional Institute for Marine Energy Discovery

Commercialization Activities (Client Driven)

PRIMED

WIND WAVE TIDAL COMMUNITIES

Tools, Methods & HQP

Academic R&D (Curiosity Driven)

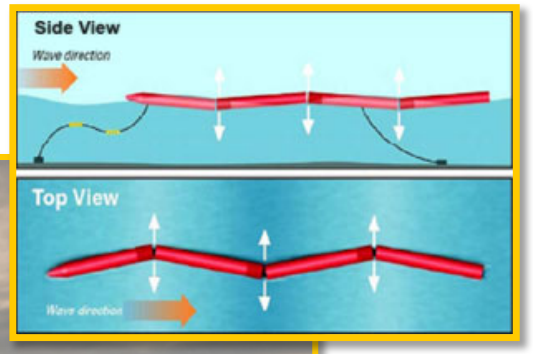
WCWI

+

SSDL Sustainable Systems Design Laboratory

Before we begin: WEC technology is NOT a new idea…

Attenuator (Pelamis)



"Anything one [person] can imagine other [people] can make real"

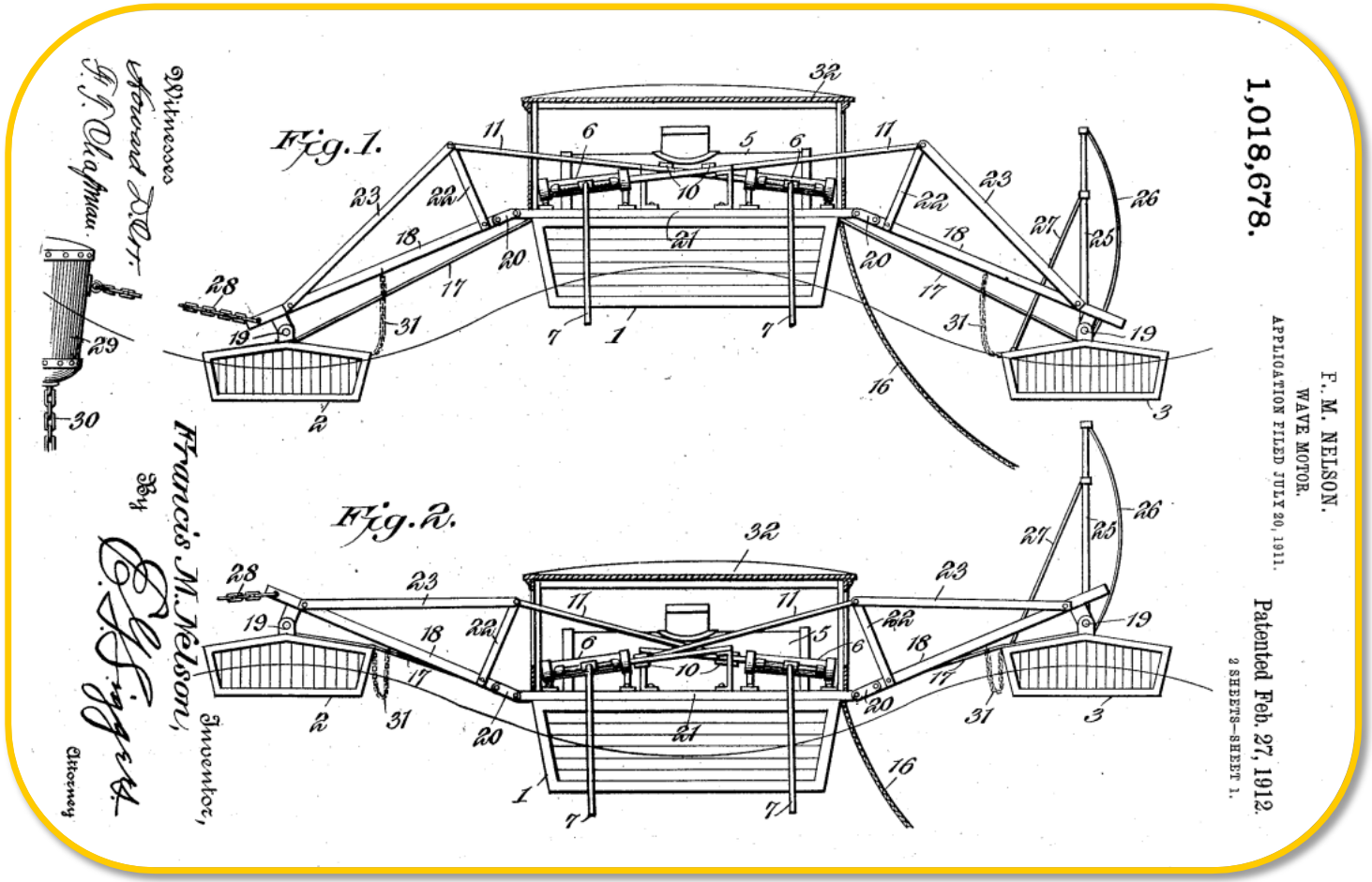
Jules Verne (1828-1905)

"Pelamis Wave Power Ltd is the manufacturer of a unique system to generate renewable electricity from ocean waves."

http://www.pelamiswave.com/

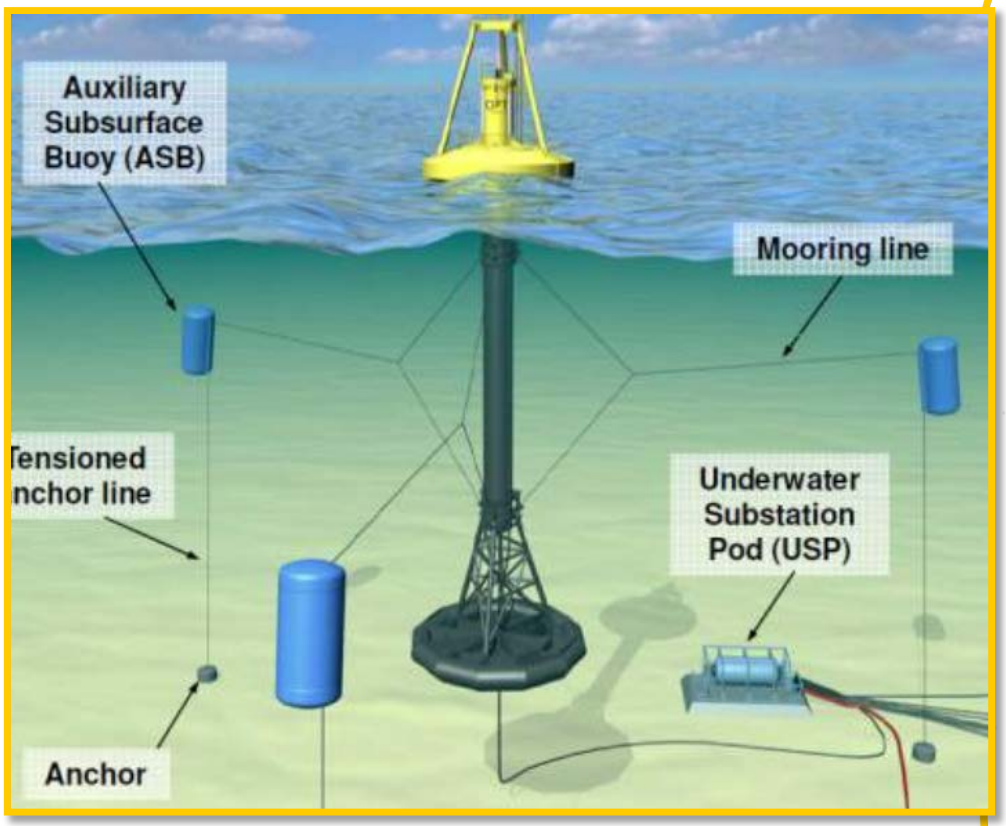
WEC technology is NOT a new idea…

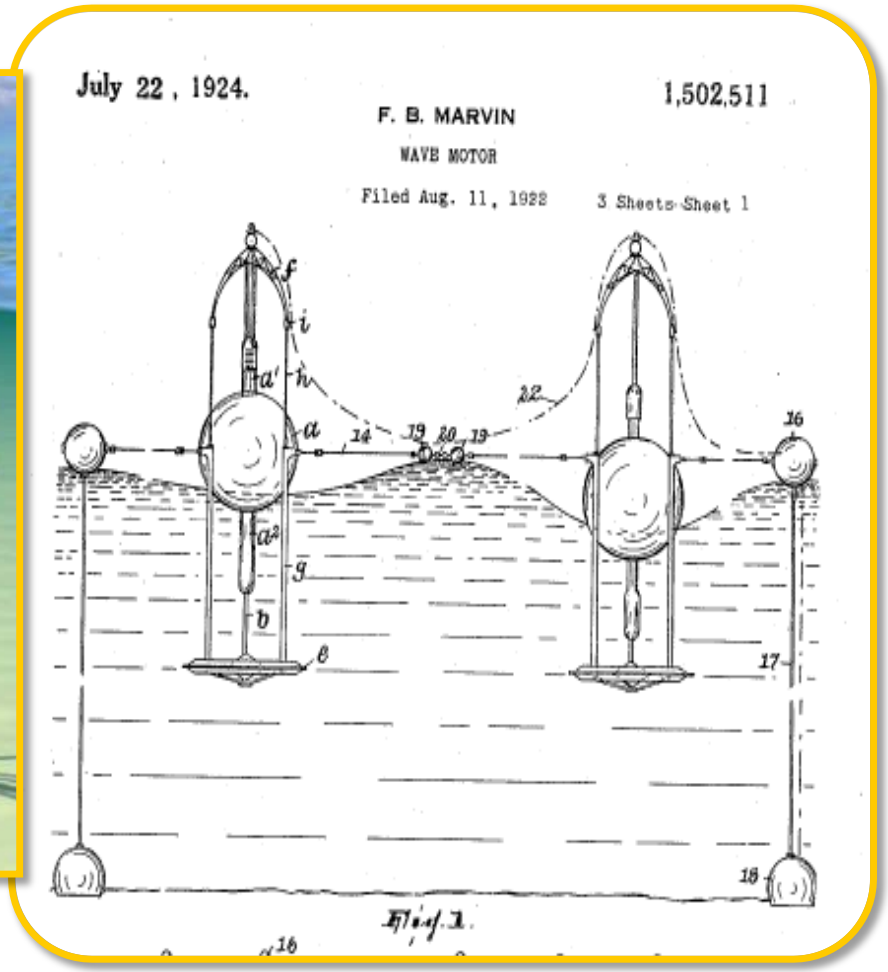
Attenuator (Pelamis?)



WEC technology is NOT a new idea…

Point Absorbers (OPT & WaveBob)




July 22, 1924. 1,502,511

F. B. MARVIN

WAVE MOTOR

Filed Aug. 11, 1922 3 Sheets-Sheet 1

What is an ocean wave?

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Basic Wave Descriptors

Water waves are formed by oscillations of water particles beneath the sea surface. The descriptors that characterize a wave's shape and behavior:

- Wave Crest: Highest vertical position of a wave
- Wave Trough: Lowest position of a wave
- Wave Height: Vertical distance from wave trough to crest (m)
- Wave Period: Time from one crest to the next crest (sec)
- Wavelength: Distance from one crest to the next crest (m)

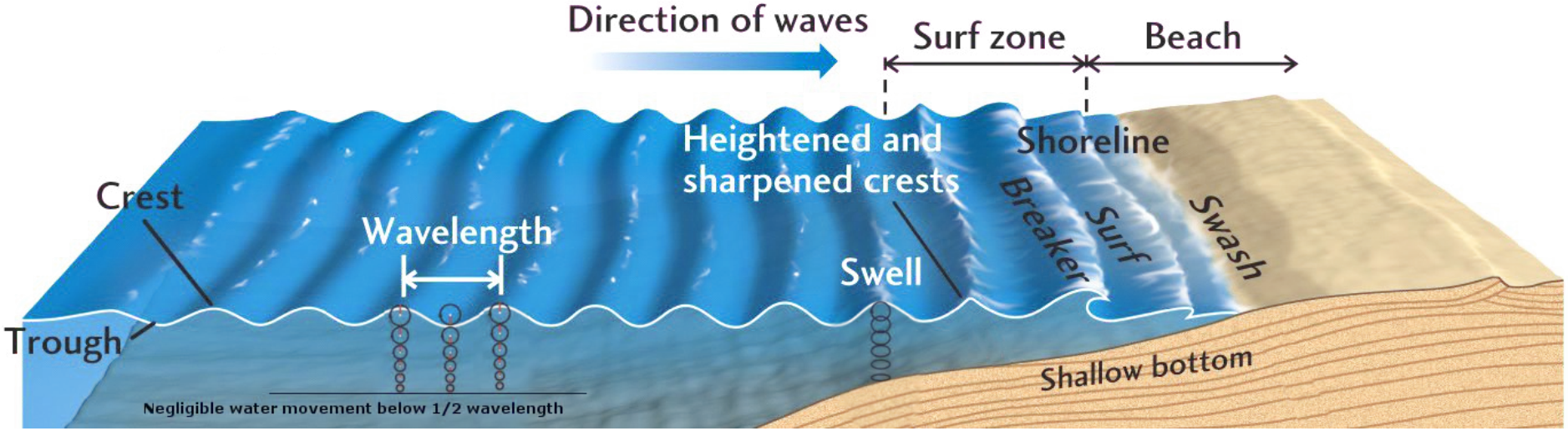
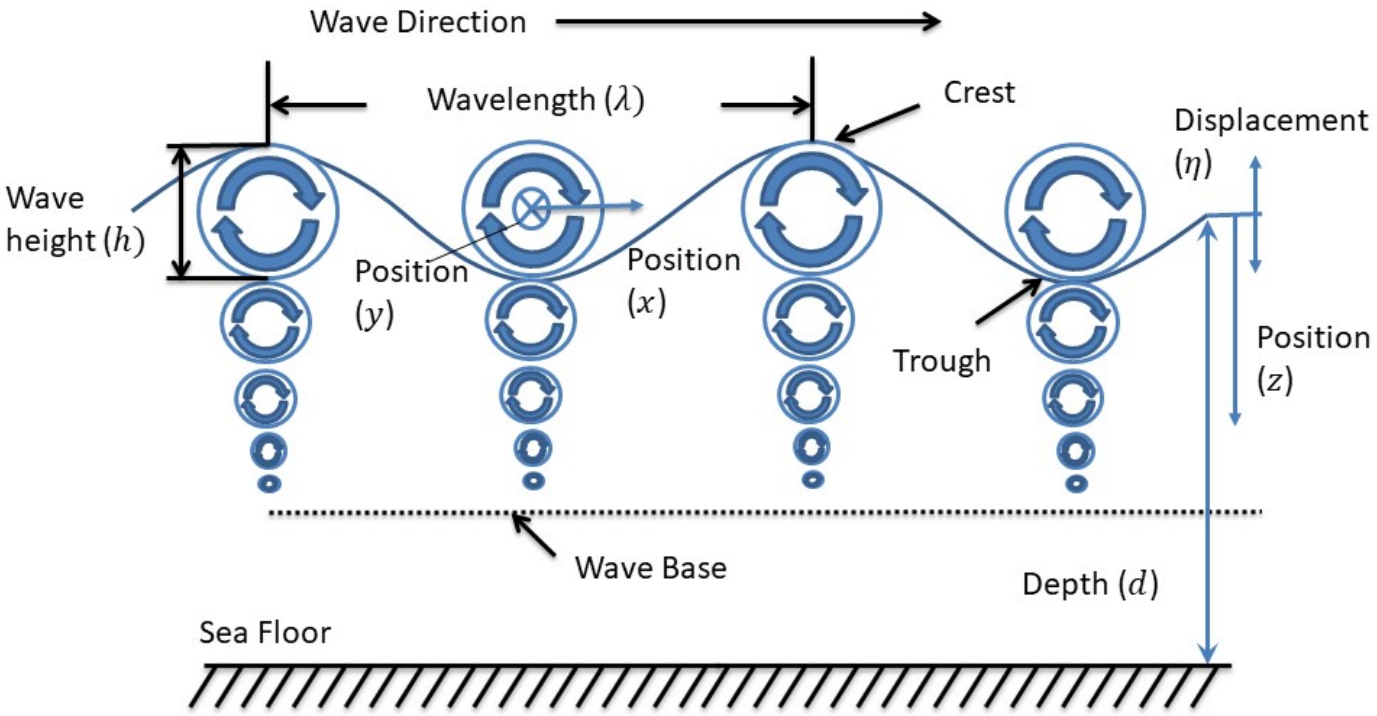


Image courtesy of: Garrison, Tom. *Oceanography: an invitation to marine science*. Cengage Learning, 2006.

Ocean waves only appear to transport mass



A water wave is formed by a out of phase elliptical orbits of water particles.

The oscillations exist well below the sea surface (down to L/2).

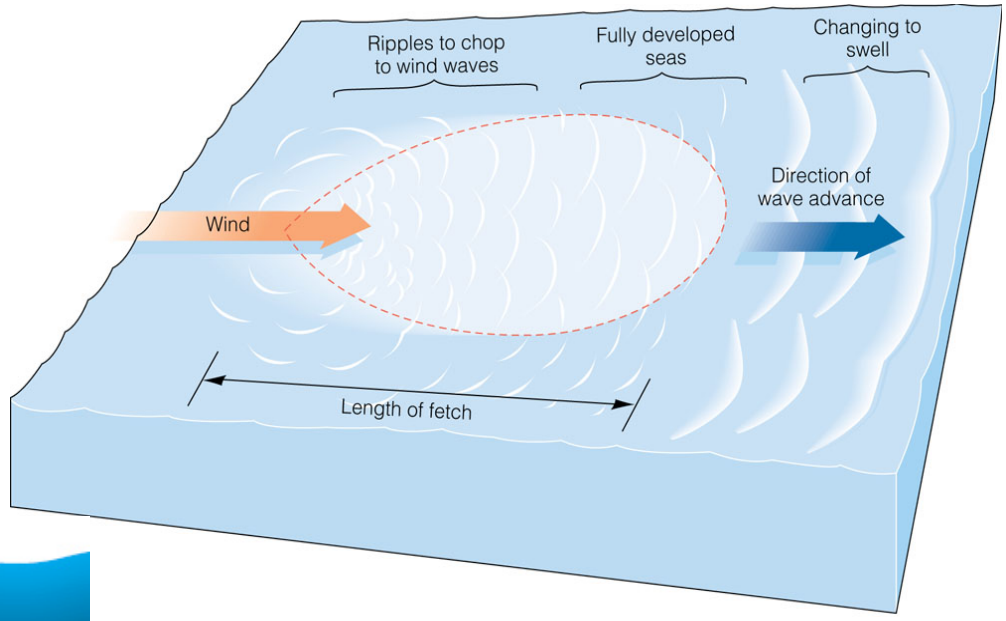
As particles are always accelerating – there is a oscillating pressure field.

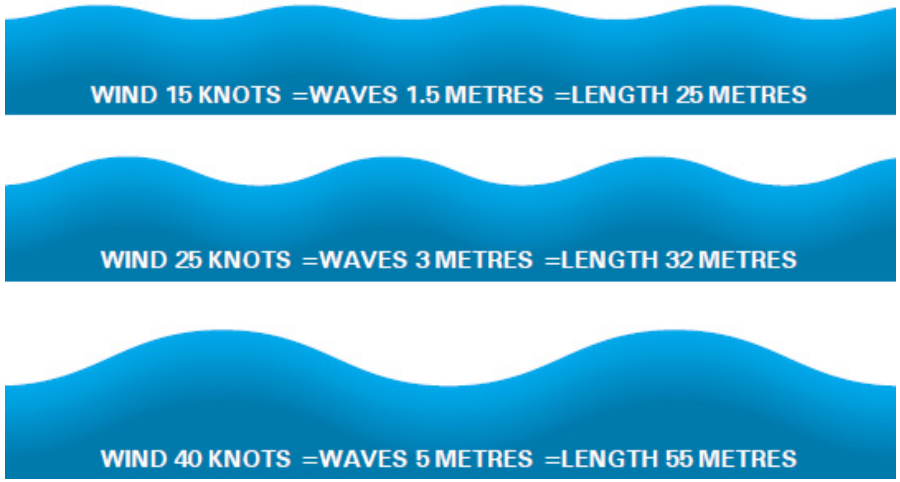
Ocean waves to ocean swell

Wave Creation:

- Wind Speed
- Fetch (distance)
- Time

Ripples > Chop
Chop > Wind Waves
Wind Waves > **Swell**





Example:

Fetch: 50 NM (90 km)
Time: 6 Hours
Wind Speed…

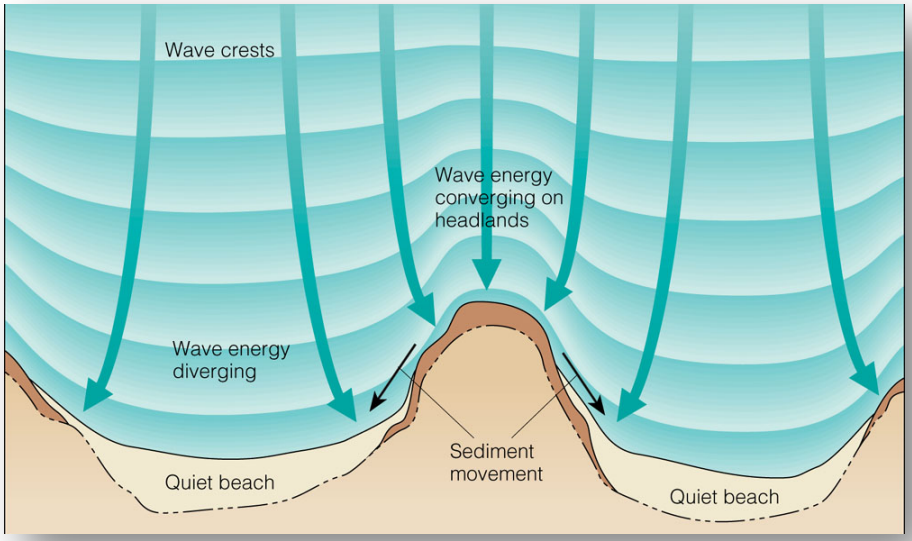
Deep & Shallow Water Wave Behaviour

To a stationary observer, wave crests propagate at a speed C across the sea surface.

The propagation speed is related to the period, wavelength and the water depth – as waves propagate into shallow water they slow down.

Waves "feel" the bottom at a depth of approximately half of the wavelength. Since the seabed has an irregular profile, lower speeds develop in localized shallower regions.

When different speeds result across a crestline, the wave crests tend to "bend" towards shallower regions - this is known as *refraction*.



Wave motions in the near shore zone

d = water depth	Deep Water d > (L/2)	Shallow Water d < (L/20)
Wave speed (C)	$C \sim 1.56\,T$	$C \sim 3.13\sqrt{d}$
In deep water 10 sec wave period → C = 15.6 m/s		
Wavelength (L)	$L \sim 1.56\,T^2$	$L \sim 3.13\sqrt{d}\,T$
In deep water 10 sec wave period → L = 156 m		

Image courtesy of: Garrison, Tom. *Oceanography: an invitation to marine science*. Cengage Learning, 2006.

Irregular waves & the Wave Spectra

Swell from storm # 1

Swell from storm # 2

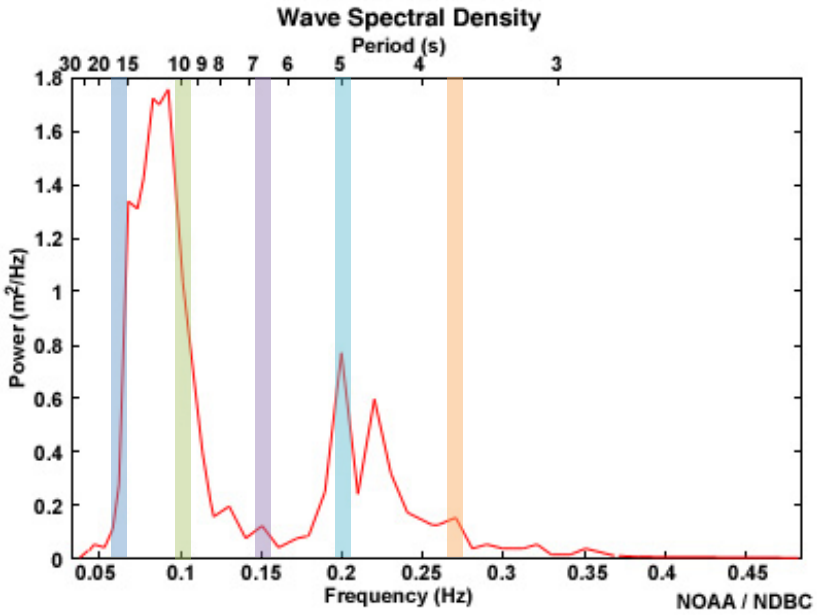
Swell from storm # 3

Swell from storm # 4

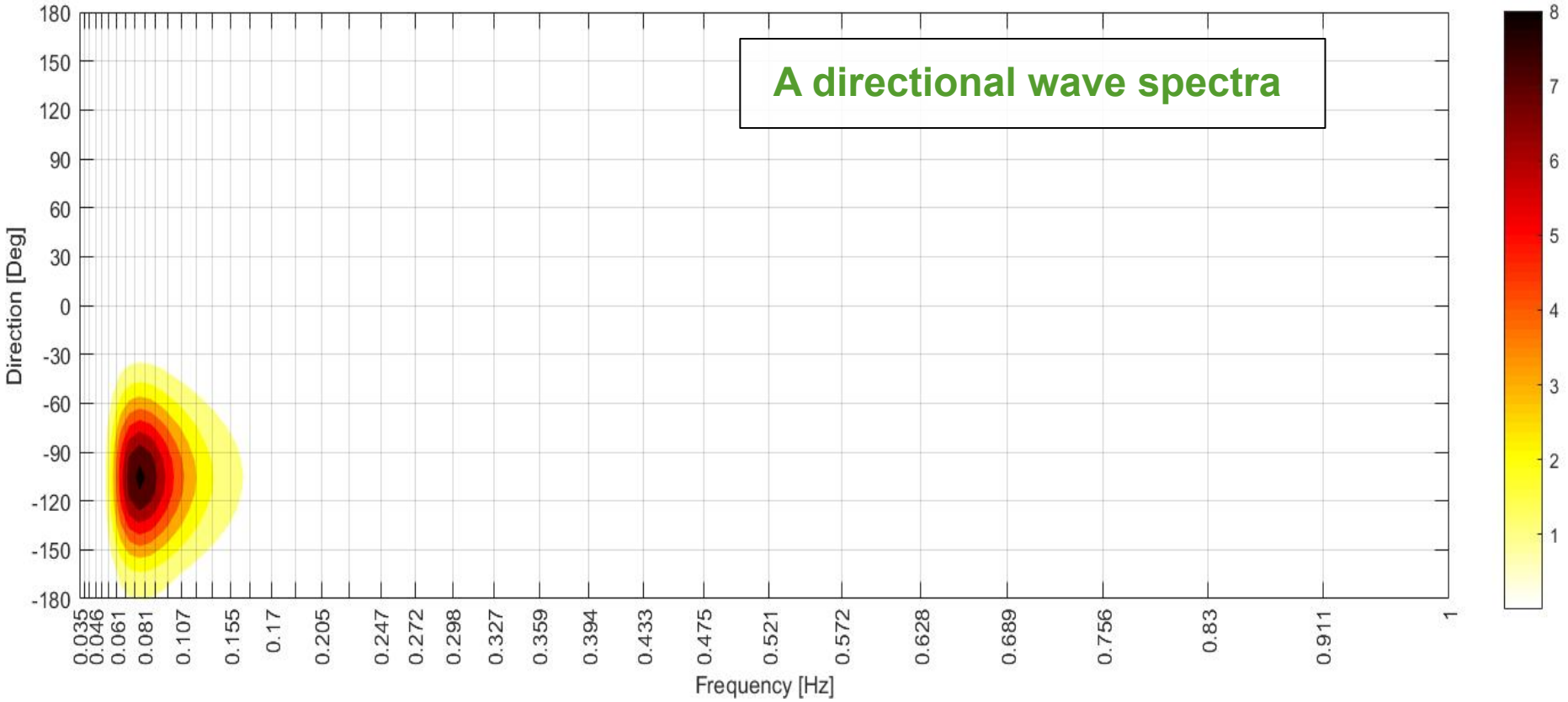
Swell from storm # 5

Final sea surface

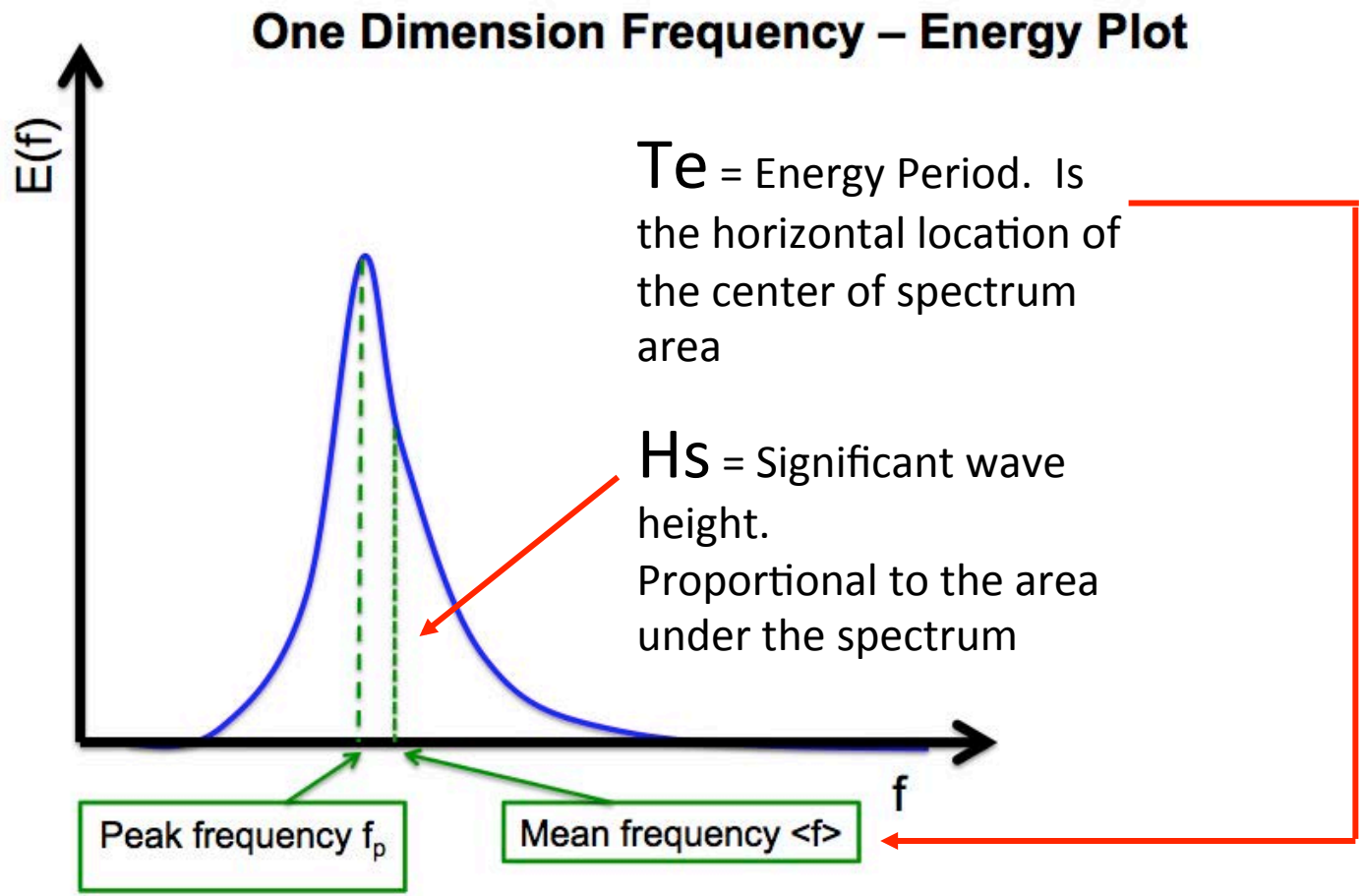
A Wave Spectrum



Directional wave spectra



Wave statistics – *average* wave height and period

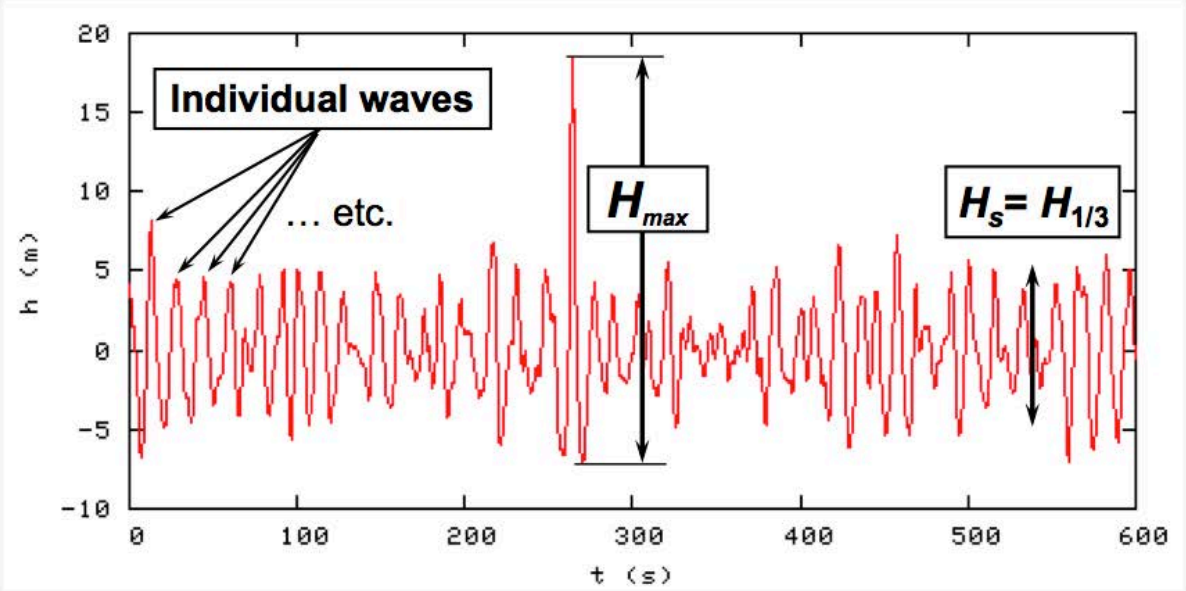


Te = Energy Period. Is the horizontal location of the center of spectrum area

Hs = Significant wave height.
Proportional to the area under the spectrum

Irregular waves – wave events

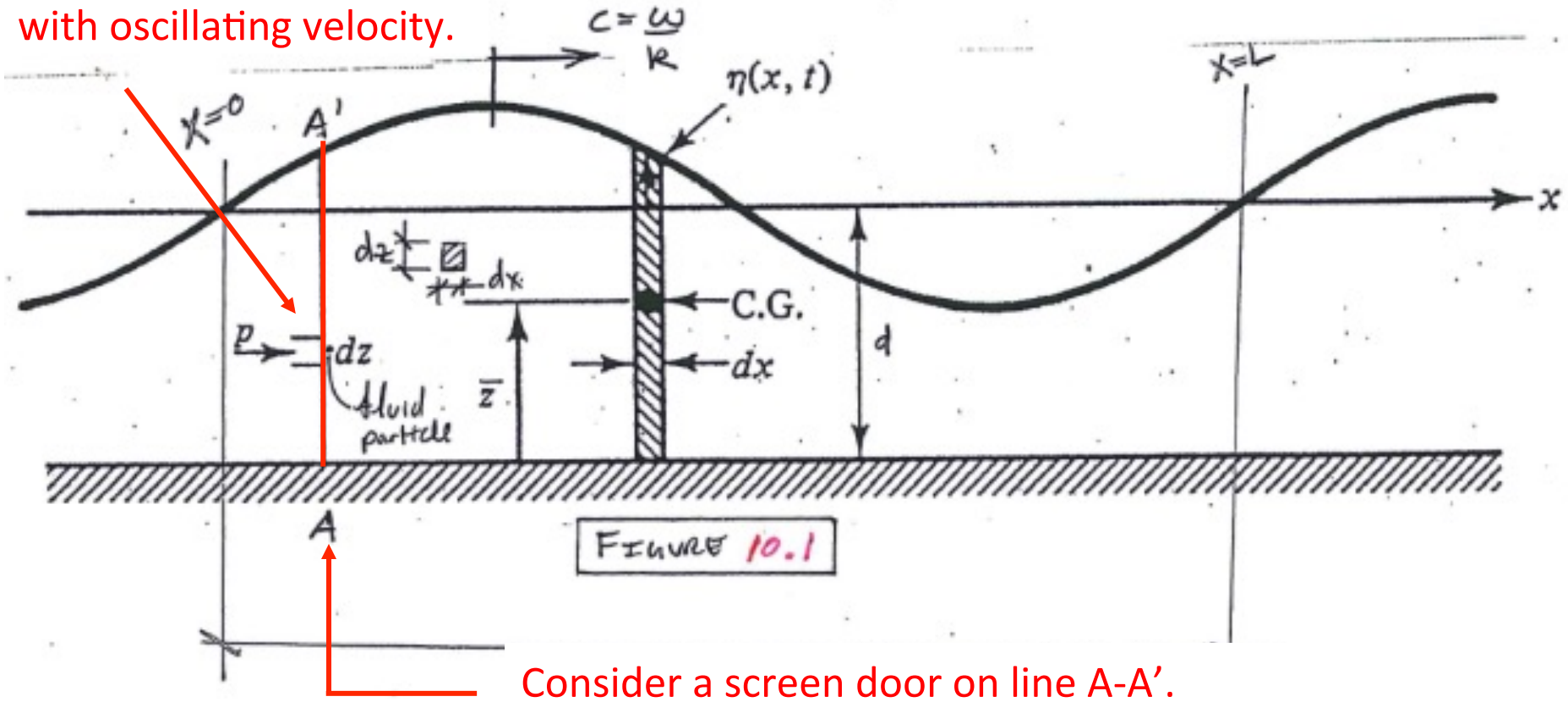
Individual Waves,
Significant Wave Height, H_s,
Maximum Individual Wave Height, H_{max}, and
Freak Wave



If $H_{max} > 2.2\ H_s$ ➔ freak wave event

What is wave energy?

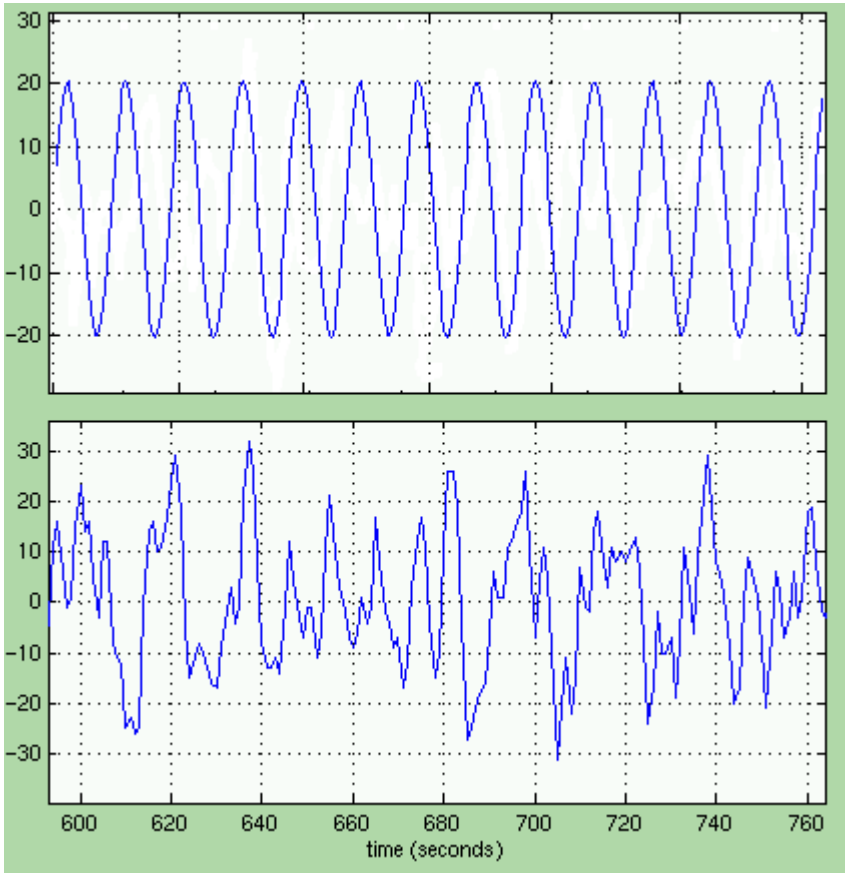
Pressure creates force on a water particle moving with oscillating velocity.



Consider a screen door on line A-A'.

There is a net '+' rate of work done on the fluid across that gate over each wave period.

Wave energy: *regular* and *irregular* waves



$$J = \frac{1}{32\pi}\rho g^2 H^2 T \quad \frac{Watts}{meter}$$

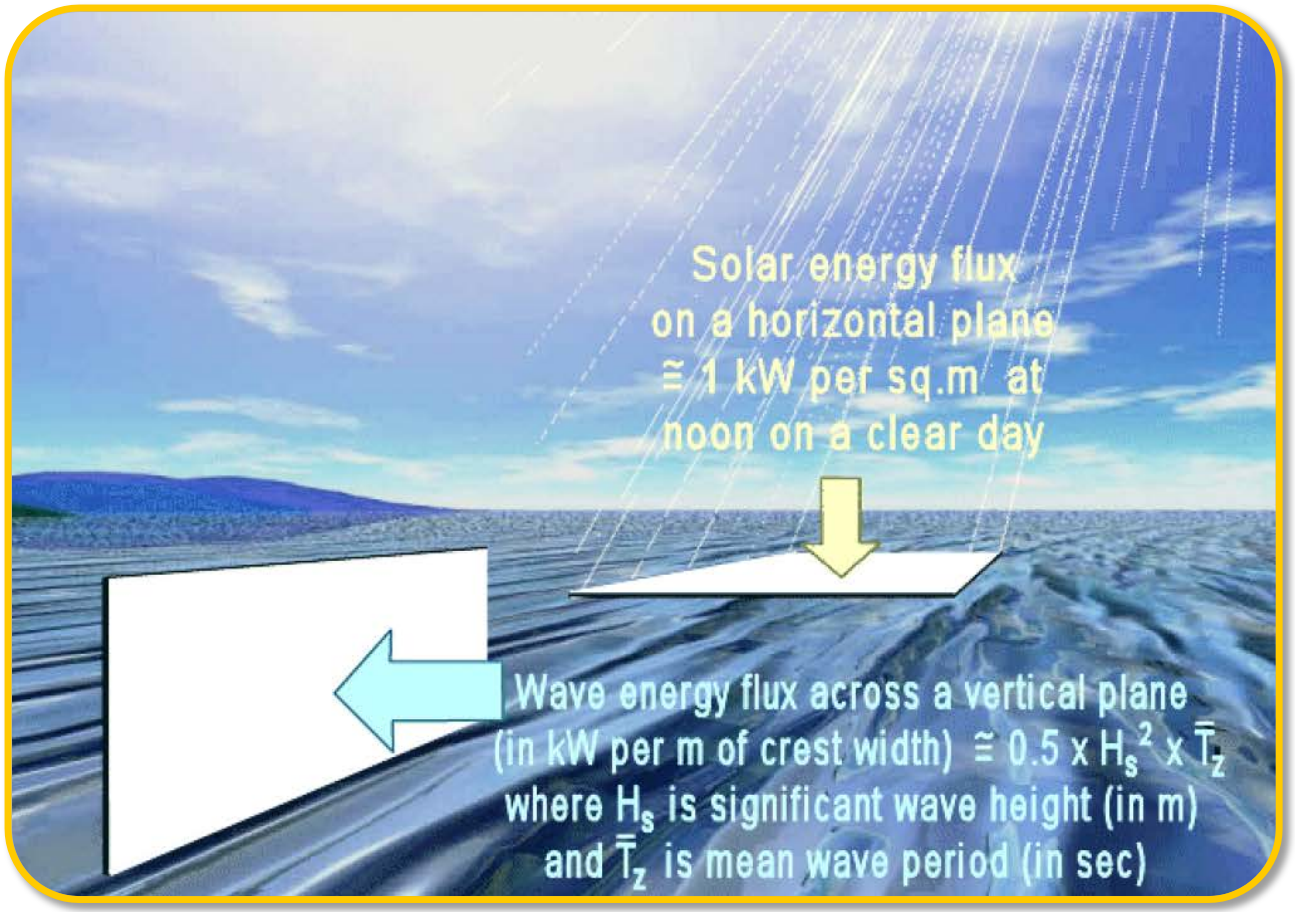
$$J \approx \frac{1}{64\pi}\rho g^2 H_s{}^2 T_e \quad \frac{Watts}{meter}$$

Hs & Te relates to the "average" amplitude & period of the waves

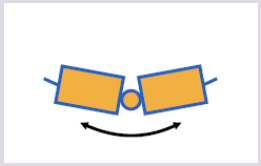
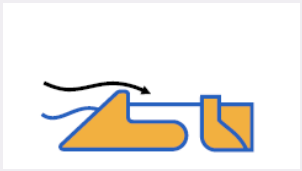
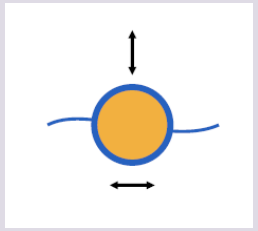
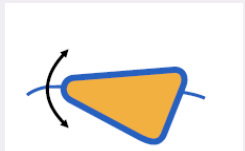
Wave Energy vs. Solar Energy

Wave Energy

- Energy continuous oscillates between potential and kinetic states in a ocean wave.
- “Wave energy” refers to the average value of the total energy across one wavelength.
- “Wave energy transport” is a measure of the rate of energy delivery through an imaginary 1m wide “door”



What is a Wave Energy Converter (WEC)?

	Definition	Example
Attenuators (Pelamis, Biopower)	• Aligned parallel to the direction of wave propagation.	 
Overtopping Devices (Wave Dragon, Limpet, Manchester Bobber, OceanLinx, ORECON, SEEWEC)	• Top of breaking wave used to drive low-head turbine.	 
Point Absorbers (OPT, WaveBob, AOE Canada)	• Omni-directional absorption – horizontal or vertical component of wave motion.	 
Terminators (AWS, OREC)	• Aligned perpendicular to the direction of wave propagation.	 

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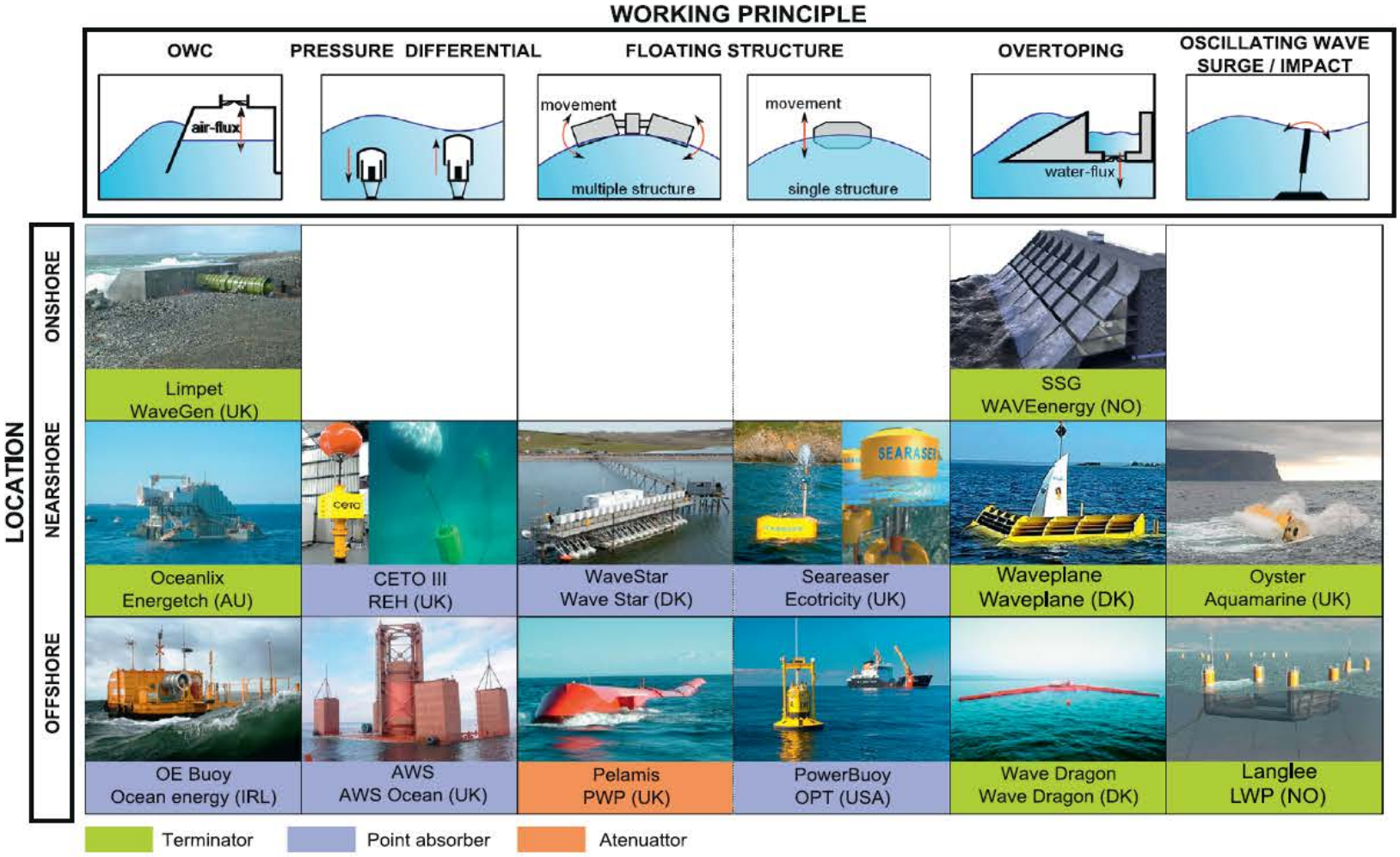
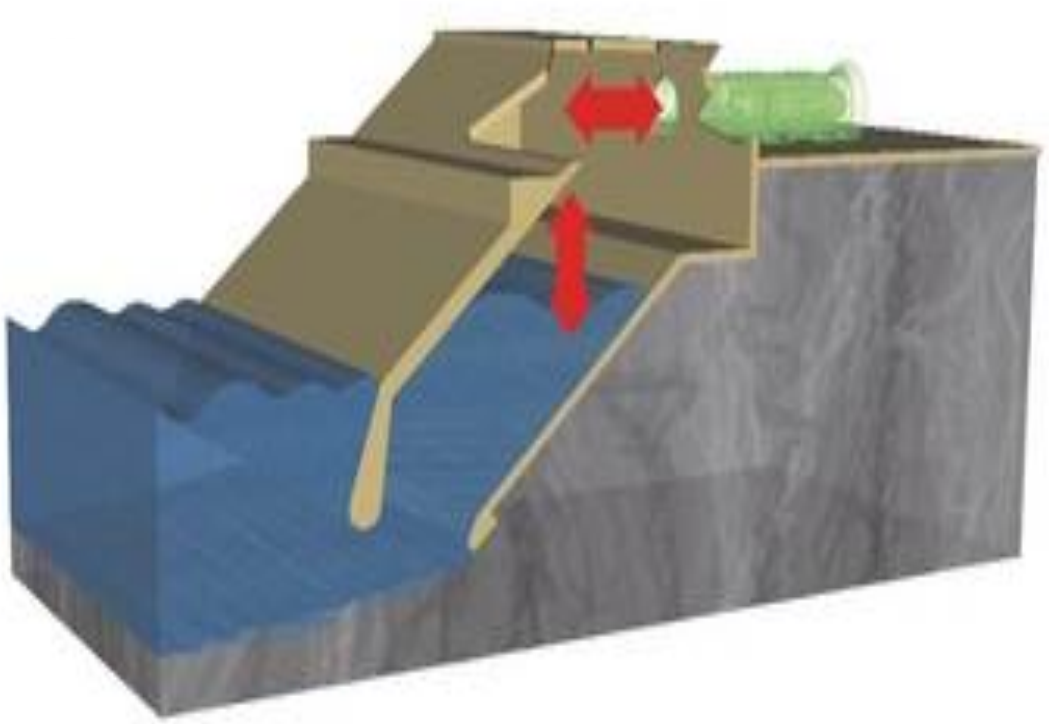


Wave Energy Converter (WEC) technologies

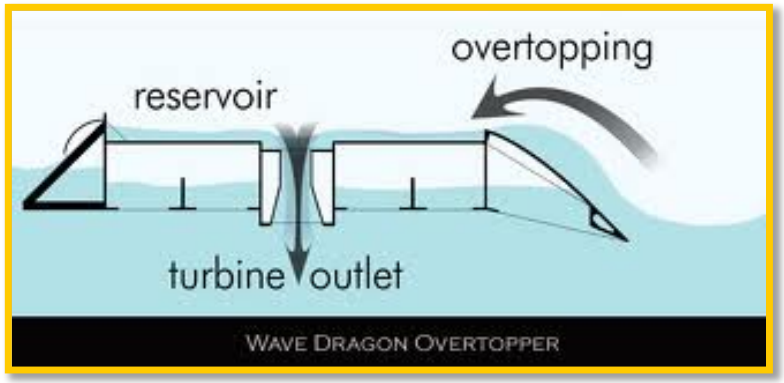
Oscillating Water Column (OWC)



Wave Energy Converter (WEC) technologies

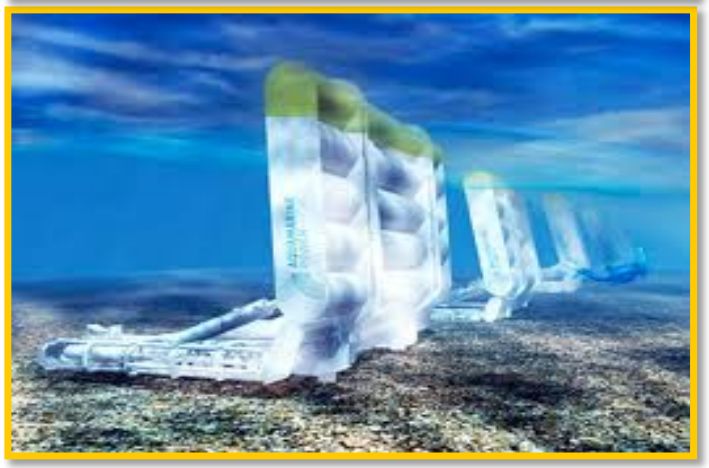
Wave Overtopping

Wave Dragon in operation



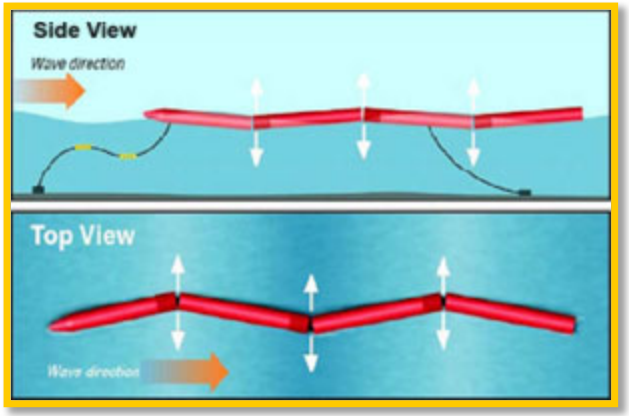
Wave Energy Converter (WEC) technologies

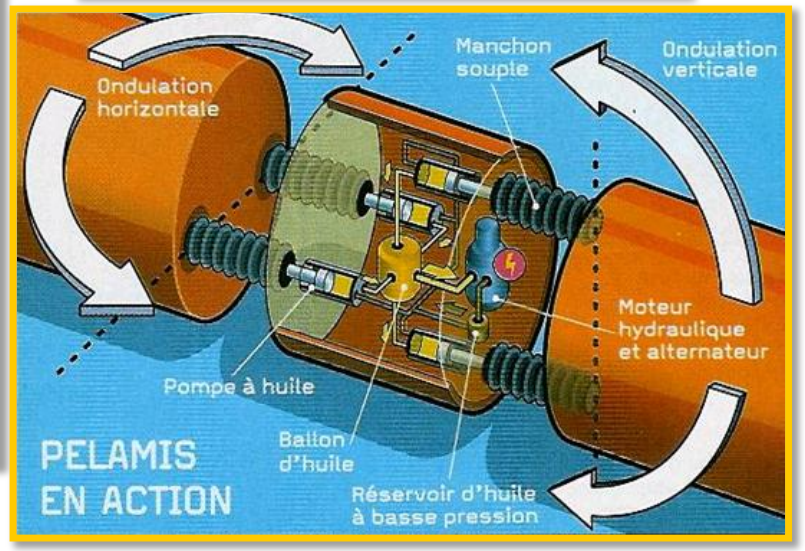
Oscillating Flap



Wave Energy Converter (WEC) technologies

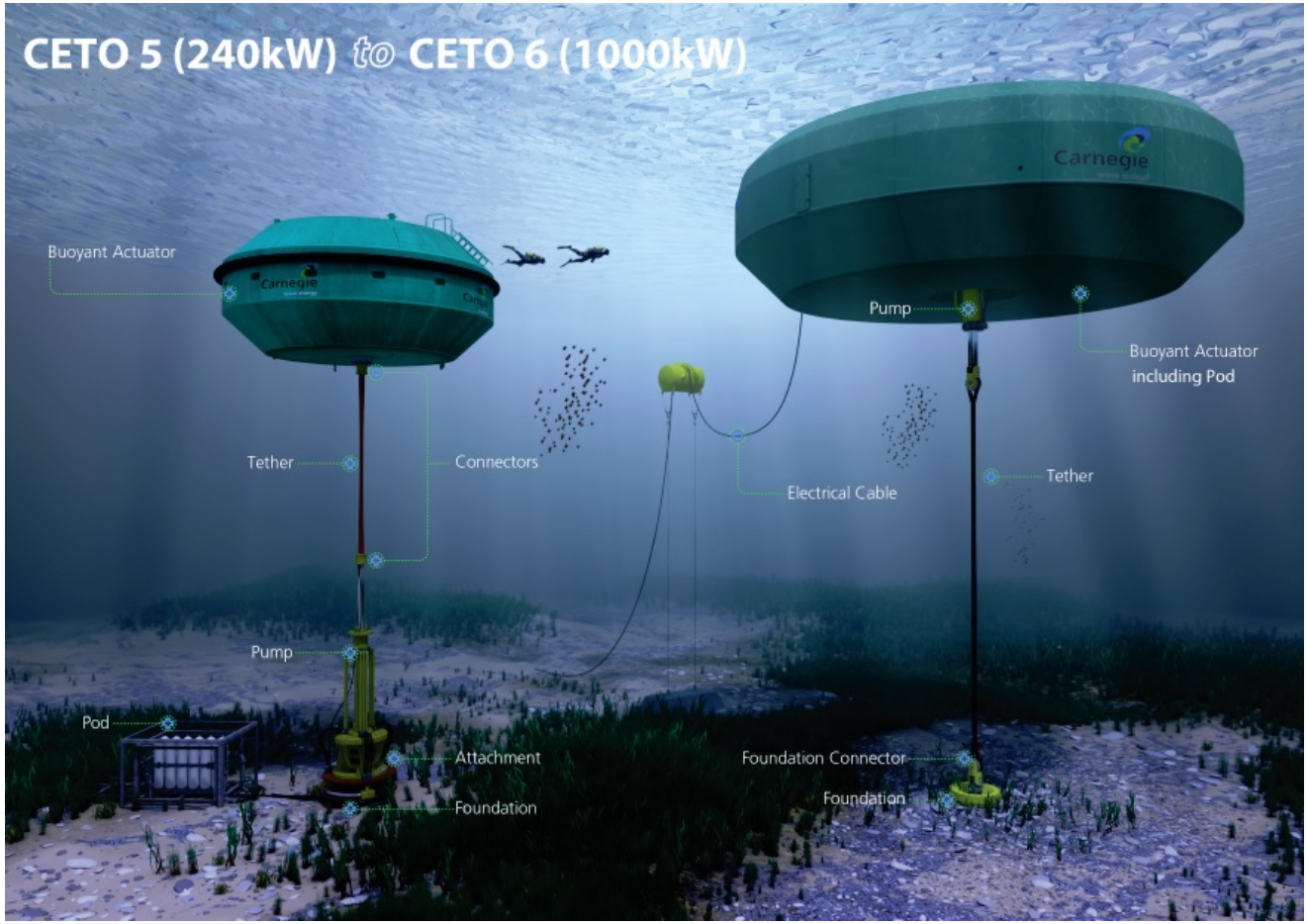
Attenuator (Pelamis)

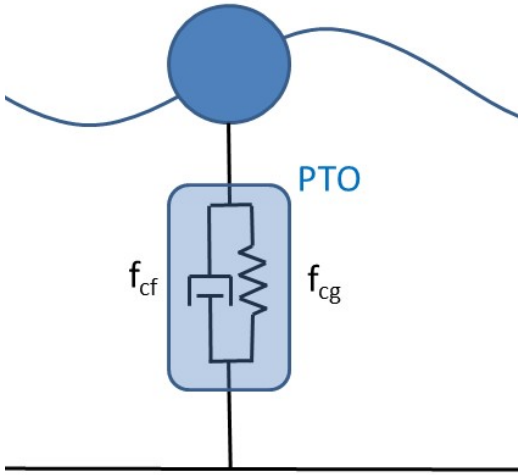




Wave Energy Converter (WEC) technologies

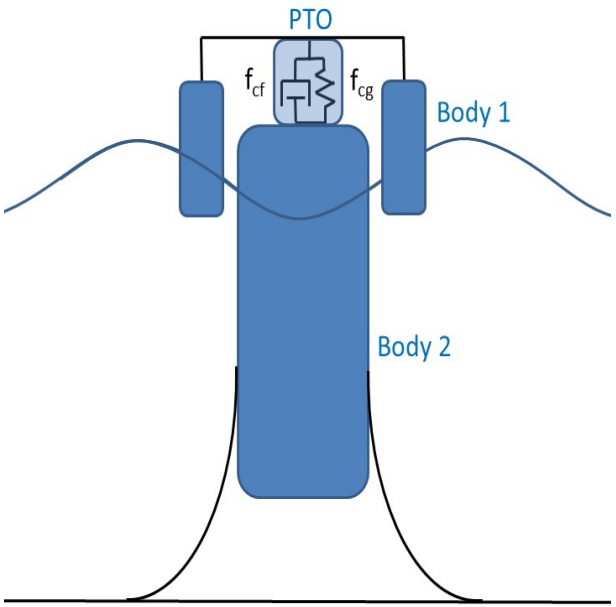
Point Absorber (CETO 5 & 6 – Single Body Point Absorber, SBPA)





Wave Energy Converter (WEC) technologies

Point Absorber (Ocean Power Tech. – Self Reacting Point Absorber, SRPA)



Who supports WEC development

WEC technology developers (purple) & dedicated infrastructure (red) (2016)

Who supports WEC development

European Programs

MARINET

FP7 funded initiative to share facilities across Europe

Standardize test methods

Coordinate test programs

Outreach and education (short courses)

FP7: EU 7th Framework Programme for Research

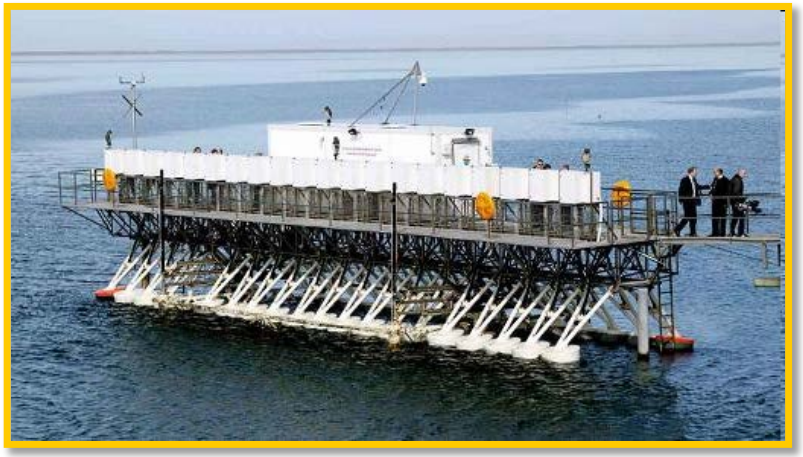
Who supports WEC development

European Programs

MARINET

WaveStar (Denmark) partnered extensively with Aalborg University.

- Wave structure interactions
- PTO control
- Tank tests – physical modeling of power take-offs



Who supports WEC development

European Programs

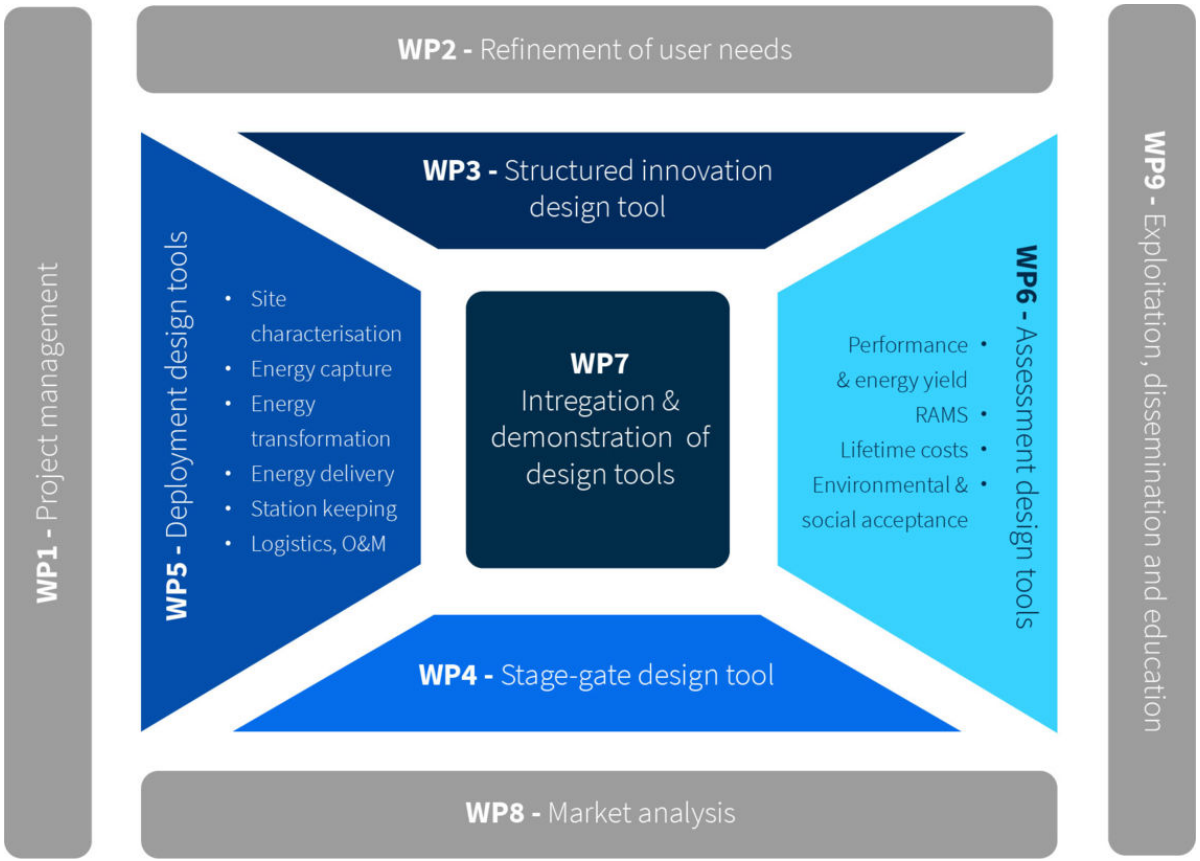
DTOcean

European Union's Horizon 2020 Fund

Develop computational tools for WEC design and assessment.

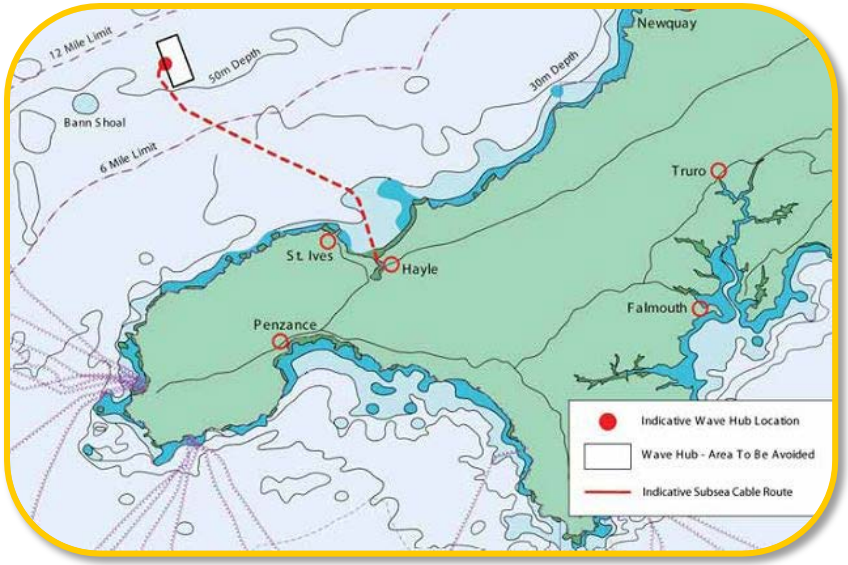
€ 8M program run between 2018-2021.

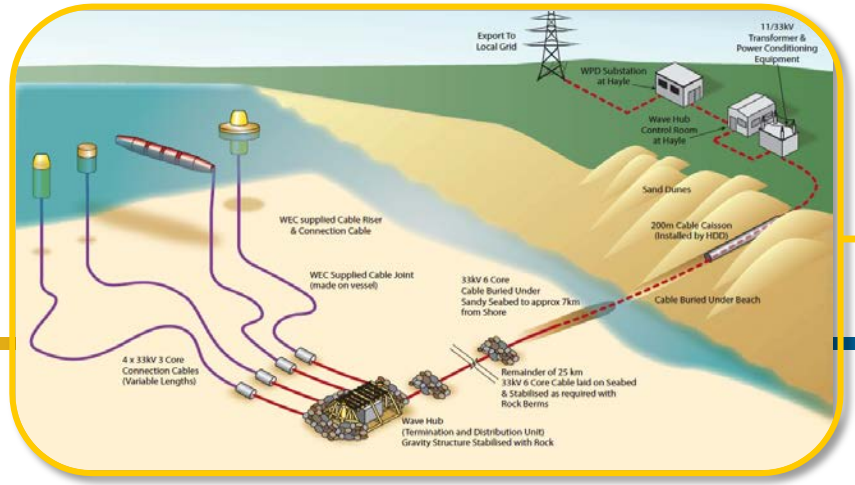
20 partners (academia, NGO, industry).

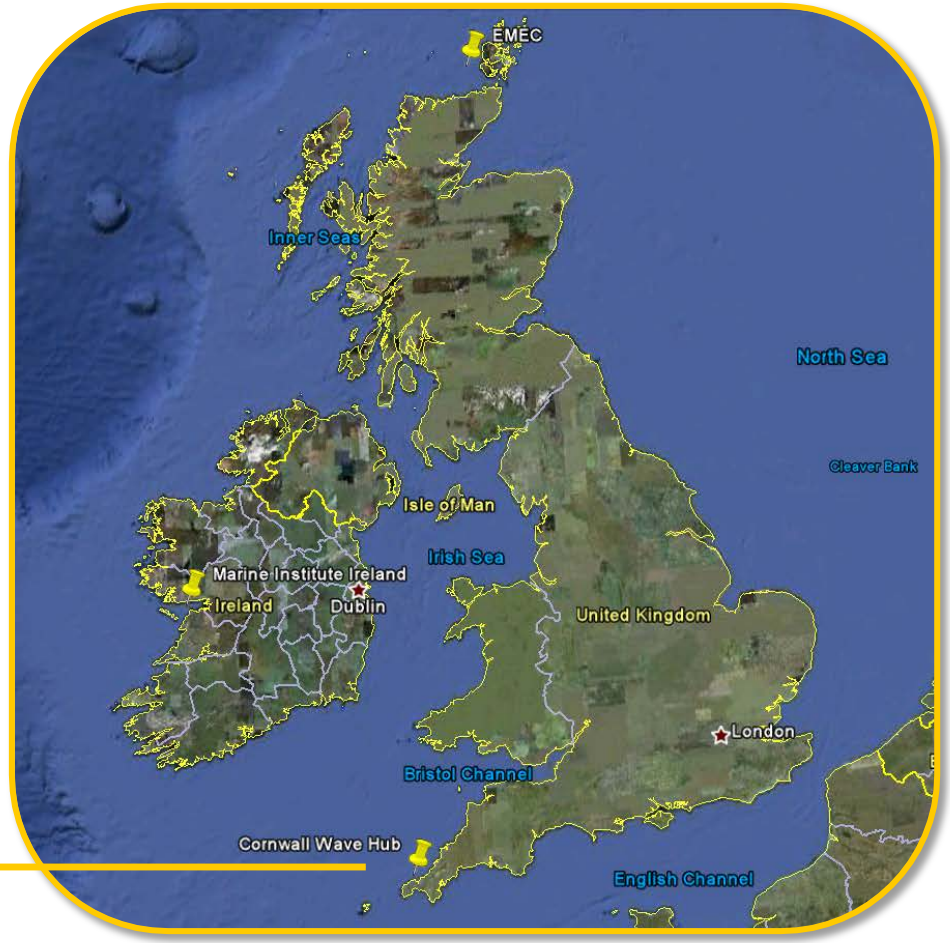


International WEC Test Sites

Cornwall Wave Hub







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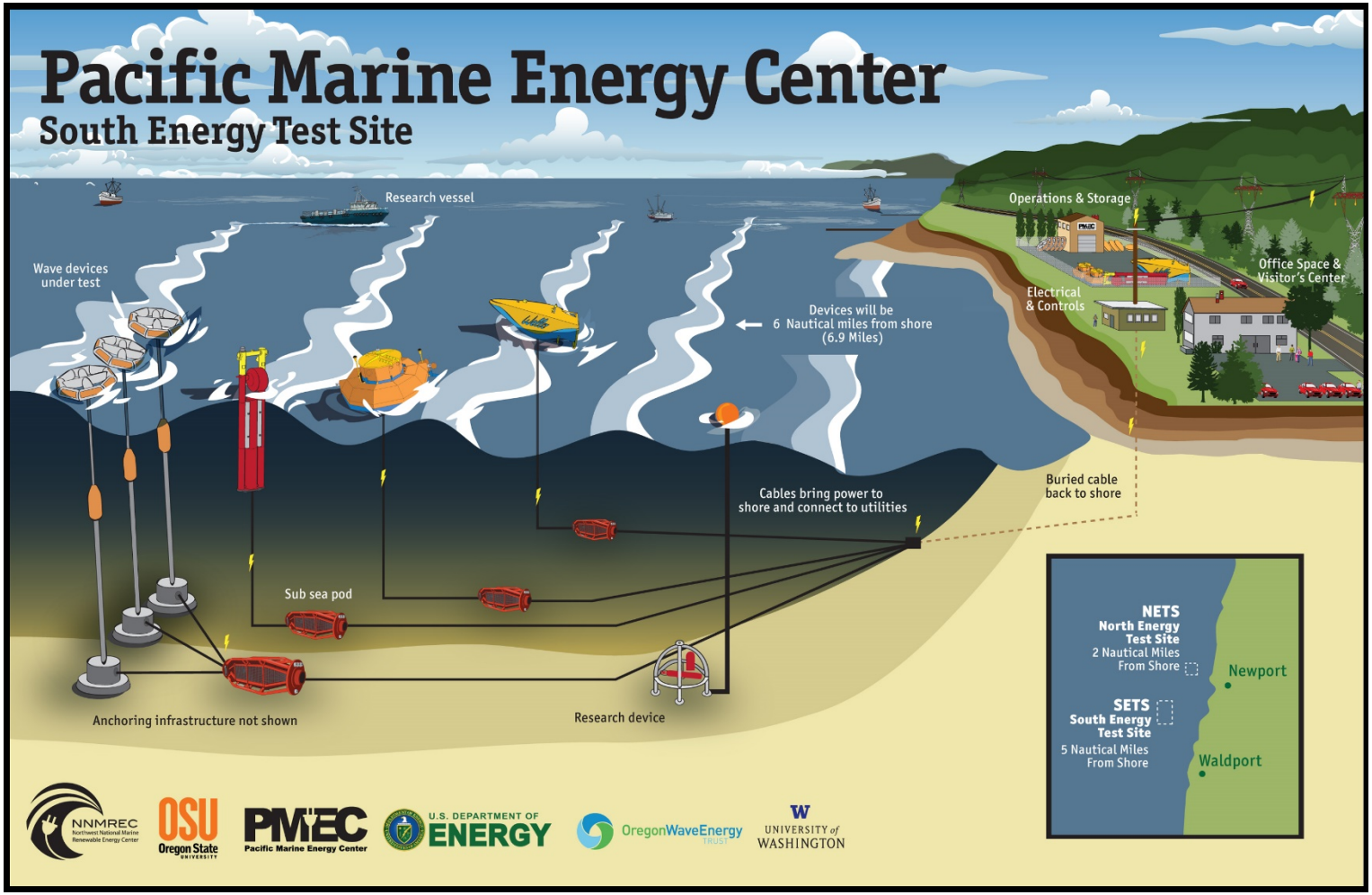
International WEC Test Sites

Wave Energy Test Site (WETS) at Kaneohe Bay, HA

US DOE, PMEC & PACWave



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US DOE, PMEC & PacWave

Marine Energy at OSU

- Early 2000s: Initial research in wave energy
- Mid 2000s: IP licensed by Columbia Power; OSU-CPwr team develop wave energy converter
- 2008: NNMREC consortium established at OSU and University of Washington through DoE grant; OSU and CPwr test wave energy converter in Newport, Oregon
- 2012: DOE requests NNMREC to accelerate development of grid-connected, multi-berth, open-water test site, PMEC-SETS
- 2014: University of Alaska Fairbanks joins NNMREC
- 2017: NNMREC awarded $35M to develop PMEC-SETS
- 2017: NNMREC rebranded to PMEC, PMEC-SETS rebranded to PacWave

External Funding (since 2009)**:** ~$108M to PMEC R&D and affiliated testing; ~$66M to OSU

US DOE, PMEC & PACWave

PMEC and PacWave activities are supported by the US DOE and the Oregon Wave Energy Trust (OWET).

US DOE – Water Power Program

- Wave energy benefits from being inside the WPP (grouped with hydroelectricity)
- Water Power program – invested $21M in US WEC developers between 2008-2014.
- Wave Energy Prize – $2.25M competition to encourage new WEC designs.

OWET

- Funded through state lotteries.
- Provided $6M between 2008-2013 to academics and industry projects.

Canada – funding WEC development

Pre-2012 Canadian WEC funding used a “technology push” model.

Syncwave Energy Systems (2008-2010) is a good case study (I think the only case study)

Sustainable Development Technology Canada – $2.7M

BC Innovative Clean Energy Fund - $2.0M

NRCan Clean Energy Fund – $4.6M

None of these funds were ever accessed as the matching private equity could never be raised.

Investors were faced with too much uncertainty in the target market, what COE could be achieved, what COE needed to be achieved…

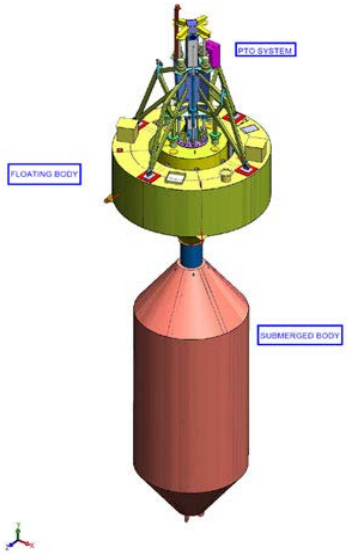
Since 2012, Canadian gov investment in WEC R&D has been limited to the WCWI and PRIMED.

Why is the WCWI necessary?

WEC demonstration deployments are necessary, but not sufficient

WaveBob (Ireland):

- Founded in 2001.
- Sea trials in 2006 & 2007.
- Selected for deployment on the Cornwall Wave Hub.
- "Innovation Company of the Year" – Engineers Ireland, 2006.
- Lockheed Martin Agreement, 2009.
- $2.4M US Department of Energy Grant, 2010.



WaveBob Shuts Down After Failing to Raise Funds, Find Partner
(Bloomberg.com, 3 April 2013)

"Some of the big players in ocean energy are in fact withdrawing from the sector entirely… Finding a strategic partner and a long-term investor has been impossible and we were almost there a couple of times but they haven't materialized."

Why is the WCWI necessary?

Detailed WEC integration studies are a necessary complement to WEC demonstrations.

A WEC demonstration is limited to demonstrating present day know-how.

By looking into the future, integration studies allow for scenario based analyses in which:

- "Know-how" evolves (WEC control).
- Priorities change ($ value of GHG reductions).
- Sensitivity of levelized cost of energy (LCOE) to these changes can be determined (62 ¢/kWh, 50 ¢/kWh, 15 ¢/kWh, …).

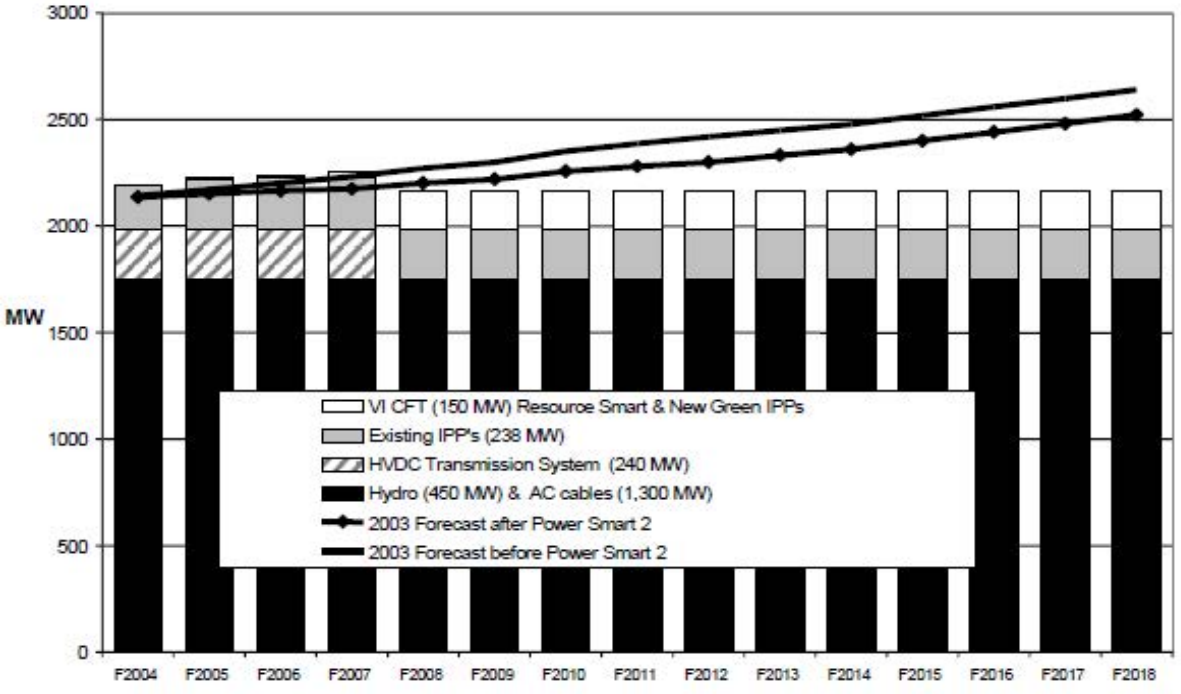
Why is the WCWI necessary?

Australia's 'OceanLynx', formerly 'Energetech' (March 2014)

WECs in BC – we almost bought an Ocean Lynx unit…

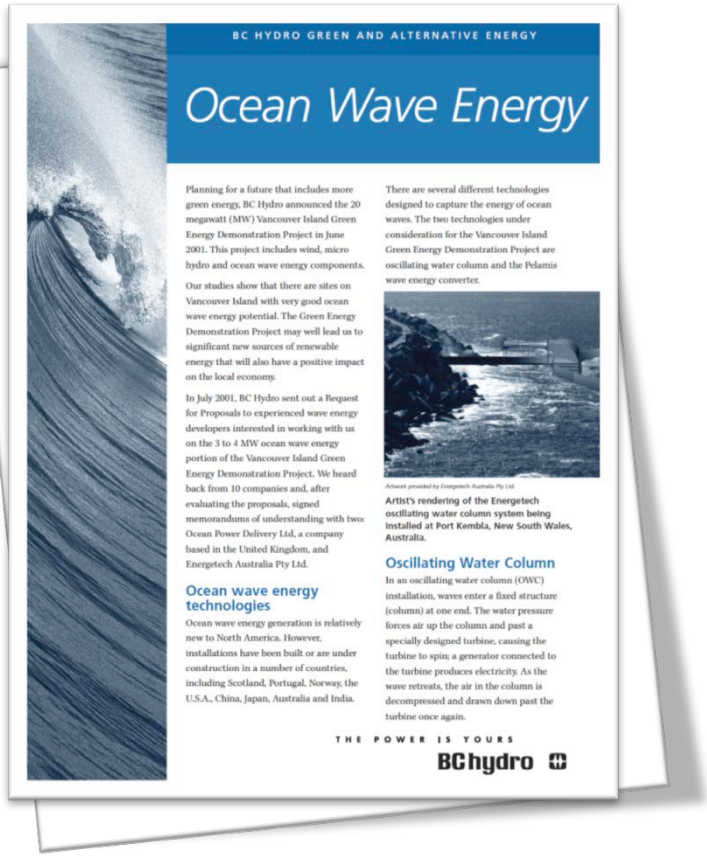
- **2000 IEP:** *The trend in deterioration of the HVDC terminal station equipment confirms that both HVDC Pole 1 and Pole 2 are expected to retire in stages by the year 2007….New supply for Vancouver Island will be required in 2007.*

Figure 6.3. Vancouver Island Dependable Capacity Demand-Supply Balance (MW)



*From the 2004 BC Hydro IEP

WECs in BC – we almost bought an Ocean Lynx unit…



BC HYDRO GREEN AND ALTERNATIVE ENERGY

Ocean Wave Energy

Planning for a future that includes more green energy, BC Hydro announced the 20 megawatt (MW) Vancouver Island Green Energy Demonstration Project in June 2001. This project includes wind, micro hydro and ocean wave energy components.

Our studies show that there are sites on Vancouver Island with very good ocean wave energy potential. The Green Energy Demonstration Project may well lead us to significant new sources of renewable energy that will also have a positive impact on the local economy.

In July 2001, BC Hydro sent out a Request for Proposals to experienced wave energy developers interested in working with us on the 3 to 4 MW ocean wave energy portion of the Vancouver Island Green Energy Demonstration Project. We heard back from 10 companies and, after evaluating the proposals, signed memorandums of understanding with two: Ocean Power Delivery Ltd, a company based in the United Kingdom, and Energetech Australia Pty Ltd.

Ocean wave energy technologies

Ocean wave energy generation is relatively new to North America. However, installations have been built or are under construction in a number of countries, including Scotland, Portugal, Norway, the U.S.A., China, Japan, Australia and India.

There are several different technologies designed to capture the energy of ocean waves. The two technologies under consideration for the Vancouver Island Green Energy Demonstration Project are oscillating water column and the Pelamis wave energy converter.

Artwork provided by Energetech Australia Pty Ltd.

Artist's rendering of the Energetech oscillating water column system being installed at Port Kembla, New South Wales, Australia.

Oscillating Water Column

In an oscillating water column (OWC) installation, waves enter a fixed structure (column) at one end. The water pressure forces air up the column and past a specially designed turbine, causing the turbine to spin; a generator connected to the turbine produces electricity. As the wave retreats, the air in the column is decompressed and drawn down past the turbine once again.

THE POWER IS YOURS

BC hydro

Vancouver Island 20 MW Green Energy
4 MW Wave Energy (1st Phase of Development)

Select JV	Monitor	Design	Build	Generate
Interim CAR Identify partners RFP Evaluate bids Negotiate Finalize	Monitoring Extra Monitoring Analyze data Prelim design	Decision making Financing Design	Engineering Procurement (EPC)	
6 months	8 months	4 months	6 months	20 years

01 Nov 2001 — 01 July 2002 — 01 Nov 2002 — 01 May 2003

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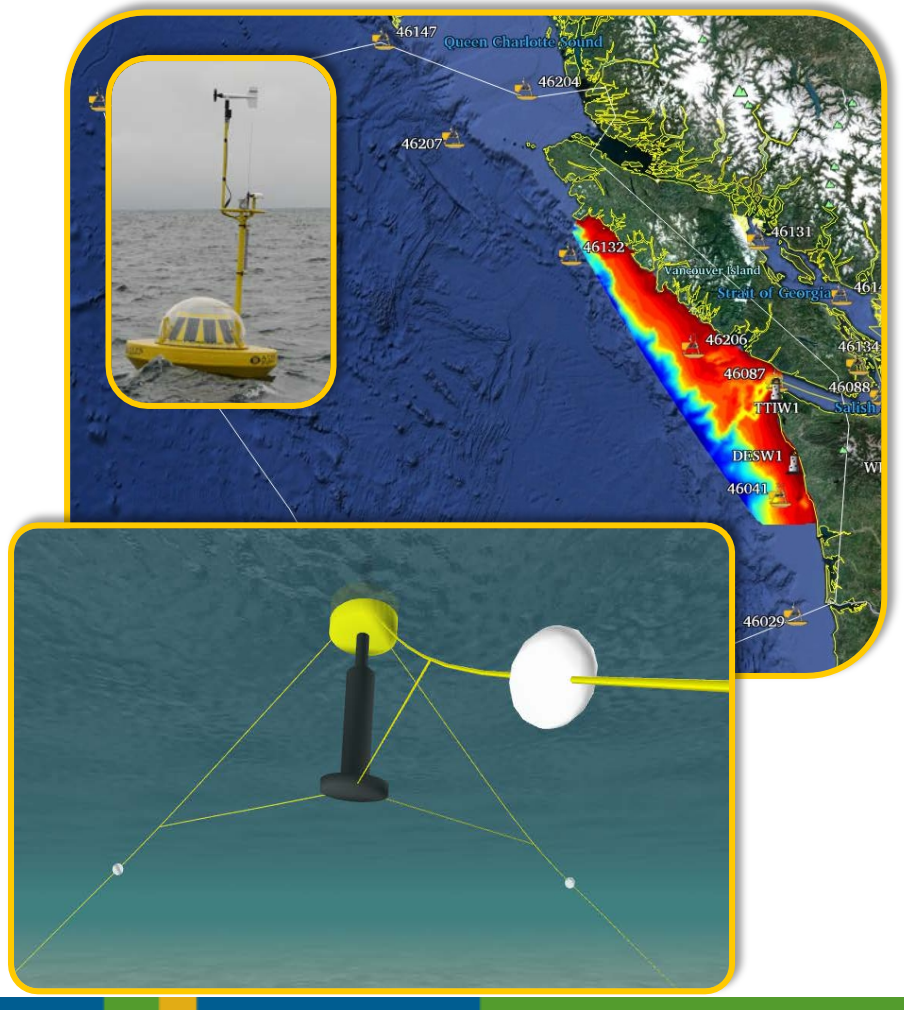
WCWI

What is the West Coast Wave Initiative (WCWI)?

The WCWI is a comprehensive wave-to-wire-to-washing machine modeling study that includes:

- Detailed assessment of the wave energy resource in an important Canadian region – Vancouver Island.
- High fidelity time domain computer simulations of Wave Energy Conversion (**WEC**) technologies.
- Detailed integration studies that examine how wave energy should be used at kW, MW and GW scales.



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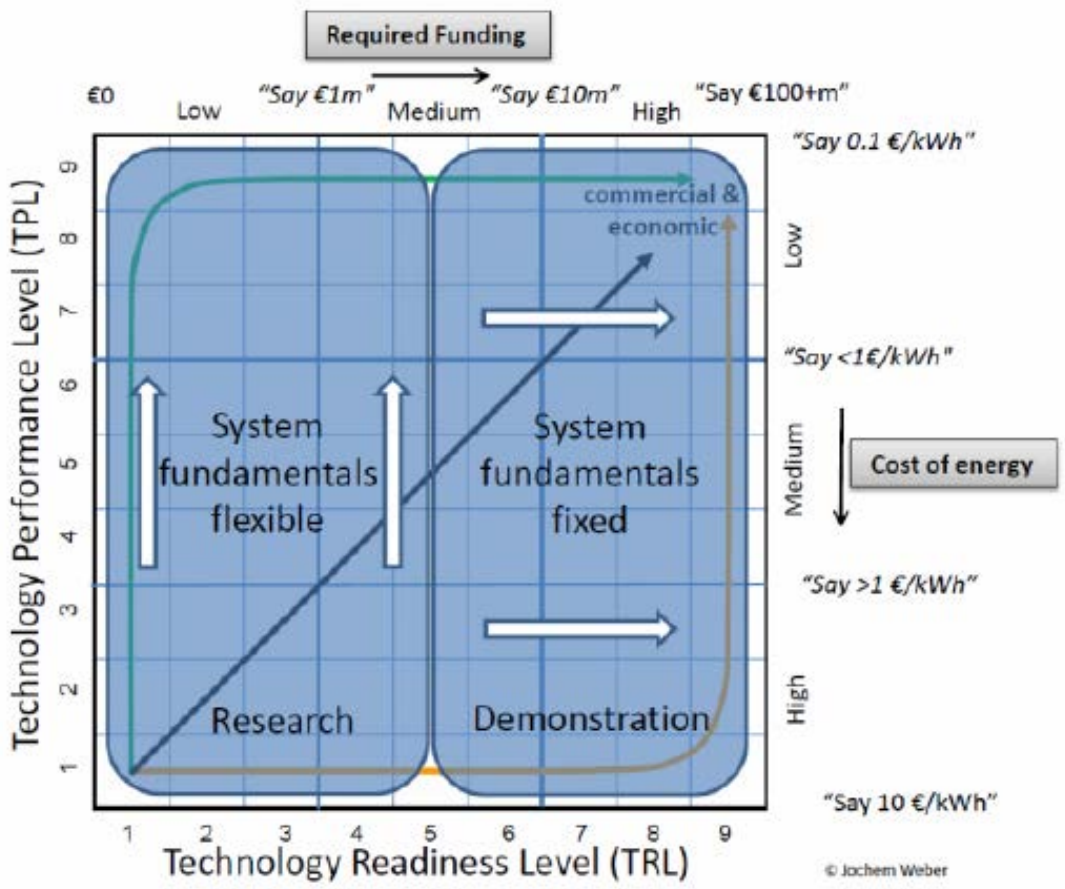
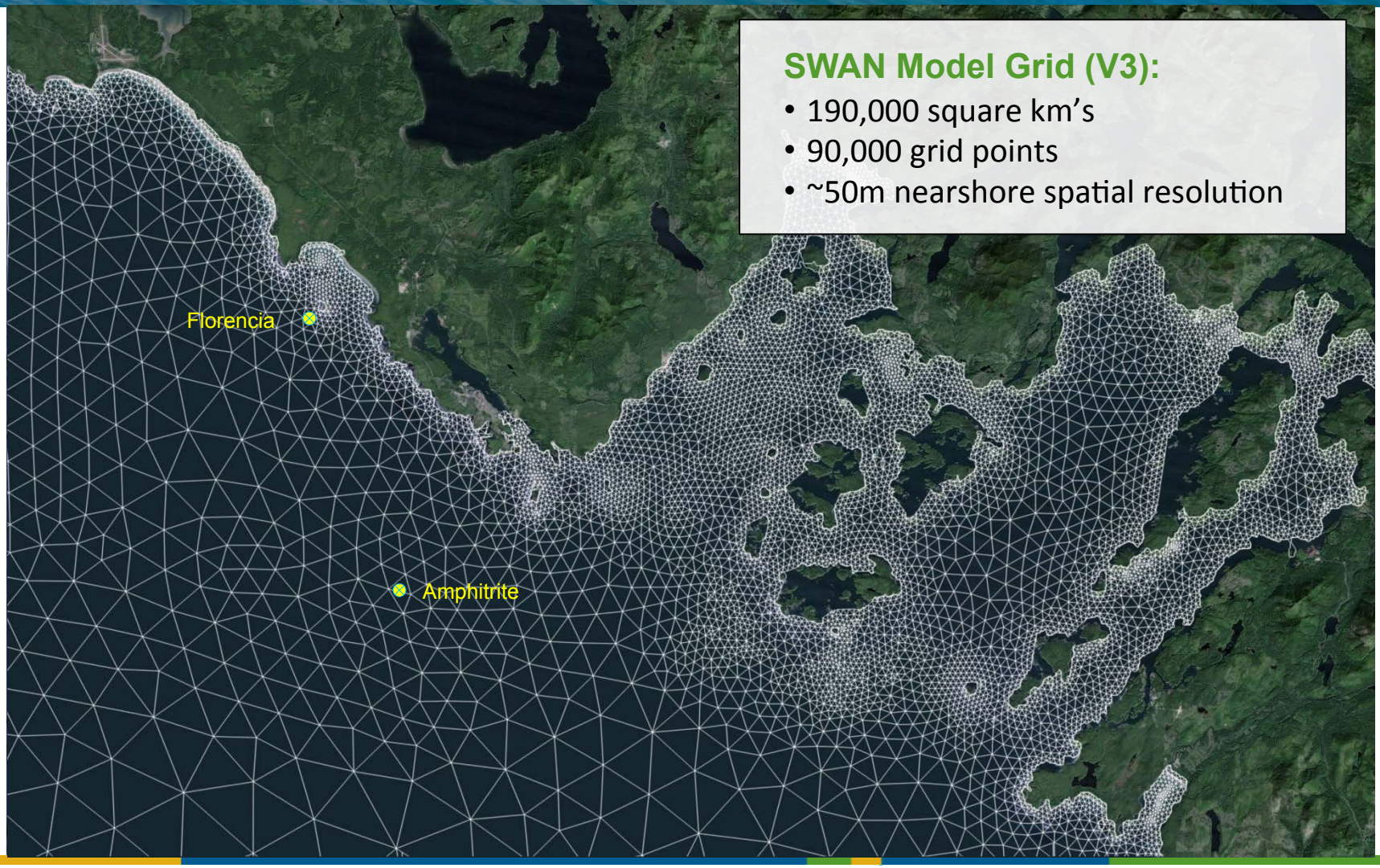
WCWI

WCWI – early stage WEC performance assessment



Weber, J (2012). "WEC Technology Readiness and Performance Matrix – finding the best research and technology development trajectory," ICOE 2012.

WCWI – BC Coast SWAN Model



SWAN Model Grid (V3):

- 190,000 square km's
- 90,000 grid points
- ~50m nearshore spatial resolution

Field Monitoring

Estevan: (Mid-island)
- Winds, Waves, Currents
- 3 years @ hourly resolution

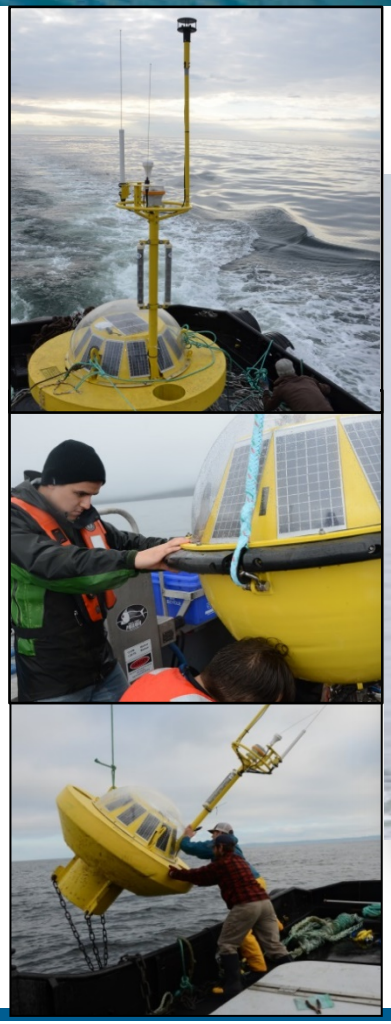
Amphitrite: (Ucluelet)
- Winds, Waves, Currents
- 5 years @ hourly resolution

Florencia Bay: (Ucluelet)
- Waves
- ~25m deep & 500m offshore
- 2.5 yrs @ 20 min resolution
- Carnegie Investigative Use Permit

Port Renfrew:
- Waves and Currents
- ~25m deep (shallow)
- 1 yr @ 20 min resolution

Port Hardy:
- Waves and Currents
- ~ 40m deep (shallow)
- Collocated buoy & AWAC

0.005 Hz frequency and 3° directional resolution



AXYS TECHNOLOGIES INC.

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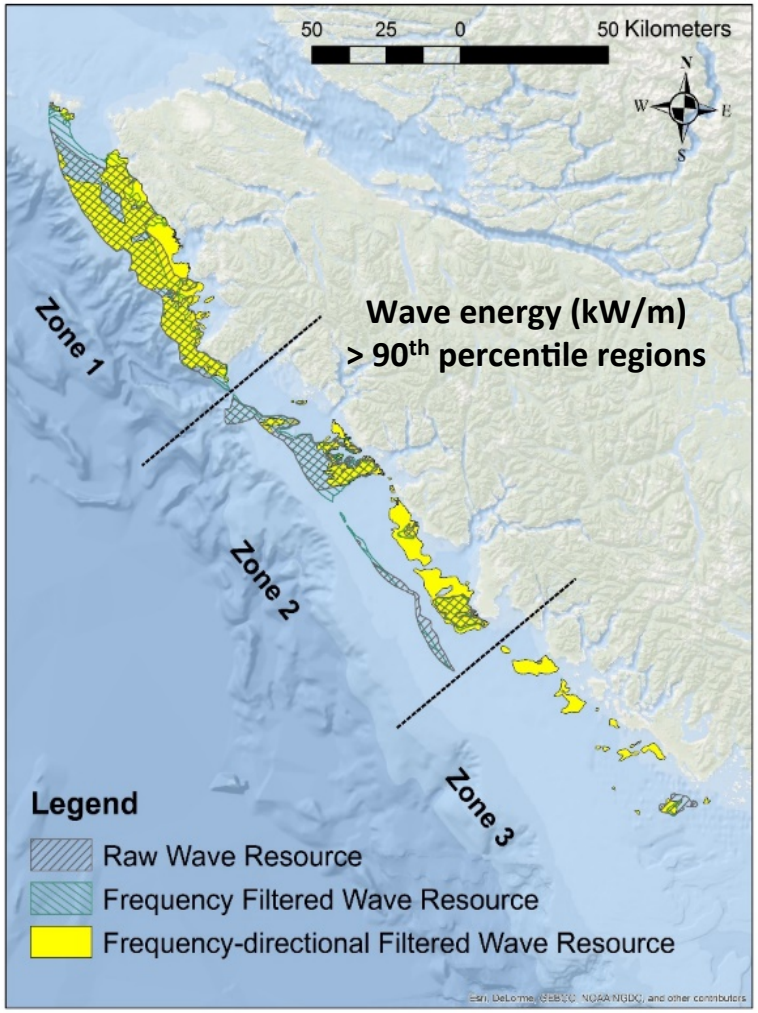
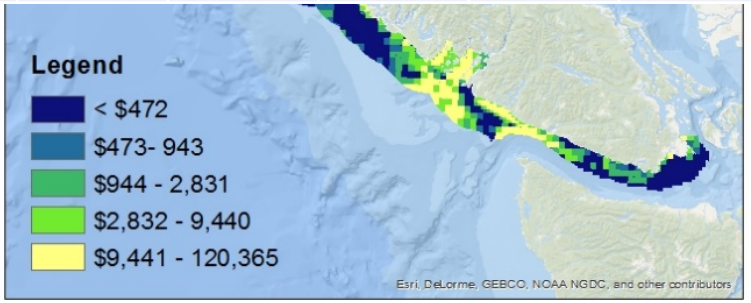
Where will WECs be Deployed (in BC)?



	Zone 1		Zone 2		Zone 3	
	Energy Flux [kW/m]	Area [km^2]	Energy Flux [kW/m]	Area [km^2]	Energy Flux [kW/m]	Area [km^2]
Raw	37.05	1040	36.67	595	36.25	47
Fre Filtered	19.85	1145	19.59	601	19.22	11
Fra di Filtered	14.15	1098	14.38	547	14.04	176

"Strategic"

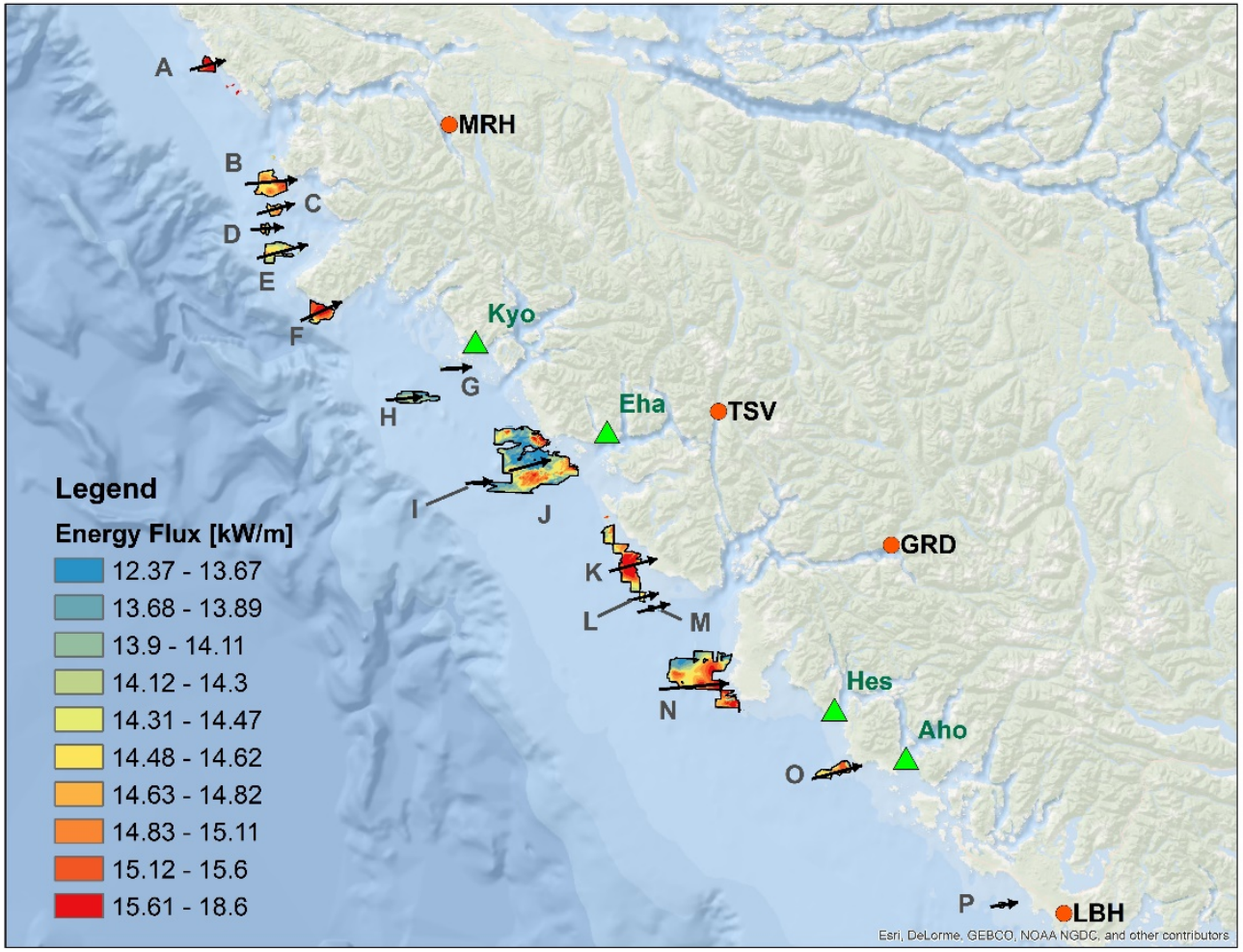
"Good from the perspective of all stakeholders"



Where will WECs be Deployed (in BC)?

WCWI: Why is it needed? | What are the objectives? | **How?** | Who?

Annual Gross Energy
28,704 GWh
Annual Extractable Energy
11,696 GWh
Van Isle Electricity Demand
9,069 GWh



MacArtney UNDERWATER TECHNOLOGY

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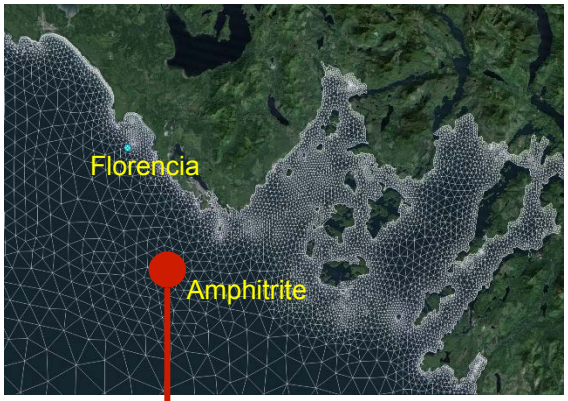
WCWI

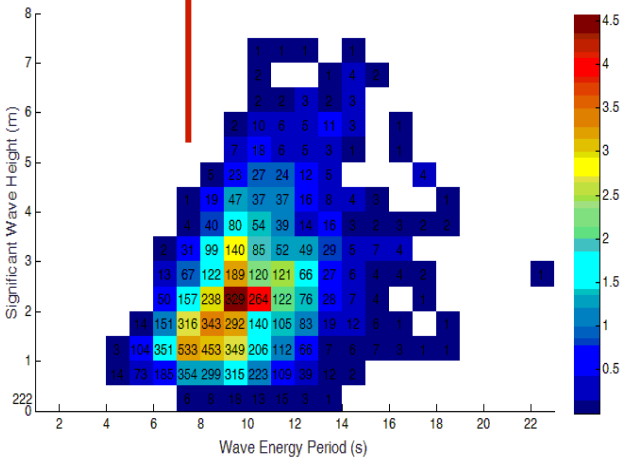
Wave energy – its good to have constraints

Ocean Energy Systems (OES) of the International Energy Agency (IEA) estimates that the global wave resource potential could be 29,500 TWh/ year.

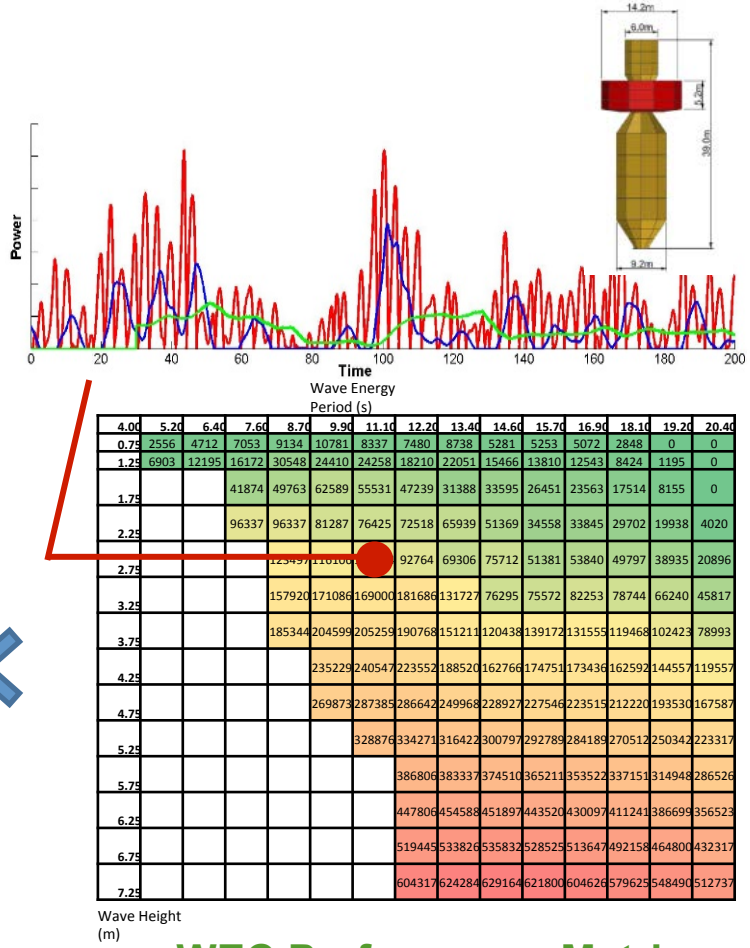
Wave energy – its good to have constraints

Annual Energy Production (AEP)





Wave Resource Histogram



Wave Height (m) \ Wave Energy Period (s)	4.00	5.20	6.40	7.60	8.70	9.90	11.10	12.20	13.40	14.60	15.70	16.90	18.10	19.20	20.40
0.75	2556	4712	7053	9134	10781	8337	7480	8738	5281	5253	5072	2848	0	0	
1.25	6903	12195	16172	30548	24410	24258	18210	22051	15466	13810	12543	8424	1195	0	
1.75			41874	49763	62589	55531	47239	31388	33595	26451	23563	17514	8155	0	
2.25			96337	96337	81287	76425	72518	65939	51369	34558	33845	29702	19938	4020	
2.75							92764	69306	75712	51381	53840	49797	38935	20896	
3.25				157920	171086	169000	181686	131727	76295	75572	82253	78744	66240	45817	
3.75				185344	204599	205259	190768	151211	120438	139172	131555	119468	102423	78993	
4.25						235229	240547	223552	188520	162766	174751	173436	162592	144557	119557
4.75						269873	287385	286642	249968	228927	227546	223515	212220	193530	167587
5.25							328876	334271	316422	300797	292789	284189	270512	250342	223317
5.75								386806	383337	374510	365211	353522	337151	314948	286526
6.25								447806	454588	451897	443520	430097	411241	386699	356523
6.75								519445	533826	535832	528525	513647	492158	464800	432317
7.25								604317	624284	629164	621800	604626	579625	548490	512737

WEC Performance Matrix

Annual Energy Production Profile

DSA DYNAMIC SYSTEMS ANALYSIS

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Annual Energy Production (AEP)

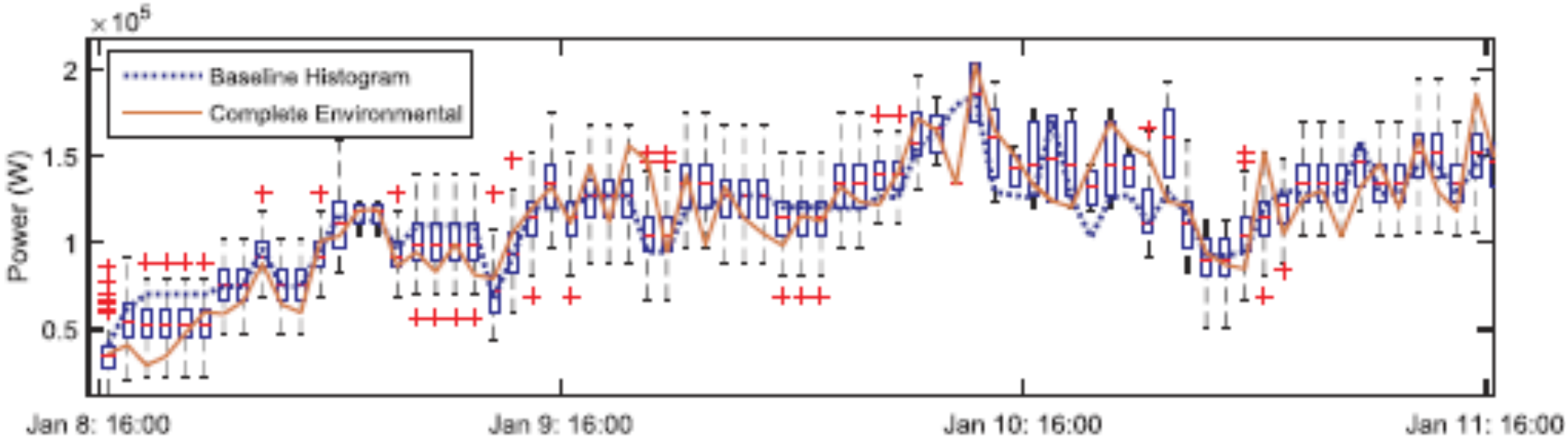

Fig. 7. WEC mean power output during January 2014

DSA DYNAMIC SYSTEMS ANALYSIS

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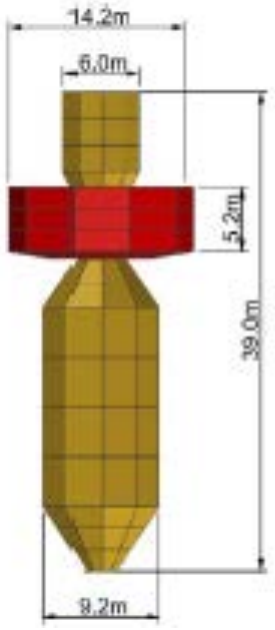
How do simulations enable design optimization

Point Absorbers and the 'other' Valley of Death

- Point absorbers suffer from a parasitic roll motion that develops (usually) right at the frequency of peak power conversion.



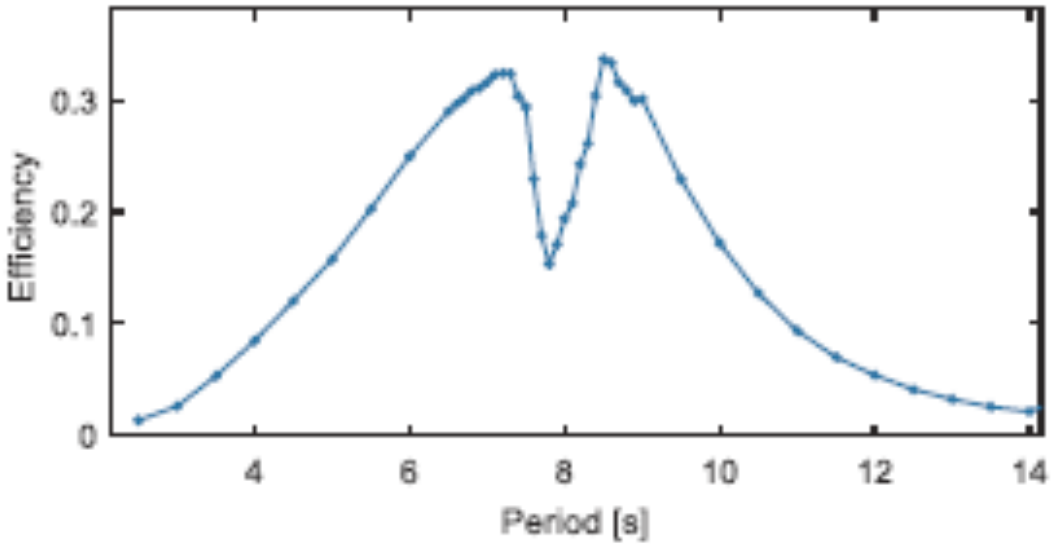
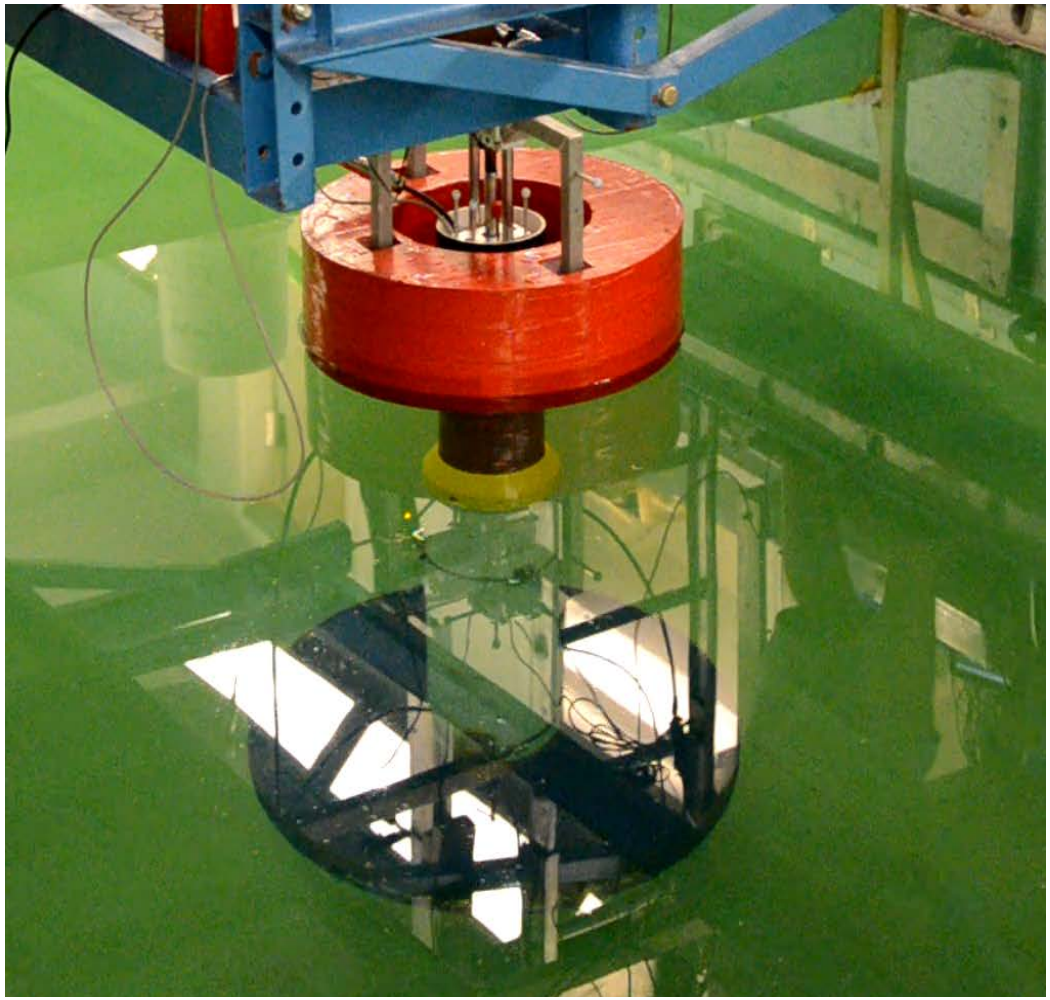
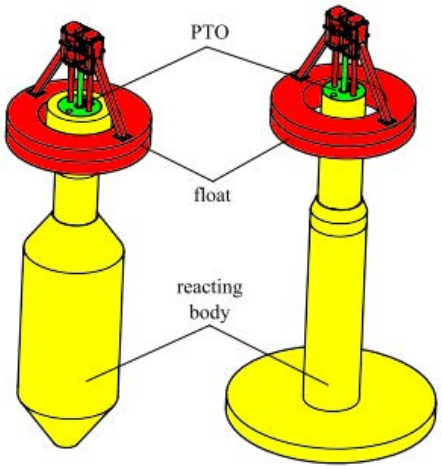


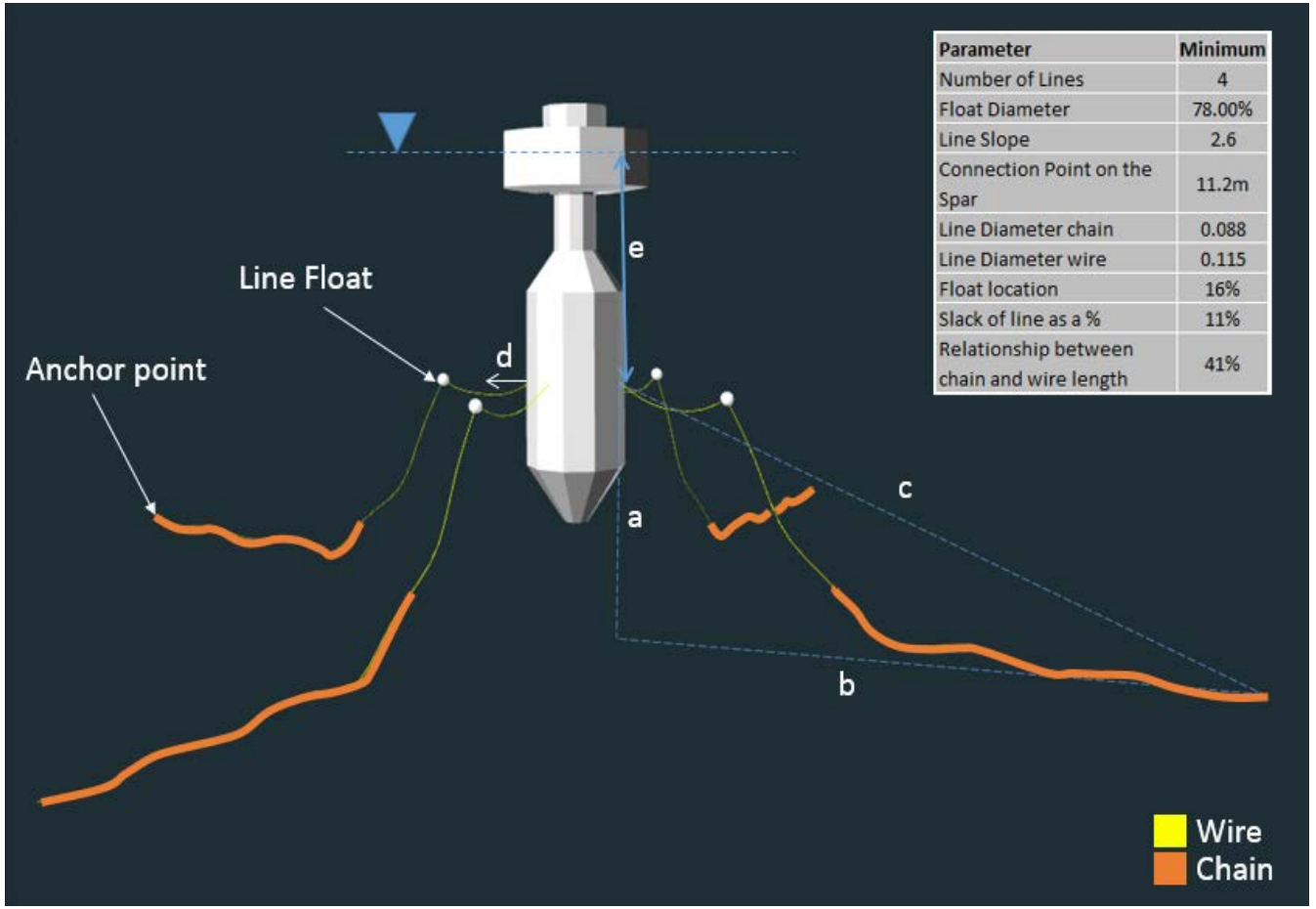
Fig. 4. WEC response under idealized regular wave conditions. Efficiency is the ratio of WEC power production to incident wave power.

A point absorber ‘walking’



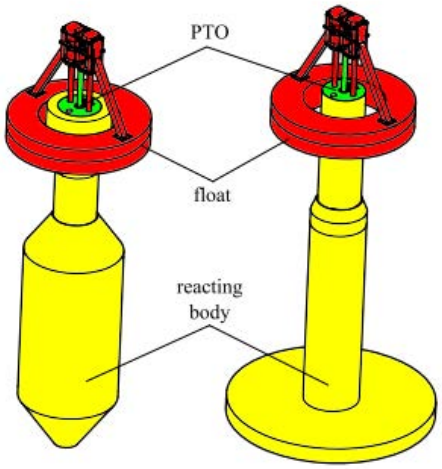
Using moorings as a design feature of the WEC

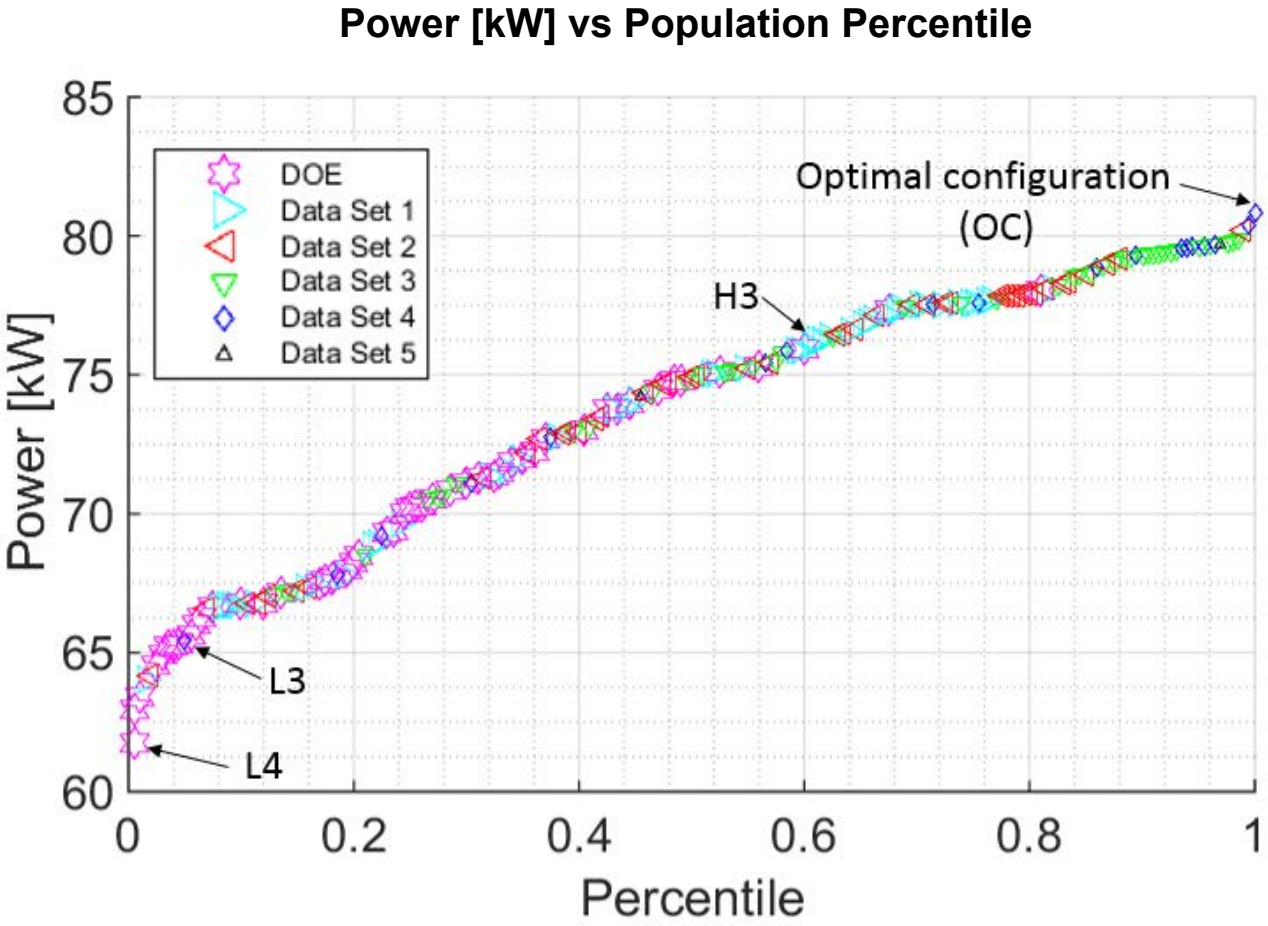




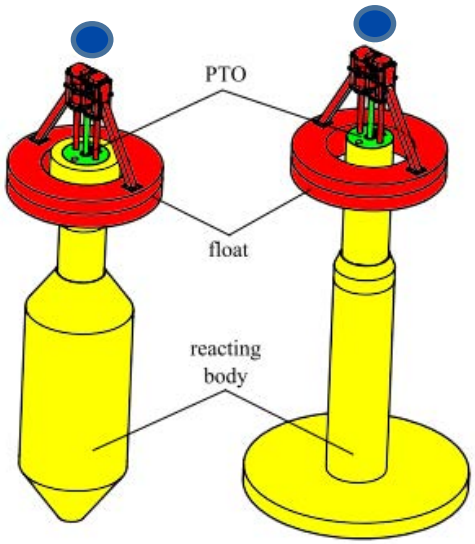
Parameter	Minimum
Number of Lines	4
Float Diameter	78.00%
Line Slope	2.6
Connection Point on the Spar	11.2m
Line Diameter chain	0.088
Line Diameter wire	0.115
Float location	16%
Slack of line as a %	11%
Relationship between chain and wire length	41%

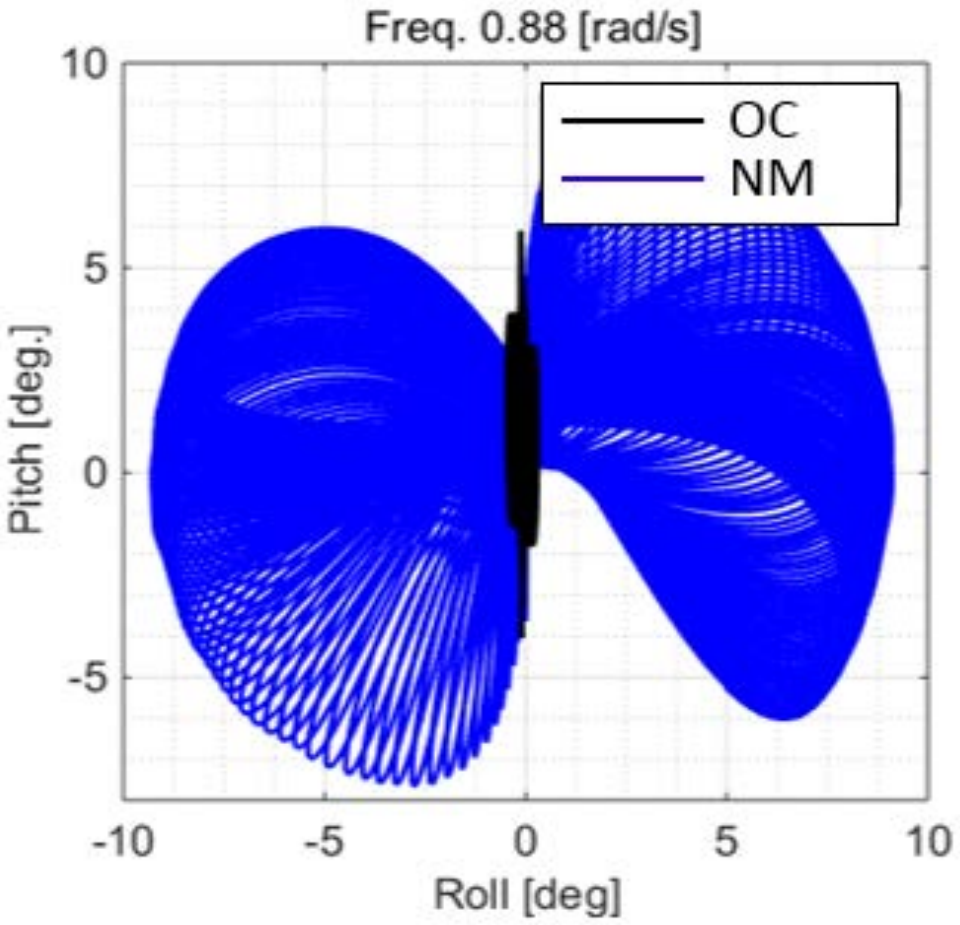
Using moorings as a design feature of the WEC



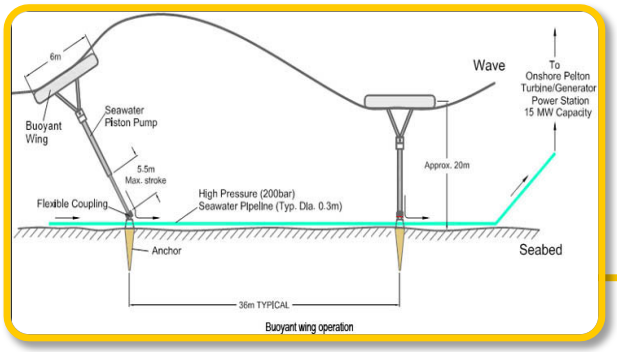


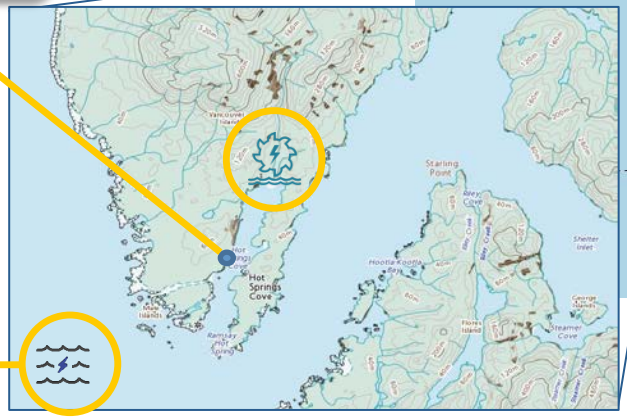
Using moorings as a design feature of the WEC

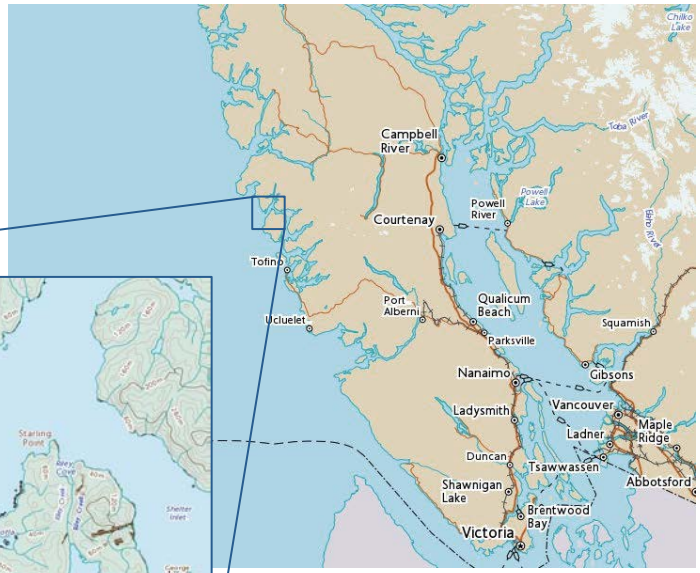




Where can WECs be exploited in BC?







Hot Springs Cove is a community of the Hesquiaht First Nation.

Currently pursuing a combination of renewables to eliminate diesel fueled energy generation on site.

Barkley project group

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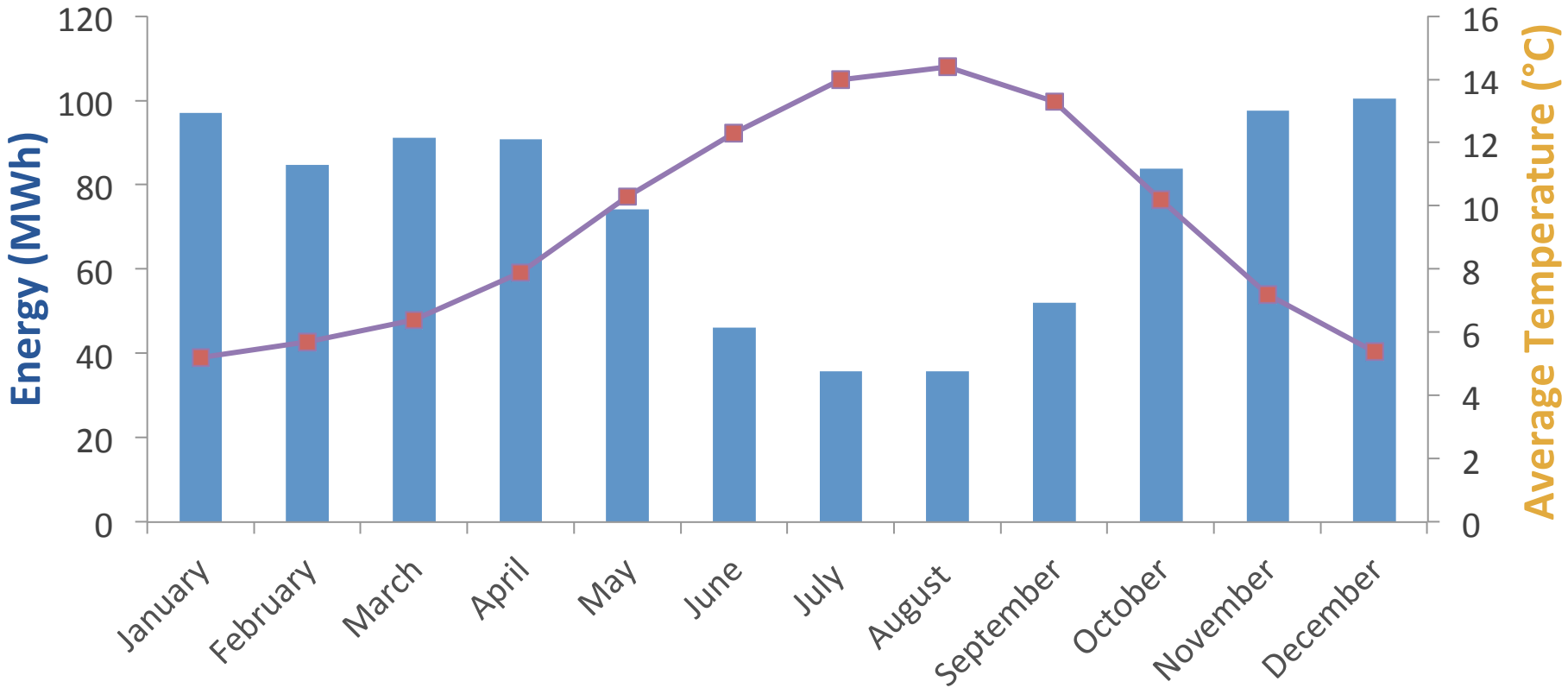
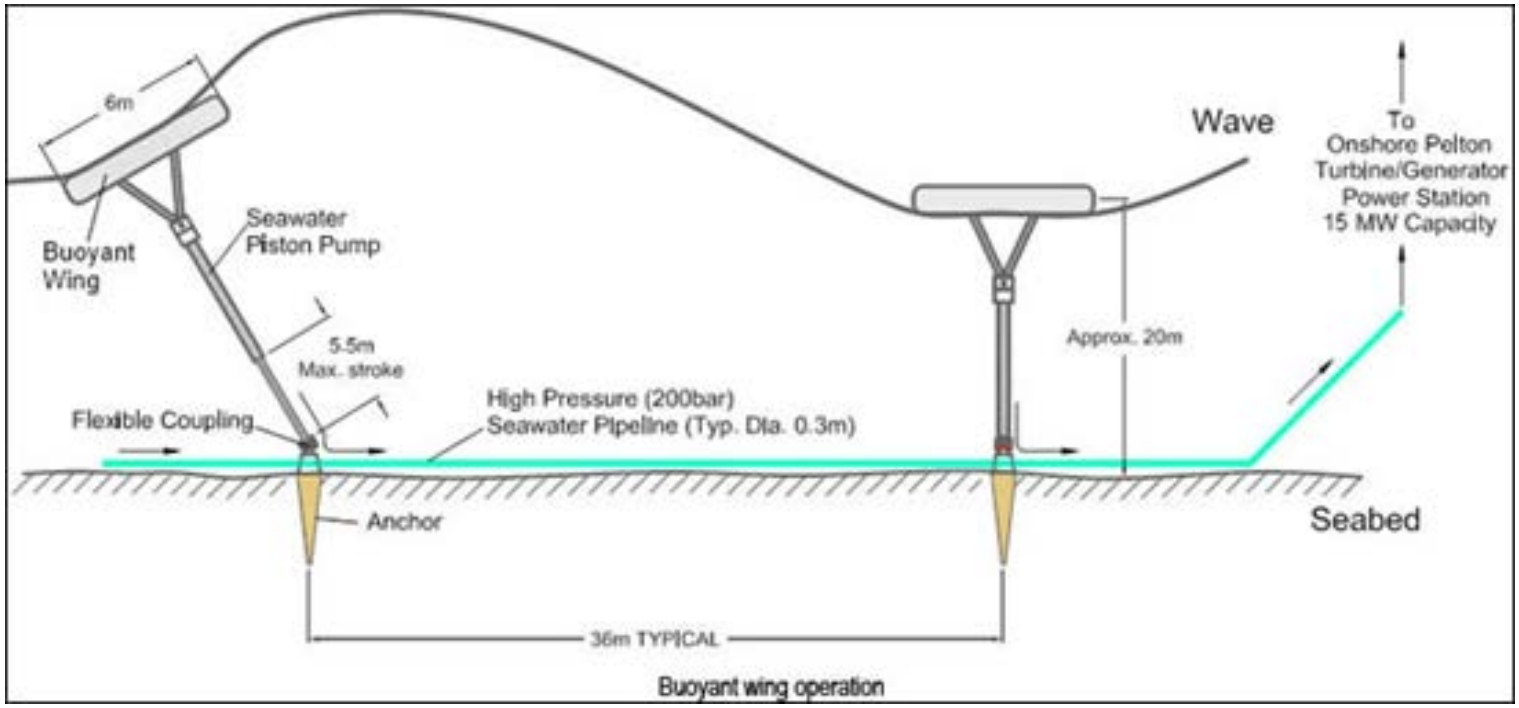
WCWI

Hot Springs Cove – energy demand



Hot Springs Cove – WEC



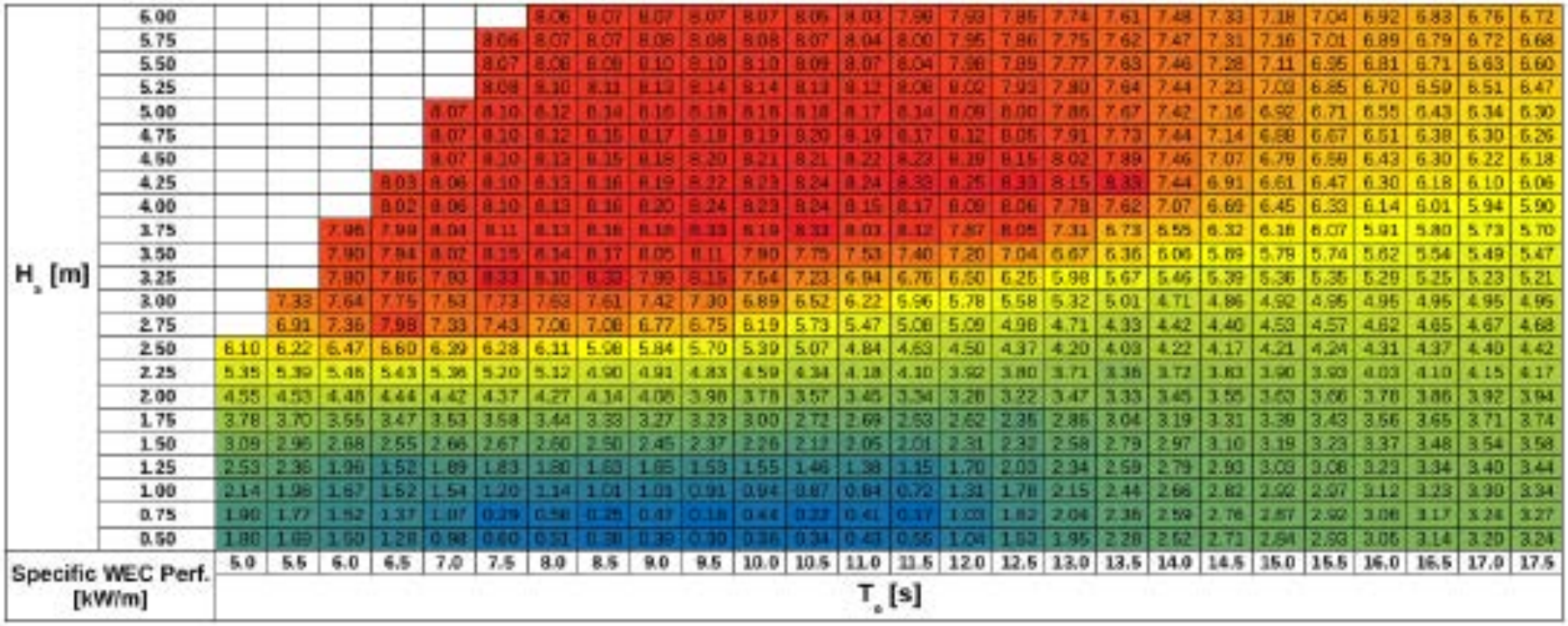
Considered a 'SurfPower' point absorber

Device power in all sea states scales linearly with length (distance into page)

Used ProteusDS to generate a performance matrix

Capped device output at 100kW

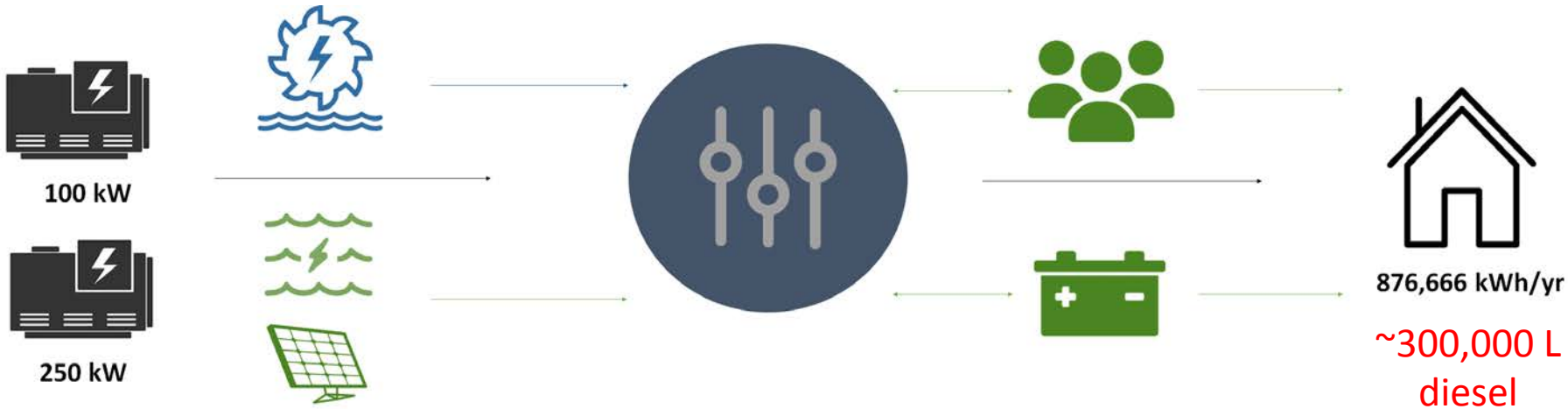
Hot Springs Cove - WEC



H_s [m]																														
	6.00							8.06	8.07	8.07	8.07	8.07	8.06	8.03	7.98	7.93	7.85	7.74	7.61	7.48	7.33	7.18	7.04	6.92	6.83	6.76	6.72
	5.75						8.06	8.07	8.07	8.08	8.08	8.08	8.07	8.04	8.00	7.95	7.86	7.75	7.62	7.47	7.31	7.16	7.01	6.89	6.79	6.72	6.68
	5.50						8.07	8.08	8.09	8.10	8.10	8.10	8.09	8.07	8.04	7.98	7.89	7.77	7.63	7.46	7.28	7.11	6.95	6.81	6.71	6.63	6.60
	5.25						8.08	8.10	8.11	8.13	8.14	8.14	8.13	8.12	8.08	8.02	7.93	7.80	7.64	7.44	7.23	7.03	6.85	6.70	6.59	6.51	6.47
	5.00					8.07	8.10	8.12	8.14	8.16	8.18	8.18	8.18	8.17	8.14	8.09	8.00	7.86	7.67	7.42	7.16	6.92	6.71	6.55	6.43	6.34	6.30
	4.75					8.07	8.10	8.12	8.15	8.17	8.19	8.19	8.20	8.19	8.17	8.12	8.05	7.91	7.73	7.44	7.14	6.88	6.67	6.51	6.38	6.30	6.26
	4.50					8.07	8.10	8.13	8.15	8.18	8.20	8.21	8.21	8.22	8.23	8.19	8.15	8.02	7.89	7.46	7.07	6.79	6.59	6.43	6.30	6.22	6.18
	4.25				8.03	8.06	8.10	8.13	8.16	8.19	8.22	8.23	8.24	8.24	8.23	8.25	8.23	8.15	8.33	7.44	6.91	6.61	6.47	6.30	6.18	6.10	6.06
	4.00				8.02	8.06	8.10	8.13	8.16	8.20	8.24	8.23	8.24	8.15	8.17	8.09	8.06	7.78	7.62	7.07	6.69	6.45	6.33	6.14	6.01	5.94	5.90
	3.75			7.98	7.99	8.04	8.11	8.13	8.16	8.19	8.33	8.19	8.33	8.03	8.12	7.87	8.05	7.31	6.73	6.55	6.32	6.16	6.07	5.91	5.80	5.73	5.70
	3.50			7.90	7.94	8.02	8.15	8.14	8.17	8.05	8.11	7.90	7.75	7.53	7.40	7.20	7.04	6.67	6.36	6.06	5.89	5.78	5.74	5.62	5.54	5.49	5.47
	3.25			7.90	7.86	7.93	8.33	8.30	8.39	7.99	8.15	7.64	7.23	6.94	6.76	6.60	6.26	5.98	5.67	5.46	5.39	5.36	5.35	5.29	5.25	5.23	5.21
	3.00		7.33	7.64	7.75	7.53	7.73	7.63	7.61	7.42	7.30	6.89	6.62	6.22	5.96	5.78	5.58	5.32	5.01	4.71	4.86	4.92	4.96	4.96	4.96	4.96	4.96
	2.75		6.91	7.36	7.98	7.33	7.43	7.06	7.08	6.77	6.75	6.19	5.73	5.47	5.08	5.09	4.98	4.71	4.33	4.42	4.40	4.53	4.57	4.62	4.65	4.67	4.68
	2.50	6.10	6.22	6.47	6.60	6.39	6.28	6.11	5.98	5.84	5.70	5.39	5.07	4.84	4.63	4.50	4.37	4.20	4.03	4.22	4.17	4.21	4.24	4.31	4.37	4.40	4.42
	2.25	5.35	5.39	5.48	5.43	5.36	5.20	5.12	4.90	4.91	4.83	4.59	4.34	4.18	4.10	3.92	3.80	3.71	3.36	3.72	3.83	3.90	3.93	4.03	4.10	4.15	4.17
	2.00	4.55	4.53	4.48	4.44	4.42	4.37	4.27	4.14	4.06	3.98	3.78	3.57	3.45	3.34	3.28	3.22	3.47	3.33	3.45	3.55	3.63	3.66	3.78	3.86	3.92	3.94
	1.75	3.78	3.70	3.55	3.47	3.53	3.58	3.44	3.33	3.27	3.23	3.00	2.72	2.69	2.53	2.62	2.35	2.86	3.04	3.19	3.31	3.39	3.43	3.56	3.65	3.71	3.74
	1.50	3.09	2.96	2.68	2.55	2.66	2.67	2.60	2.50	2.45	2.37	2.26	2.12	2.05	2.01	2.31	2.32	2.58	2.79	2.97	3.10	3.19	3.23	3.37	3.48	3.54	3.58
	1.25	2.53	2.36	1.96	1.52	1.89	1.83	1.80	1.63	1.65	1.53	1.55	1.46	1.38	1.15	1.70	2.03	2.34	2.59	2.79	2.93	3.03	3.06	3.23	3.34	3.40	3.44
	1.00	2.14	1.96	1.67	1.52	1.54	1.20	1.14	1.01	1.03	0.91	0.94	0.87	0.84	0.72	1.31	1.78	2.15	2.44	2.66	2.82	2.92	2.97	3.12	3.23	3.30	3.34
	0.75	1.90	1.77	1.52	1.37	1.07	0.79	0.98	0.28	0.47	0.16	0.44	0.27	0.41	0.17	1.03	1.62	2.04	2.36	2.59	2.76	2.87	2.92	3.06	3.17	3.24	3.27
	0.50	1.80	1.69	1.59	1.28	0.98	0.60	0.51	0.38	0.39	0.30	0.36	0.34	0.43	0.35	1.04	1.63	1.95	2.28	2.52	2.71	2.84	2.93	3.05	3.14	3.20	3.24
Specific WEC Perf. [kW/m]		5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
		T_e [s]																									

Figure 2.24: SurfPower specific performance matrix

Hot Springs Cove – break even analysis

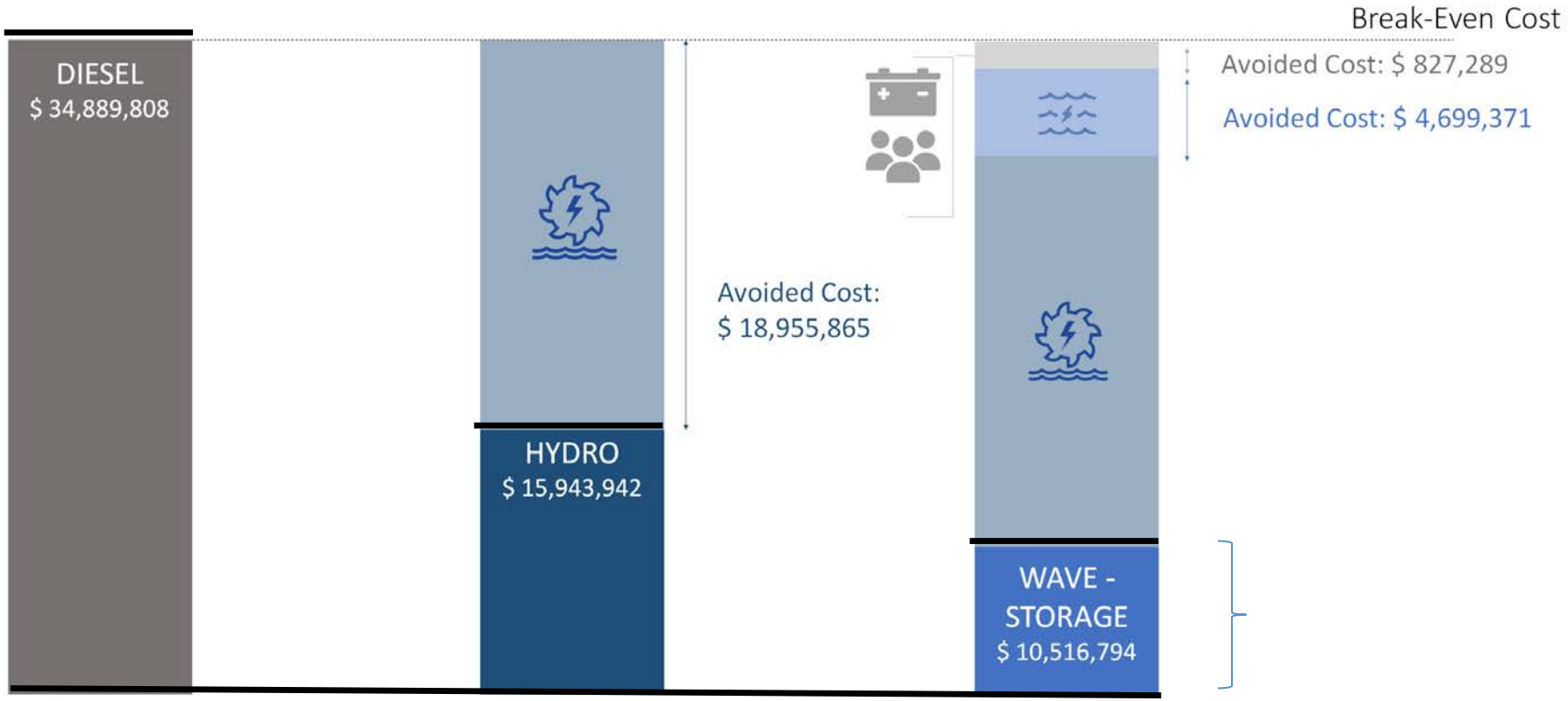


We consider all renewables to be added at zero cost – we want to assess savings over the Business as Usual (BAU) case over lifetime of project.

Converting those savings into present day value gives us a measure of a (CAPEX+OPEX) allowance for the renewable device.

Demand side: peak shifting (delaying loads to reduce peak demand)

Hot Springs Cove – Avoided costs



Hot Springs Cove – LCOE

Diesel system

1.519 $/kWh

* Includes an overhaul

Hydro system

0.6995 $/kWh

Wave system

0.6534 $/kWh

Optimized system

0.4545 $/kWh

Hot Springs Cove – planning renewable buildout

Results illustrate the synergy of wave supplied power with a winter heating dominated community demand profile.

Wave resource is somewhat correlated with hydro but persists more in the summer – this leads to further decreases in system LCOE.

Load shifting and battery storage (200kWh) didn't show much benefit with hydro or wave.

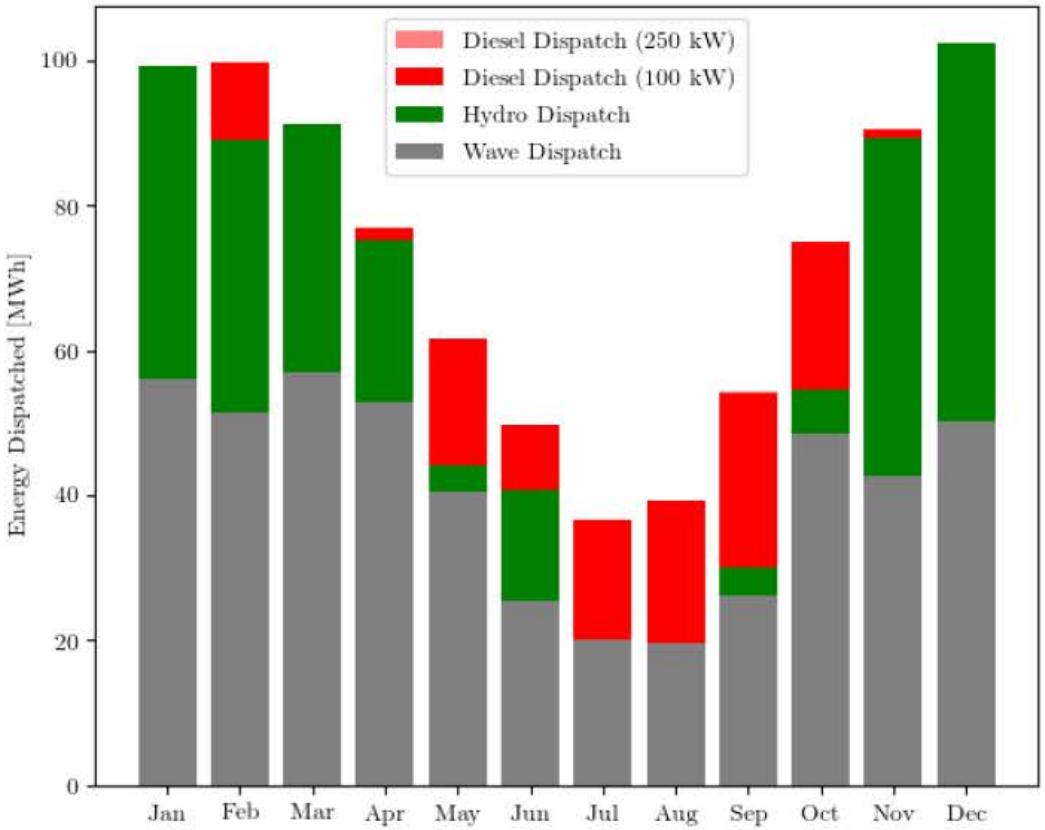
At HSC – hydro is now being built to form a Micro-Hydro Diesel system (MHD)

Can we provide some guidance to HSC on how to continue to evolve their energy system after the MHD step?

- wave vs. solar.
- Battery storage – 200kWh, 500kWh, …?
- Energy Saving – new insulation, windows, … (ES)

Hot Springs Cove – planning renewable buildout

MHD + 100 kW Wave + No BSS



	NPOC [$M]	Fuel Use [L/yr]	Emissions [tCO2e/yr]
BAU	15.94	85,305	227
Wave	11.21	44,664	119
Δ	- 29%	- 48%	- 48%

Allowable Cost=$M 4.70

( ) = BAU	Winter Cap. Fact.	Summer Cap. Fact.
100 kW diesel	0.074 (0.096)	0.203 (0.417)
250 kW diesel	0.000 (0.052)	<0.001 (0.018)

Barkley project group

University of Victoria | Institute for Integrated Energy Systems

WCWI

Hot Springs Cove – wave pathway

By examining the differences in NPOC, emmisions and fuel consumption between cases we can create pathways of incremental improvements

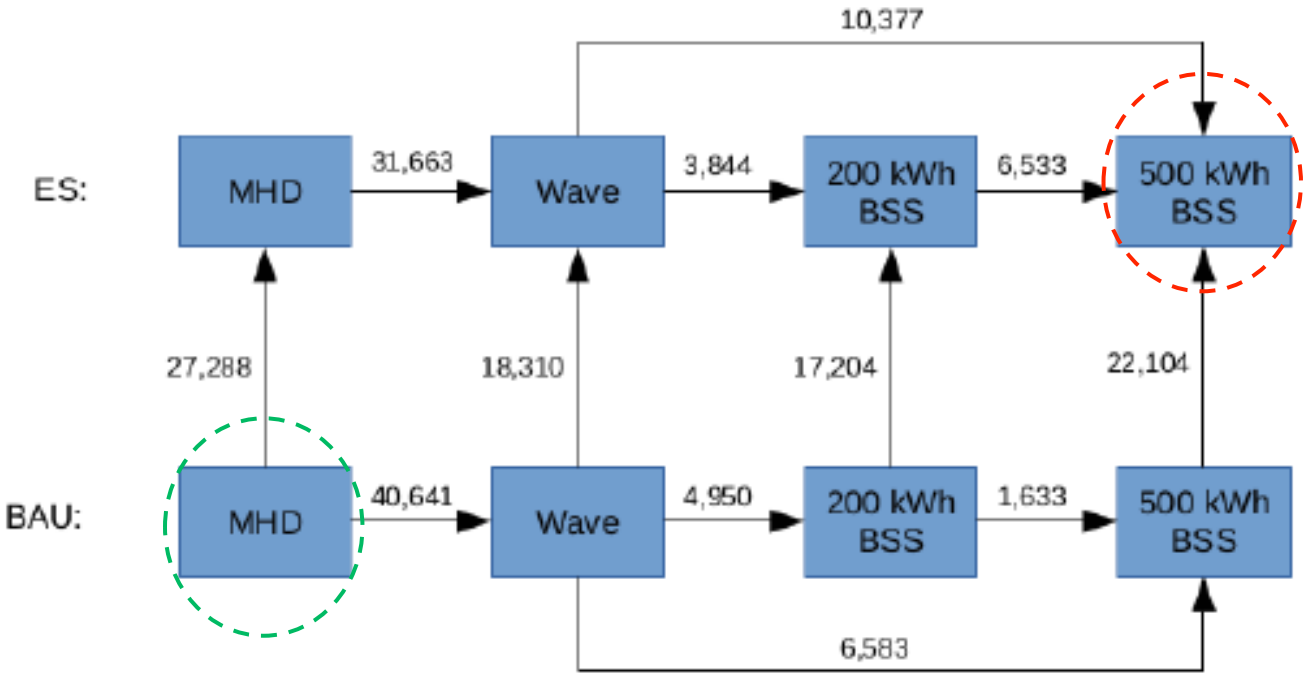


Figure 4.7: Expected incremental diesel displacements [L/yr] due to traversing the wave (100 kW) tech tree

Hot Springs Cove – WEC costs

Commercial Potential of Marine Renewables in British Columbia, Natural Resources Canada, 2019

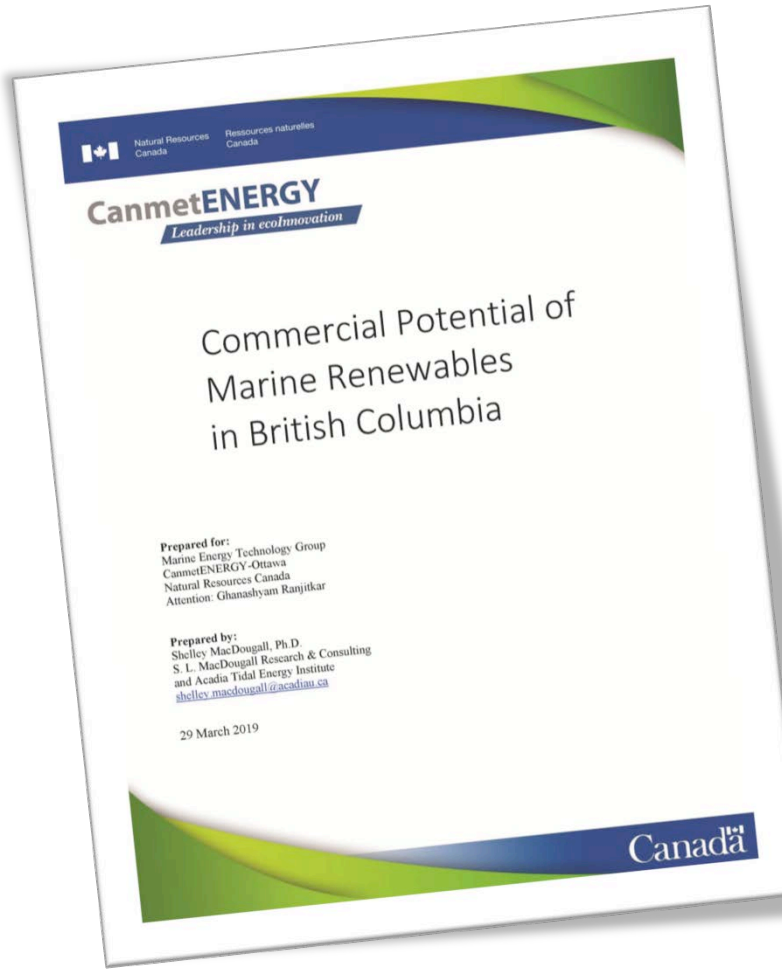
Surveyed:

- WEC CAPEX costs (30,000 $/kW)
- expected learning rates (12%)
- Capacity Factors (~28%)

Established projection for WEC LCOE reductions over time.

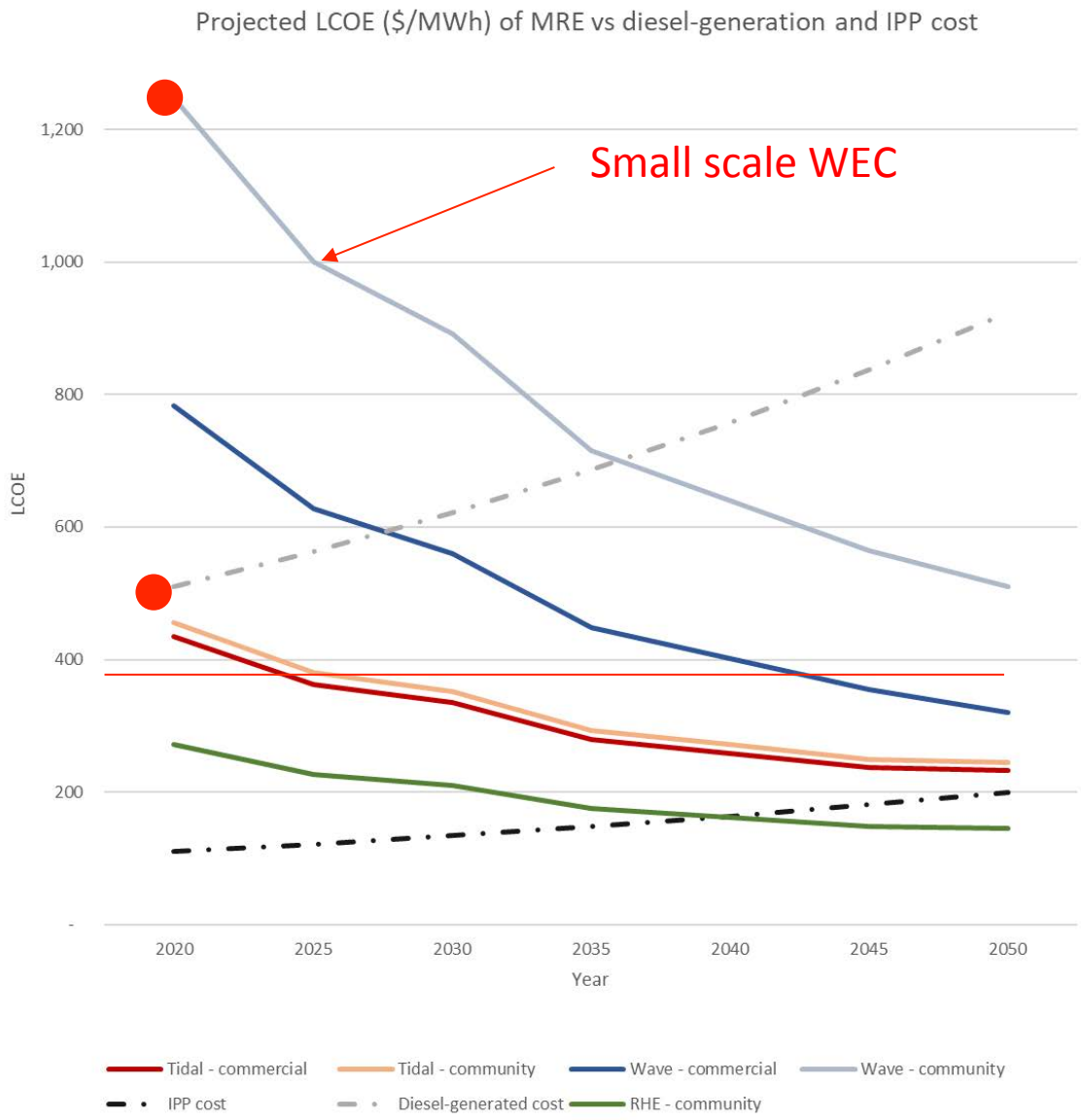
At HSC the 100kW WEC plant can have an allowance of $4.7M. It produces 496 MWh/yr

- Allowable LCOE = 379 $/MWh



Hot Springs Cove – energy balance & incremental costs

WCWI: Why is it needed? | What are the objectives? | **How?** | Who?



WCWI

CleanBC & remote communities

- Majority of BC's off grid energy systems are in First Nations communities.
- BC First Nations have made it very clear that cleaning their energy systems is a priority.
  - 78 projects with over 1.8 GW of installed capacity (60% micro-hydro).
  - 48 projects in planning or pre-planning.
  - 250 projects in early stage feasibility.
- A majority of existing projects (42) are grid connected, but recent projects are off-grid.
- Clean energy systems are a means to shape (re-shape) communities consistent with traditional ideals of *people and place*.

WEC technology & BC remote communities

- There still remains a lot of uncertainty in WEC technology
  - Concepts haven't converged.
  - CAPEX & OPEX.
- Advancement of the sector depends on motivated people who want to pursue transformational change.
- In BC, it is Indigenous communities that are taking the lead.
- IEA – OES:

  "Ocean Energy is facing a dilemma: how to fund technological development and first deployments at sea oriented to gain experience, improve performance, limit risks and finally reduce costs in a challenging long-term scenario. The participation of public bodies committed to a clean energy future using indigenous sources is essential to help solve this dilemma. It can bridge the gap between a promising present and a profitable future".

WEC technology & Global remote communities

How many litres of diesel do we need to displace in order to fill the 6.1Mt missing piece?

$2.3 \times 109\ L$

There are 3000 off grid communities in Chile…