Introduction

Beginning in 2010 it was decided to purchase a wave power system to provide clean renewable energy for our cottage on Keats Island. Waves seemed to be a better choice than wind or solar energy because we could see that the waves were active all day and all night long, most of the time. But we could not find any to buy, so we decided to make one, shouldn't be that hard we thought . . .

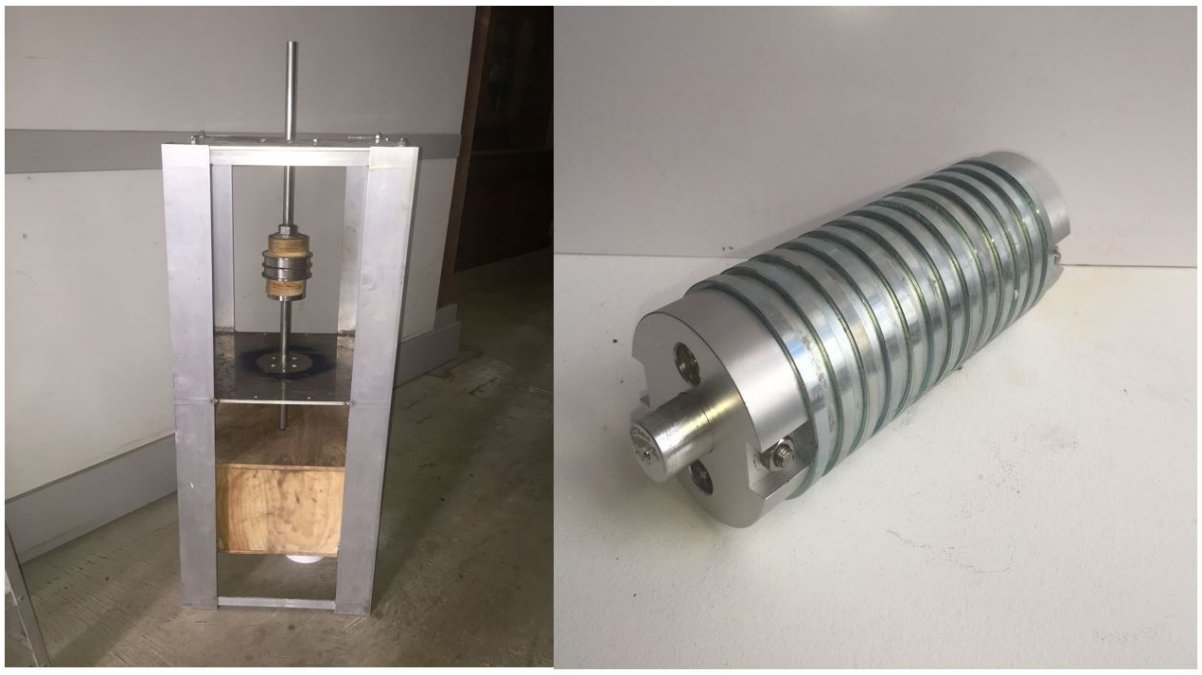
After the first attempt, using the obvious float pushing and pulling a linear generator, we could see that two problems needed to be solved to make electricity from wave power that was economical and more reliable than from wind and solar. First, how the deal with the change in water level due to tides approximately twice a day (up to 5 meters) and the height of largest waves at top and bottom(up to 2 m). Secondly, how to make the linear generator work more efficiently (the slow moving stop & go aspect needed to be improved). The parts that worked well & which we considered essential from the first (2010) model were the use of the float (point absorber) and the direct drive of the generator from the wave action.

2010 - Nep 0.1 Linear Generator

We began by building a test model with the obvious approach of using a float constrained inside a frame so it could only move up and down. We attached a push rod to the top of the float and extended this above the water level where the linear generator was housed.

A custom made magnet pack was attached to the moving end of the push rod (the translator) and we made a custom stator with multiple small circular coils, (using the smallest gauge wire possible), arranged in rows extending horizontally away from the translator.

We tested this in a swimming pool and found that while the moving float and the direct drive approach were keepers, the fact that we have a 5 m tide and the slow moving and stop & go movement of the generator translator needed mitigating.



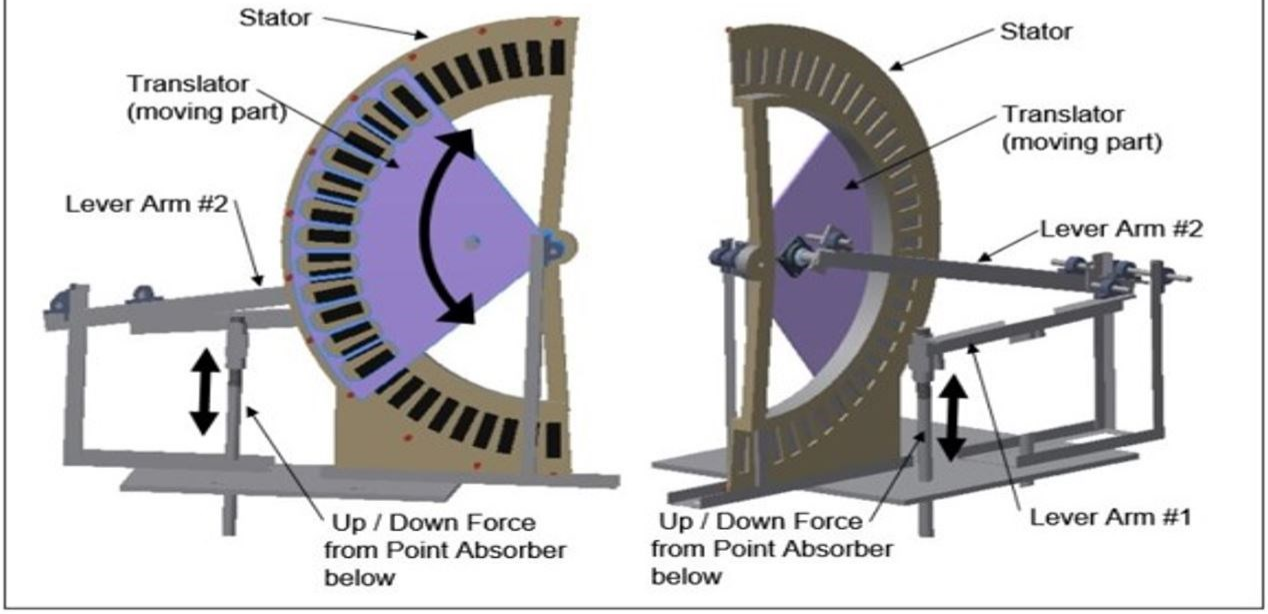
2010 Neptune 0.1
Linear Generator Direct Drive with generator on top out of water

2011 Nep 0.2: Hybrid Linear Generator

We hypothesized that we could increase the slow moving aspect of the linear generator with compound levers. Sound in theory impractical in reality.
Stopping the increased speed of the Translator (now with the coils) when it came to the end of the stroke presented a physical problem. We could make it strong enough to not break but it would be prone to high maintenance and high costs.

We then hypothesized that a variation on the well know uni-directional rotating generator using a direct drive PTO may be economical and produce a greater amount of power than the stop n' go linear generator. Our first attempt was to put two of the compound lever units together, as the image shows, turning the linear generator into a rotating generator. Of course this would require we make a custom generator that could handle variable speeds & a PTO that would convert the reciprocating motion from wave action on the float into uni-directional rotation motion.

Drawing of Hybrid Lever-Linear Generator showing two compound levers moving the Translator lever past the magnetic Stator



2011 Neptune 0.2 *Hybrid Linear Generator With speed increasing compound levers*

2012 Nep 1A: Custom Generator Part

At this point we understood that the wave energy problem is primarily about generating the electricity from the often small waves and slow moving reciprocating motion of the float induced by the waves. We hypothesized that a large diameter axial flux permanent magnet generator (which Hugh Pigott in Scotland helped us make) would produce substantial electricity from the uni-directional rotation motion that the new PTO, we were working on at the same time, would deliver from the smaller waves.

We wound our own coils in the 30 coil by 80 magnet generator (40 on each side) of the stator coils. This generator was designed to produce 6 KW 3 phase power from 0.5 m by 4 s waves (.5 m high by 4 second period waves).

This generator coupled to the new PTO (see 2013) produced power in the Neptune 2, 3 & 4 test units all deployed in the sea.

2012-2013
Neptune 1A

Custom Axial Flux Permanent Magnet Generator,

to handle the relatively slow and variable speeds induced by the waves on the motive float.

2012-2013 Nep 1B: Direct Drive Wave Energy PTO Patent *CA2808614*

It was hypothesized that an endless chain driven by the reciprocation forces from floats could replace a rack and pinion drive (as a pinion can easily move a rack but a moving rack does not easily move a pinion) and that if a sprag clutch were used on one of the chain sprocket shafts it would turn on, say, the up stroke but not on the down stroke, AND, if a similar system we used opposite the first and the sprag arranged to allow the shaft to turn on the down stroke that these could be arranged to provide unidirectional motion to a generator shaft with energy from both the up and down movements of the float. We did this, patented it, and it works.

We now have solved the linear generator stop and go issues, and, with increaser gears solved the slowness issues with a custom direct drive PTO.

2013 Neptune 1B

Direct Drive Wave PTO
Patent: CA2808614.

Solves linear generator speed and stop & go issues while maintaining direct drive from float to generator.

View Videos of PTO Operation at: https://www.neptunewave.ca/history (Year 2013)

2014 Nep 2: Floating Wave Engine

A complete electricity producing full sized unit with the new PTO and generator was was made and tested. It produced 460 Volts, no load 3 phase power from 0.5 m waves.

The unit was made of non-corrosive polyethylene plastic tank outriggers, aluminum motive float point absorber, wooden and steel deck and a welded aluminum and ABS geodesic dome.

The unit proved to be stable in the waves, but the attachment of the polyethylene floats proved to be unstable over time and likely to wear to breaking within 6 months due to the 4 million wave duty cycle at the Keats island test site. Unit was brought back for mitigation.

2014 Neptune 2
Complete floating system produced electricity from wave actions on motive float.
Tested at 2nd Narrows Bridge, North Vancouver, BC, Canada

2015 Nep 3 Tidal Compensator PCT Patent PCT *WO 2014/138964 Al*

This, mostly steel unit, address the original issue of dealing with the 5 m tides in the test area. The tidal compensator mechanism maintains the fixedness of the floating body "vessel" to the seabed, for the point absorber to react against, while allowing the floating body to move up and down the 5 m required due to tidal flow and enables the motive float to distance of the highest waves at any time.

The operation of the electrical generator from the float movement transferred through the PTO worked flawlessly, producing power as expected. In addition the unit was built to Transport Canada requirements for vessel registration which would allow it to be anchored in most parts of the world without cumbersome permits.

The fail-safe device on the tidal compensator winch proved to be unreliable and failed operationally during testing and the wave engine was brought back to land for mitigation.

2015 Neptune 3 *Shown moored at Maritime Museum, Vancouver, Tidal Compensator and electricity production from direct drive PTO-Generator tested at Keats Island.*

2016 Nep 4

Harmonizing the Frequency of the point absorber movement so that it can react against the movement of the floating vessel, is known as the "attenuator problem".

We hypothesized that a 10:1 weighted floating "vessel" would ensure that it moved in dis-harmony with the point absorber motive float movement, thus providing a body for the motive float part to react against to twist the generator.

Our tests proved it is a valid hypothesis but only in small < 0.75m waves; the cost for ensuring that this would work in larger waves > 4 m rendered the wave engine not commercially viable due to associated high costs. The wave engine was brought back to land for mitigation.

2016 Neptune 4 Dis-harmony of Floats Experiment *Neptune 4 moored at Keats Island, with 35 tonne outrigger floats testing the frequency of the floating part to the motive float in waves of various sizes.*

2017 Nep 5A

We hypothesised that a levered float off a pile (different from the jetty based Wavestar and Eco Wave Power lever arm approaches) would not have the drawbacks of the disharmony of 2 floats and be economically viable at large sizes. Testing of this concept was conducted under 4 conditions with 3 tests each for 3 wave sizes (36 tests) in Indian Arm proved successful, would be economically viable and scalable with no problems.

We then hypothesized that a full size 2 to 4 lever arm float-pile system that transferred the float power to the patented direct drive Neptune PTO from a point near mid way along the lever arm would solve the inefficiency problems associated with the hydraulic PTO and permit full operations at any tide level (with 5 m change) and any wave height (up to 2 m) as are found in the Georgia Strait.

2017 Neptune 5A *Test of Lever Arm Float attached to Pile to determine suitability of this approach under various conditions in various wave sizes (36 test runs), Mud Flats, Indian Arm, Vancouver Harbour.*

2018 Nep 5B

These floats on lever arms have required mitigation due to high 2.6 m/s (5 knot) currents at test location and 6 m/s horizontal wave transfer forces.

After several failures a stable "lateral force" bearing with a "bridge-like" lever arm was built to provide a stable float system for all currents and waves at the test location, however this system would not be economically viable at larger scales and would require constant maintenance. Mitigation was required, see 2019.

This Neptune 5B engine is deployed under a 5 year Investigative Use License issued by the MLRNRO, BC Government, 800 m off Point Grey in the Georgia Strait

2018 Neptune 5B *Deployment of levered floats off pile under 5 year IUL license 800 m off Point Grey Strait of Georgia to test full size system and experiment with various ways to achieve continuous power output from waves that are 2 to 10 seconds apart.*

2019 Nep 6

This complete wave engine uses the 'float on a pile" and the modified PTO with custom generator connected to a 20 kW resistor bank at sea. It will use the existing pile framework and the domed enclosure built for Neptune 2-5 and include a testing station on piles approximately 10 – 20 m away.
We hypothesize that this float on a pile with reducer gearing will enable the power from the float in all tides (5 m) and wave heights (up to 2 m) levels will be transferred to the direct drive PTO, and that modifications Saved to this PC ill produce continuous power from waves as small as 0.1 m high as well as other hypotheses.
The testing station will allow 3rd parties to verify the amount of power produced from waves of various sizes. See: https://www.neptunewave.ca/test-results

2019 Neptune 6 *Float on Pile &Test Station, provides interested potential partners to verify with their testing equipment continuous power from various verifiable wave sizes.*

2020 Neptune 7 24 float-piston wave engine add-on to offshore wind turbine concept

From a feasibility study for otary.be to add-on to wind turbines that have a 6 + m mono-pile, are +/- 106 m high with a rotor diameter of +/-154 m. The Wave Engine is 25 m high by 30 m dia. Scatter chart below shows projected, not verified, power values.

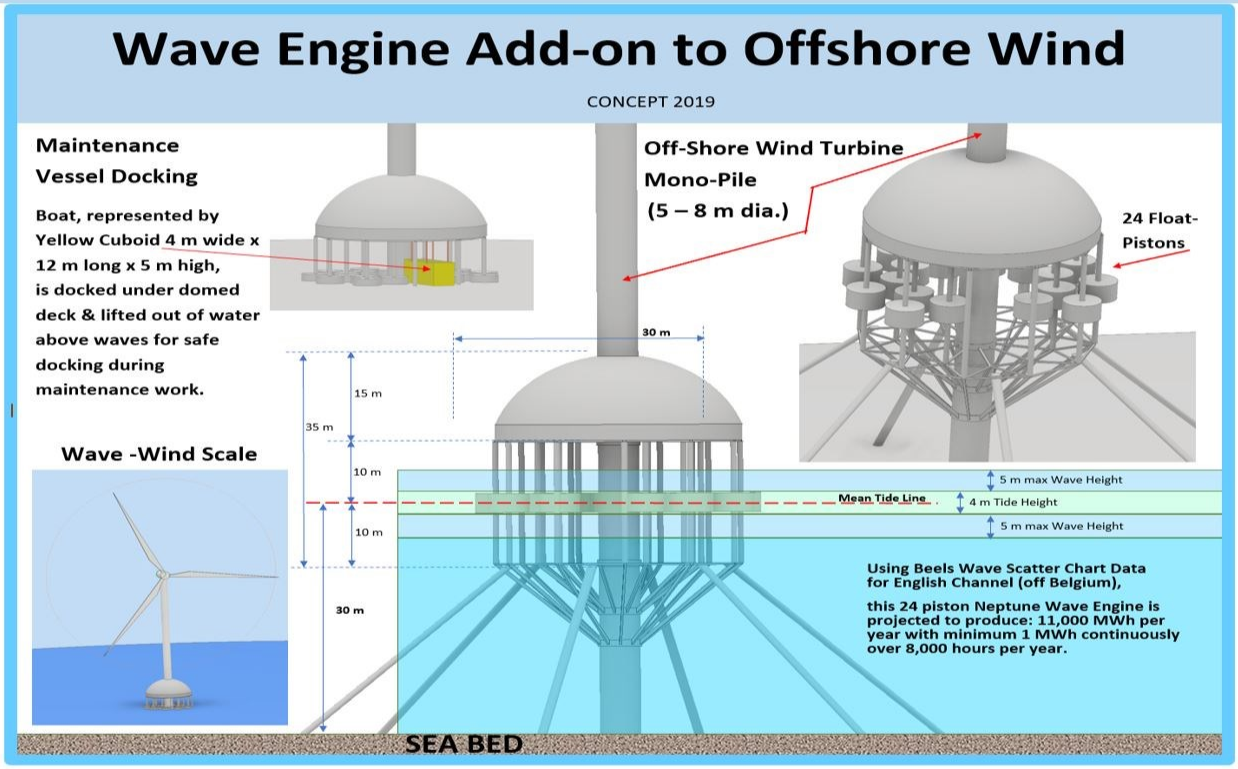


Chart 3	kWh / cell	NEPTUNE WAVE ENGINE MODEL: **OT-245019** - NPRv: **1 to 4 MW** - CFv: **.72**							Actual Hrs/ yr =	8766
W. Height [m]	Tm [s]	0 -2.5	2.5 - 3.5	3.5 - 4.5	4.5 -5.5	5.5 - 6.5	6.5 - 7.5	7.5 - 8.5	**Sum**	**Sum**
W. H.Avg.	**W. Period Avg.**	1.25	3	4	5	6	7	8	**kWh / W.H.**	**Hours / W.H.**
0.10										
0.25		5,160	194,347	397,617	104,999	11,824	1,106	161	715,214	1,893
0.75		3,096	789,429	1,984,215	648,570	123,187	16,585	967	3,566,049	3,265
1.25			62,346	1,713,977	1,158,345	196,712	24,877	1,612	3,157,870	1,930
1.75				426,640	1,166,601	303,990	34,828	1,129	1,933,188	934
2.25				11,609	619,934	386,975	69,656	1,451	1,089,625	451
2.75					161,756	276,687	101,351	3,547	543,341	198
3.25					13,415	128,562	62,285	8,384	212,646	70
3.75						29,023	19,349	12,093	60,465	18
4.25						7,310	9,398	5,482	22,190	6
4.75							3,501		3,501	0.88
>5.0									**Sum MWh / yr.**	**Sum Hr. / yr.**
	Sum kWh / W.P.	8,255	1,046,123	4,534,058	3,873,620	1,464,271	342,934	34,828	**11,304**	**8,766**

Location: English Channel off Westhinder, Belgium

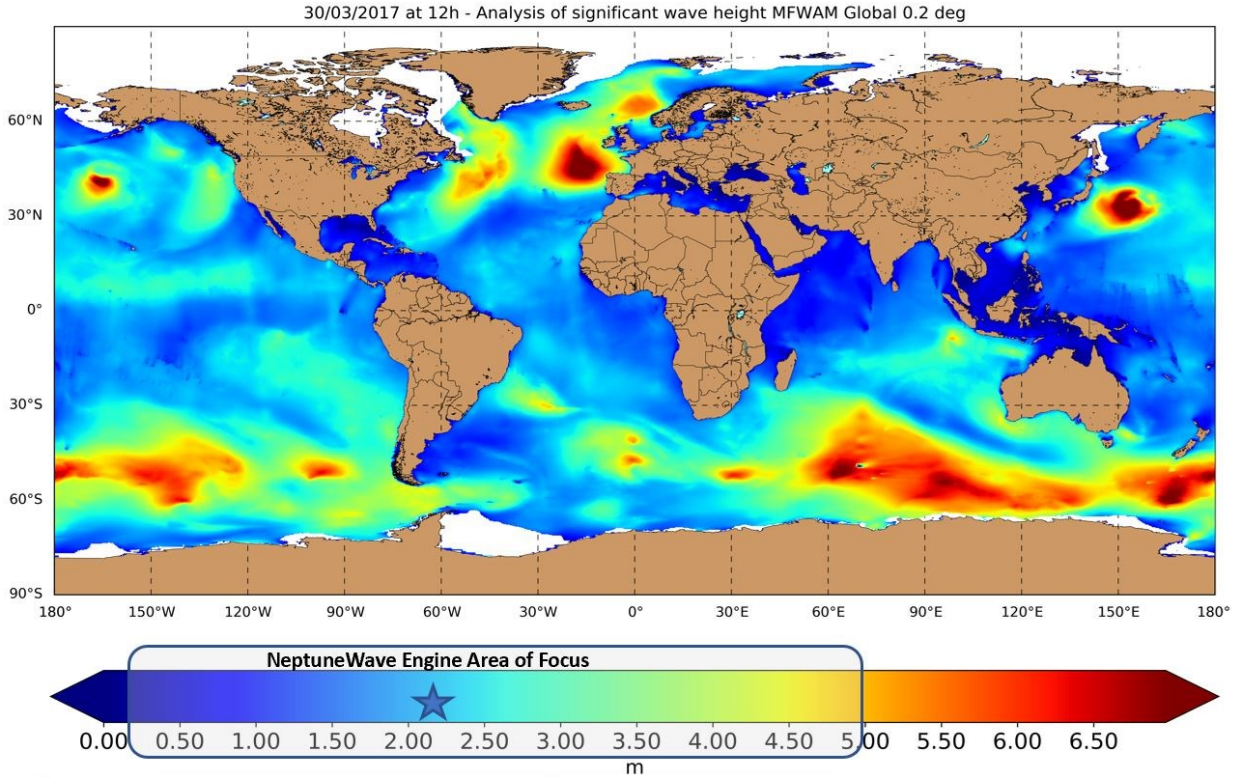
Global Wave Energy

OMAE 2010 reports:[1] Global wave energy potential = 3.7 TW per year, hence x 8766 hours = 32,434 TWh per year.

Globally 356,000 km of Coastline[2] with 2.4 Billion people (2018) within 100 km. [2]
Japan = 29,751 km (7), USA = 19,924 km (9)

Average Available Energy Density:
Wave[3] = 5,000 watts / sq. m (4 m high wave by 4 s wave period) formula: $E = \frac{1}{8}\rho g H^2$
Wind[4] = 500 watts / sq. m (50 m high @ 7.5 m/s)
Hence: 4 m high waves are 10 X more energy dense / sq. m, than wind 50 m high at 7.5 m/s (17 mph).

Note: if use horizontal wave transport energy at 7.5 m/s = 80,000 watts per lin. m wave crest: $P = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e$



1 *ASSESSING THE GLOBAL WAVE ENERGY POTENTIAL*, 2010: OMAE2010-20473, ASME.

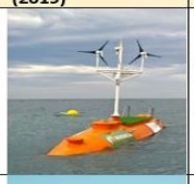
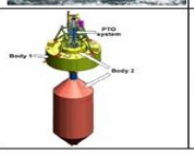
2 CIA World Factbook (2017-01-17) http://world.bymap.org/Coastlines.html

3 Vertical Wave Force, kinetic lift water + potential water weight energy at wave crest, J per sq. m / wave period = watts http://marinespecies.org/introduced/wiki/Wave_energy_converters_in_coastal_structures
If use wave horizontal transport energy at 7.5 m/2 = 80,000 watts per linear m of wave crest !

4 *David Darling PhD Encyclopedia*
https://www.daviddarling.info/encyclopedia/W/AE_wind_power_density.html

UPDATED: Top 10 2014
Wave Energy Converter Devices

Summary: 2019 STATUS of these 10 Device Companies:
8 of 10 = Closed or Bankrupt
2 of 10 = Still Open, But NO POWER DATA yet, both Oscillating Water Column types: #1 & #9.

Device	Photo (2019)	Power per Unit (kW)	Wave Movement	Depth (m)	Size	Name & Type (2019)	2019 Status (2019)
1. Oceantec (UPDATED from 2014) https://tethys.pnnl.gov/annex-iv-sites/oceantec-wave-energy-converter-14-prototype		500 & 10 = .5 & .01 MW	heave (& surge)	30–50 (N/A)	medium	"Spar Buoy" FLOATING OSCILATING WATER COLUMN *Updated:* LINEAR ABSORBER or ATTENUATOR *Name:* "Wave Energy Converter 1:4 prototype"	**NO POWER DATA Sept. 2019** New Unit deployed 2017
2. Pelamis https://www.powertechnology.com/projects/pelamis		750 = .75 MW	surge & heave	50–70	medium	Pelamis Wave Energy Converter FLOATING ATTENUATOR	**BANKRUPT Nov 2014** After 12 years intensive development
3. P P Converter No reference on internet	No Image Does not exist	3,620 = 3.6 MW	heave	deep	large	N/A	**DOES NOT EXIST 2019** -- Google search
4. Seabased https://www.seabased.com/		15 = .015 MW	heave	30–50	small	SG17 SeaBased SEABED POINT ABSORBER with linear generator	**CLOSED Jan 2019**
5. Wave Dragon http://www.wavedragon.net/		7,000 7 MW	Over-topping	30–50	large	Wave Dragon FLOATING OVER TOPPING	**SCRAPPED 2011** Continued proposals & reports until 2017
6. Aqua Buoy https://www.greencarcongress.com/2007/09/finavera-renewa.html		250 = .25 MW	heave	>50	small	AQUA BuOY 2.0 FLOATING POINT ABSORBER	**OUT OF BUSINESS 2010** Unit sank in 2007 Co. surrendered Permits 2009 Co. sold all assets 2010
7. AWS (Archimedes Wave Swing) https://openei.org/wiki/MHK_Technologies/Archimedes_Wave_Swing		2,320 = 2.3 MW	heave	40–100	medium	Archimedes Wave Swing SEABED PRESSURE DIFFERENTIAL	**OUT OF WEC BUSINESS 2014** Last News 2016 Offers Consulting Services
8. Langlee http://www.langleewp.com/		1,665 = 1.6 MW	oscillating flaps	deep	medium	Langlee Wave Energy Converter "water wings" SEABED HORIZONTAL WAVE SURGE	**CLOSED IN 2016** Last News Release March 2014
9. OE Buoy http://www.oceanenergy.ie/oe-technology1/platform		2,800 = 2.8 MW	oscillating column	deep	medium	OceanEnergy Buoy *Based on Masuda's "Backward Bent Duct Buoy"* FLOATING OSCILATING WATER COLUMN	**NO POWER DATA Sept. 2019** Last Press release Jan. 2018 "signed deal to deploy OE Buoy in Hawaii"
10. Wavebob https://en.wikipedia.org/wiki/Wavebob		1,000 = 1 MW	heave	deep	medium	Wavebob FLOATING POINT ABSORBER	**CLOSED IN 2013**

Source: Eugen Ruse: Evaluation of the Wave Energy Conversion Efficiency in Various Coastal Environments, *Energies* 2014, *7*, 4002-4018; doi:10.3390/en7064002

"Photo (2019)", "**Name &Type 2019**", "**2019 Status**" columns, & **Web URLs**, were added and **dated** by NeptuneWave.ca, 09-2019