IS THIS THE RIGHT TIME FOR LARGE SCALE WAVE ENERGY CONVERSION?

Rik van Hemmen, Mike Raftery, Martin & Ottaway, Inc.

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ABSTRACT

Wave Energy Conversion (WEC) should be part of the sustainable energy toolbox. Solar and wind are now competitive sustainable technologies, but, even though there have been Wave Energy Conversion development efforts as long as there have been solar and industrial wind efforts, wave energy conversion simply has never made it out of the experimental starting blocks. This paper examines prior efforts and examines why they failed and describes emerging technologies that could make large scale wave energy conversion competitive with present state of the art large scale wind and solar.

KEY WORDS

Renewable Energy, Marine Renewable Energy, Wave Energy Converter, WEC, Marine Hydrokinetic, MHK, SurfWEC, Future Energy, Sustainable Energy

TERMINOLOGY

ABS: American Bureau of Shipping: Standards, Certification, and Classification Agency
Aliquot: A 1.2km x 1.2km portion of a 4.8km x 4.8km BOEM – OCS permit block
BOEM: Bureau of Ocean Energy Management, Division of the US Department of Interior
DNV-GL: Det Norske Veritas - Germanischer Lloyd: Standards, Certification, and Classification Agency
DNV-OSS-312: document pertaining to: Certification of Tidal and Wave Energy Converters
EMEC: European Marine Energy Centre
ERFD: European Fund for Regional Development
IEC: International Electrotechnical Commission
IEC TC-114: IEC Technical Committee for Marine Energy Standards development and management
LCOE: Levelized Cost of Energy
Name Plate Capacity: See Plate Capacity
NJBIN: New Jersey Business Incubation Network
NJ BPU: New Jersey Board of Public Utilities
OCS: Outer Continental Shelf
OREC: Offshore Renewable Energy Certificate (New Jersey state program)
OSW: Offshore Wind
PJM: Pennsylvania-New Jersey-Maryland Interconnection, a Regional Transmission Operator (RTO), part of the Eastern Interconnection electric power grid management companies

Plate Capacity: Nameplate capacity, Rated Capacity, maximum electric power output of a device, not continuously produced using solar, wind, or wave energy conversion devices
PTO: Power takeoff
SCADA: Supervisory Control and Data Acquisition
SURFWEC: Surf-making Wave Energy Converter
TLP: Tension Leg Platform
USGS: United States Geological Survey
USPTO: United States Patent and Trade Office
Wave Hub: 48MW Wave power research facility opened off Hayle, Cornwall U.K. in 2010
WEC: Wave Energy Converter
WEHD: Wave Energy Harnessing Device (Raftery acronym associated with patent US8093736B2)

INTRODUCTION: THE ARC OF ENERGY INNOVATION

Energy is the central driver of human development. Human progress is directly related to the way that humans harvest, store, and use energy. In human terms, access to energy is power.

Initially humans only harvested energy through hunting and gathering. In primitive societies, humans learned to store some foods to use when there was limited fresh food available. This allowed humans to migrate from equatorial climates, where food is continuously available, to parts of the world where most of the food supply is dependent upon the weather in various seasons.

With the discovery of fire, humans were able to extend the productive part of their day with light and heat they could control and improve their productivity by building tools from metals.

Harnessing of wind allowed humans to increase their transport efficiency through sails, and the invention of steam-powered machines allowed the creation of more productive factories.

At that stage, humanity began to transition from a wood to a coal-powered society. In the early 1900's, humans started transitioning from coal to more efficient oil and gas-powered machines and, in rough terms, it can be noted that in the late 1900's humanity started taking an interest in more sustainable energy sources for society.

The demarcation lines are not all that sharp; in the mid 1900's nuclear power arrived as a sustainable energy source and other forms of sustainable energy have existed for thousands of years in the form of sail transportation, hydro and windmill power. Even, wood and other biomass energy in its purest forms is also sustainable power with recorded uses dating back tens of thousands of years.

Today, in the twenty first century, there is a definitive trend to dominance of sustainable power over hydrocarbon power. It is actually quite difficult to define sustainable power, but there are two approaches to defining it. The first approach is to define sustainable power as power options and innovations that continually reduce humanity's overall CO2 emissions. The other approach is to list technologies that are somehow recognized as sustainable power.

The latter option is much more open for debate, but, for the sake of discussion, we provide a list of sustainable power technologies in Table 1.

Type	Theoretical Viability	Technical Viability	Truly Sustainable?	Carbon Neutral?	Carbon Zero?	Cost Competitive?	Installed Base
Hydro	viable	viable	mostly	yes	yes, nearly	yes	at maximum
Landbased Wind	viable	viable	yes	yes	yes, nearly	yes	fights for land
Thermal Solar	viable	viable	yes, mostly	yes	yes, nearly	maybe	fights for land
PV Solar	viable	viable	yes, mostly	yes	yes, nearly	yes	fights for land
Rooftop PV	viable	viable	yes	yes	yes, really close	close	growing
Tidal	viable	sometimes	yes, mostly	yes	yes, nearly	occasionally	occasional
Offshore Wind	viable	viable	yes	yes	yes, nearly	not quite yet	growing
Biomass	viable	viable	in right application	could be	depends	sometimes	modest
Corn Ethanol	poor	viable	nope	not really	not really	nope	too high
Algae	questionable	possible	unknown	could be	could be	unknown	zero
Nuclear Fission	viable	viable	yes, mostly	yes	yes, but …	could be	probably too low
Nuclear Fusion	viable	maybe in 30 years	yes	yes	yes	who knows?	zero
Wave Energy Conversion	viable	in some cases	yes, mostly	yes	yes	never at large scale	minuscule
SurfWEC	viable	early development	yes	yes	yes	yes	zero

Table 1: Sustainable Power Technology Comparison

This paper does not delve deeply into the comparisons of the various sustainable technologies. It can be claimed that everybody may have their favorites for various reasons. However, the table does provide an interesting illustration. While wind and solar are now established players in the sustainable energy basket, wave energy has not found a commercial footing. This is a shame since wave energy is available in extremely large quantities comparable to, or even in excess of, wind and solar. Wind and solar both require more space to harvest energy than waves, and solar has very little generation capacity during cloudy days and no generation capacity at night.

This paper will provide some guidance as to why WEC has not yet become economically viable and will provide some suggestions to make WEC viable (based on both lessons learned in the past and emerging technologies) and become a component in a wind, wave, and solar sustainable energy triad.

Developing a sustainable power society (reduced carbon or even zero carbon) is more complicated than simply producing energy. The large inertial force against the switch from a hydrocarbon-based (more accurately; fossil fuel) energy system to a sustainable energy system is related to the remarkable versatility of hydrocarbons as a fuel[1]. Hydrocarbons are inherently a form of predictably available stored energy that can be readily transported prior to use. Meanwhile, sustainable energy struggles with predictability, harvesting, storage and transport. Instead of living within a society where one energy type size fits all, to achieve sustainability, we now have to switch to a society where we have to build systems and infrastructures where energy gets delivered through a wide variety of approaches. While this may lead to confusion and frustration, there is a bright side to the switch to sustainable energy. At first glance, the bright side might be seen as the opportunity to save our planet from the ill effects of global warming, but there is actually a much brighter side to this societal change. The switch to sustainable energy is a very significant opportunity to increase the world's standard of living and to fight the tyranny of monopolies. Energy is power, but if energy can be harvested from many sources, energy becomes social power.

A well designed and versatile sustainable energy society will reduce the blackmail effect of oil rich countries and will even allow energy generation down to the individual level, thereby providing greater opportunities for freedom and energy fairness.

To some extent, this is occurring today where small communities like the Orkney Islands, small villages in Africa, or even individual home owners in New Jersey are starting to set their own energy destinies.

The most effective way to achieve this is to ensure that there are as many sustainable energy approaches as possible and to let them compete on a technological level. This is an entirely new approach. Today's sustainable technologies harvest a "free" resource (sun, waves, and wind) and feed it into a community network (the electric grid) for distribution to consumers. In a system such as this, the most innovative technologies will win until another innovator shows up with a better idea. This is in sharp contrast to the last century that focused entirely on ensuring access to fossil fuels (oil and gas) by hook or by crook.

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[1] In a very large portion of human energy needs, obtaining energy is not the problem. Storage and transport is the problem, and we may still be using a large amount of non-fossil fuel hydrocarbons in future storage and transport applications. Those hydrocarbons could be synthetic, biomass, or grown but would compete with other stored energy concepts based on their economics and sustainability.

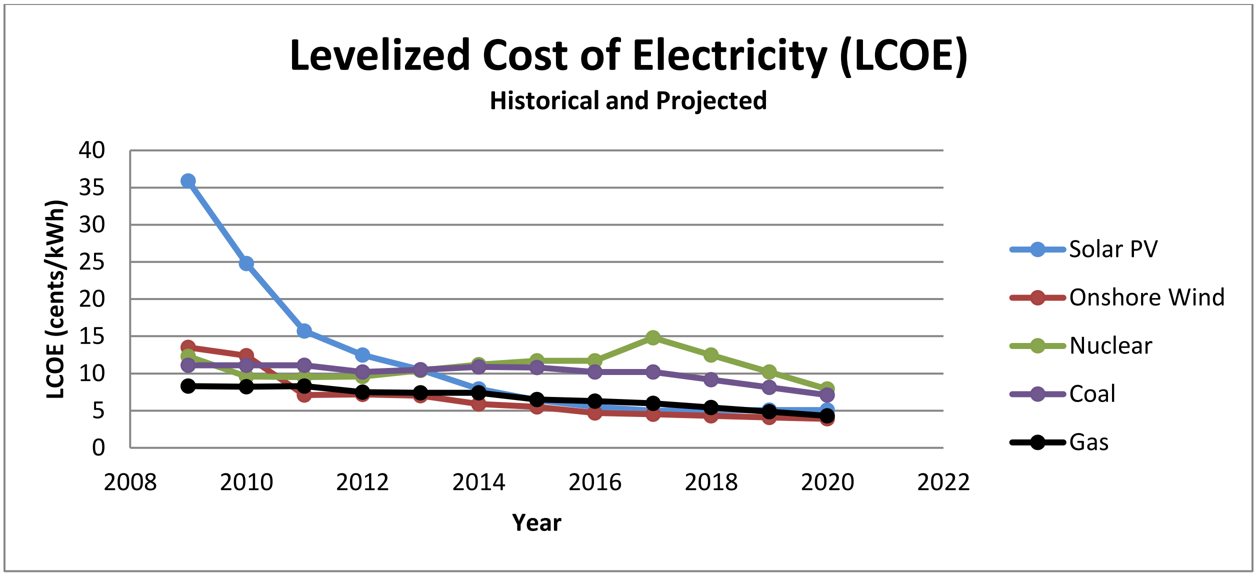

Figure 1: Comparison of Levelized Cost of Energy of various producers (source: energyinnovation.org). Offshore wind is still in the 16 c/kWh range

Figure 1 shows that, today, land-based wind and solar harvesting approaches are starting to beat the fossil fuel energy (oil and gas) approach, but where is the wave harvesting approach?

WAVE HARVESTING HISTORY

Wave energy conversion has been discussed for decades, if not longer. A Martin & Ottaway survey has identified at least 28 wave energy conversion efforts where substantial expenditures have been made to harvest ocean waves.

Table 2 provides a list of efforts.

It can be argued that none of those efforts have been successful, but, in the arc of technology, that would be an incorrect statement. Flight did not happen in one try, steamship propulsion took decades to become commercially viable, and submarines were first tested in the Revolutionary War, but did not become viable until World War I. Occasionally a new technology existed for many years, but did not catch on until there was a specific use for it in warfare, or until it became commercially viable.

To date, it can be stated that there have been a substantial number of efforts at developing wave energy conversion, but they have not shown an ability to be commercially viable.

	Project	Trial Result	Location	Technical Viability	Commercial Viability	Utility Viability	Largest Proven Capacity (kW)	One Size Fits All?
1	**LIMPET 250 kW (2000 – present, Oscillating Water Column/terminating)**	18 years	UK	good	marginal	local power supply only	250	no
2	**Mutriku 300 kW (2009 – present, Oscillating Water Column/terminating)**	9 years	Spain	good	marginal	local power only	300	no
3	**Bolt Sea Power Fred Olsen device 50 kW (2000 - present, point absorber reel device)**	working	Multiple	good	marginal	local power only	50	no
4	**Ocean Power Technologies 15 kW (1984 – present, point absorber)**	working	Multiple	good	marginal	special need only	15	no
5	**Wavesub 5MW (not confirmed) (2009 – present, submerged point absorber using wave circulation with an apparent shoaling effect)**	not known	UK	poor	poor	poor	5	no
6	**Uppsala University WEC Concept 30 kW (2007 – present, Point Absorber with linear electric generator)**	working	Sweden	good	marginal	local power only	30	no
7	**Resolute Marine Energy (RME)- AirWEC 2 kW (2009 - present, point absorber)**	working	US	good	marginal	special need only	2	no
8	**ARCHIMEDES WAVE SWING 25 kW - 250 kW (2004 – present, submerged point absorber)**	unknown	UK	marginal	poor	poor	0	no
9	**AW-ENERGY WAVEROLLER 1MW (1993 – present, attenuator)**	unknown	Multiple	marginal	unknown	poor	0	no
10	**Carnegie Clean Energy, CETO (2008-present, submerged point absorber)**	working	Australia	good	unknown	local power only	250	close
11	**WELLO OY, PENGUIN 500 kW (2008 – present, attenuator)**	planned	Indonesia	unknown	marginal	local power only		no
12	**CorPower Ocean 250 kW (2009 – present, point absorber)**	under trial	Sweden	unknown	marginal	local power only		unknown
13	**Laminaria 200 kW (2014 – present, point absorber)**	planned	UK	good	marginal	local power only		unknown
14	**Eco Wave Power (EWP) 10 kW (2011 – present, attenuator)**	working	Black Sea	good	marginal	special need only	10	no
15	**OE Buoy (OE35) 1.25MW, 2008 - present OWC**	unknown	Hawaii	good	unknown	unknown	0	no
	Inactive Systems							
16	**Salter Duck (6MW?) (1973, attenuator)**	never trialed		good	marginal	local power only	0	possibly
17	**OSPREY 2MW (1995, OWC)**	sank	Scotland	poor	poor	poor	0	possibly
18	**Wavebob 1MW (1999 – 2013, point absorber)**	14 years	UK	good	marginal	poor	unknown	possibly
19	**Finavera AquaBuOY 250 kW (2007, point absorber)**	sank	OR	marginal	marginal	unknown	0	no
20	**Oregon State University SeaBeav I 10kW (2008, point absorber)**	worked	OR	marginal	poor	poor	10	no
21	**Trident Energy - Direct Energy Conversion Module (DECM) 20 kW (2009, attenuator)**	capsized	UK	poor	poor	poor	20	no
22	**AQUAMARINE OYSTER 800 kW (2012, Flapper/attenuator)**	worked	UK	marginal	poor	poor	315	no
23	**Pelamis 750 kW (1998 - 2012, attenuator)**	unknown	Portugal	marginal	poor	poor	unknown	no
24	**Ecole Centrale de Nantes - SEAREV G1 70 kW? (2002 - ?, point absorber/termination)**	never trialed	France	marginal	poor	poor	0	no
25	**Seatricity – Oceanus 2, 1MW (2016, point absorber)**	unknown	UK	poor	poor	poor	unknown	no
26	**Wavedragon 1.5MW – (2003-2012, overtopping)**	scale test	Denmark	good	marginal	poor	0	no
27	**SDE Energy/WERPO**	worked	Israel	good	marginal	special need	10	no
28	**TAPCHAN - (1985- 1988 overtopping)**	worked, destroyed by storm	Norway	challenging	marginal	local power only	350	no

Table 2: Historical Wave Energy Conversion projects[2]

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[2] The authors have made a best effort to evaluate these projects based on available information. Many of these projects are very poorly documented. The authors would welcome corrections and additions to improve this table.

For wave energy conversion, commercial viability depends on cost to produce the system and on the ability to earn back the cost to produce the system by selling the energy. This is basic economics, and low cost to produce the system and high sales prices for energy are a ticket to great wealth, but as long as the cost to produce is more than the ability to earn back the investment, a technology is not viable.

This is the central consideration, but it assumes that the technology can actually reliably produce energy, and wave energy conversion has not had a very successful track record at that either.

As Table 2 shows, some efforts have simply failed to produce any energy. Indeed, some of the efforts sunk before they even had a chance to produce energy. This is frustrating, but is far from atypical for any new technology, especially in a challenging environment like maritime. In engineering development, the flip side to failure is the window to new insights. Failures like this should really be regarded as normal. Engineers deal with such failures by stating: “if it were easy, everybody would do it”. At the same time, it should also be noted that a significant portion of these efforts simply were not engineered by teams with hardcore maritime experience and, as such, should barely be counted as engineering development efforts. Unfortunately, another portion of WEC efforts can only be described as snake oil on the level of cold fusion or commercial ocean plastic recovery.

However, there have been a number of efforts that have produced energy and show promise to reliably produce energy. In particular, Ocean Power Technologies in NJ and Bolt Sea Power show promise for small scale wave energy production. At the engineering level, it is noted that these efforts have made excellent progress in engineering sufficiently rugged components to withstand the rigors of ocean deployment.

Unfortunately, while they are achieving engineering successes, the ability to be commercially viable is less attractive and this is related to a physics barrier that exists in conventional ocean wave energy conversion. These systems may be able to reliably harvest small amounts of energy, but they cannot be economically scaled to utility level power production.

THE WAVE HARVESTING PHYSICAL BARRIER

Wave harvesting is simply more difficult from a physics point of view than other free energy harvesting systems. This physical barrier does not exist in wind or solar where a larger windmill or more solar acreage will simply produce more energy and where stronger winds (up to a limit) and more sun will also generate more energy. Wave energy conversion is trickier because it has to deal with waves, which tend to be irregular and difficult to predict. Instead of simply capturing wind or solar energy like butterflies in a fancy static net, a wave energy conversion device rides in the energy that it is supposed to harvest. Wave energy conversion is like trying to capture butterflies in a fancy free flying net.

As such, the physics and engineering of wave energy conversion is substantially more complex than the physics of wind energy or solar energy. Headway is being made with regard to engineering, but there is one particular and specifically vexing problem with WEC in scaling.

With solar power, scaling considerations are not terribly important.[3] A wafer is the minimum size and panel sizes may be a manufacturing consideration, but one large panel will generate as much energy as 10 smaller panels that, combined, contain the same number of wafers, regardless of the amount of sunlight.

However, in wave energy harvesting, 10 small WEC devices will not generate the same energy as one equivalent larger WEC device.

WEC physics are such that in small waves 10 small devices are more effective than one equivalent large device while in large waves the larger device will probably be more physically effective and certainly more cost effective.

In essence, a large WEC will simply have to wait for large waves before it becomes any good at harvesting energy while a larger number of smaller WEC's of equivalent capacity will become ineffective when the waves become larger and, moreover, will be less effective simply based on economies of scale.

Therefore, WEC device developers face a devil's dilemma, build small devices that can capture small and large waves, but that are not cost effective when scaling up to utility level power production, or build large devices that are only effective when there are large waves.

Today some developers such as Ocean Power have effective WEC devices, and to generate utility level amounts of power they could build and deploy a very large number of these devices, but the cost per kW is too high for these relatively small devices to make them cost effective for utility level power generation. If Ocean Power were to scale up the size of their WEC's, the cost per kW would go down, but they would need much larger waves than are generally found in the oceans to be cost effective.

Therefore, WEC will not become commercially viable at the utility level until a WEC device can be developed that will be both large and effective at harvesting smaller waves.

Basically, WEC requires a large tunable device that can, somehow, efficiently convert both small waves and large waves. This is technically frustrating, but there is another way to achieve the same end and that is to convert small waves to large waves and then use a large device to harvest the converted waves.

This type of wave conversion is a very well-established principle and occurs with every wave that comes ashore at a beach.

It is called the breaking (or shoaling) wave effect and is the reason why surfers can only surf near the shore.

Ocean waves can be made to break anywhere as soon as an ocean wave encounters shallow water, and this can be accomplished by mooring a platform below the ocean surface.

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[3] Scaling in wind power is somewhat more complex, but still quite manageable. Bigger is more efficient, and big is just as effective at catching light winds as small.

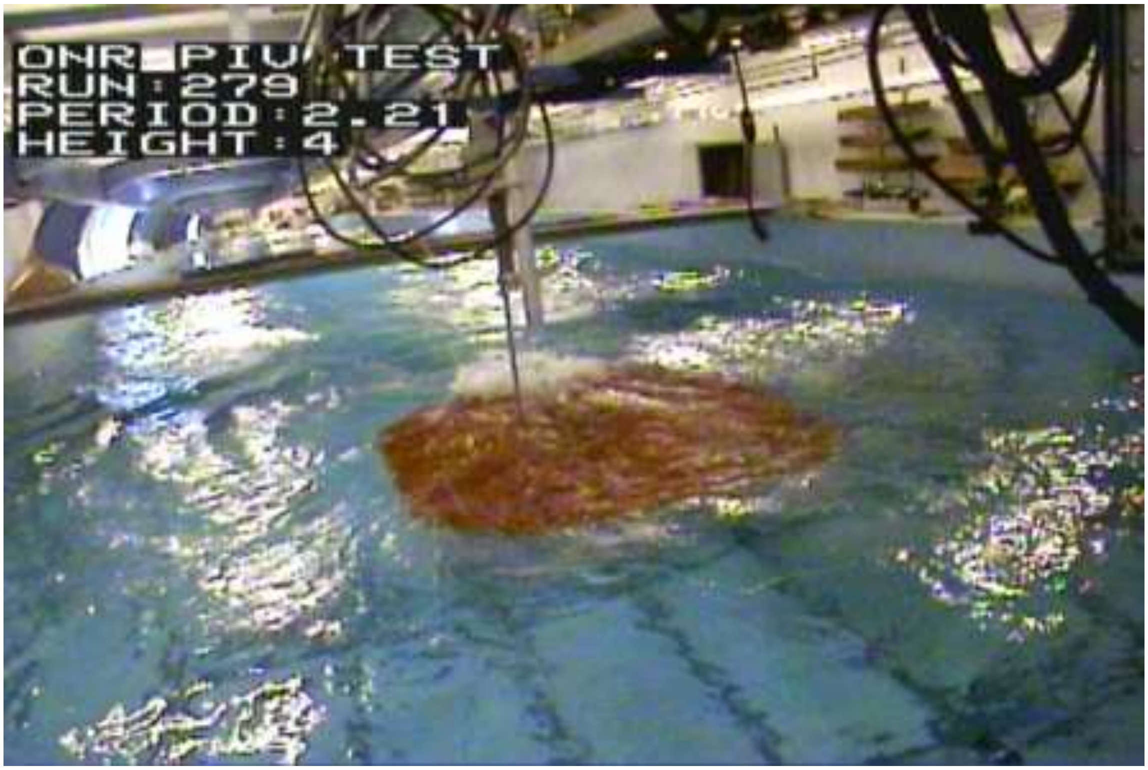

Figure 2: The Stevens submerged platform test. Note the wave breaking over the platform.

The use of a variable-depth platform to create surf conditions offshore was researched in the model basin at Stevens Institute of Technology from 2010 through 2011 with a grant from the Office of Naval Research (Dr. Ronald Joslin – program manager). The platform had a foam core that made the platform buoyant and it was moored and pulled under the surface by 4 – 1200lb capacity cable pullers. Figure 2 shows the shoaling effect where the platform was moored parallel to the still surface at a depth of 15cm (6 inches). The recorded incoming spectral waves were 10.4cm (4.1 inches) high at 2.21 second periods.

The wave crossing the platform, in effect, compresses the wave, but no energy in the wave is gained or lost[4]. As figure 3 shows, there is an increase in power density because the wave stalls over the platform.

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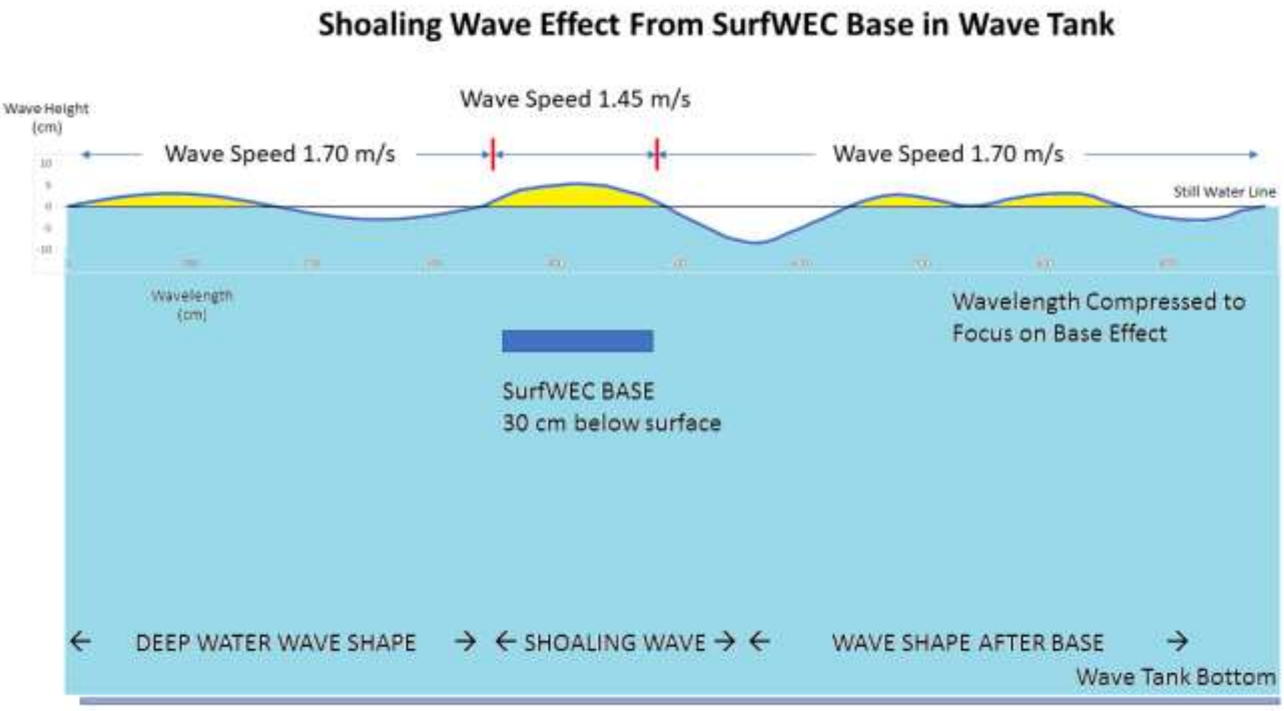
[4] There is a small loss, but it is insignificant.



Shoaling Wave Effect From SurfWEC Base in Wave Tank

Figure 3: This cross-sectional representation of a wave tank shows how a SurfWEC base concentrates wave power over the base based on wave-wire data.

Therefore, if one were to create an artificial beach in the ocean, there would be breaking waves and these waves would be more harvestable. However, since waves break at a water depth of roughly twice the wave height, and since the ocean has tides and variable size waves, this beach would have to be moveable.

Mike Raftery's studies of this problem at Stevens resulted in a WEC patent in 2012 now called SurfWEC.

SurfWEC CONCEPT

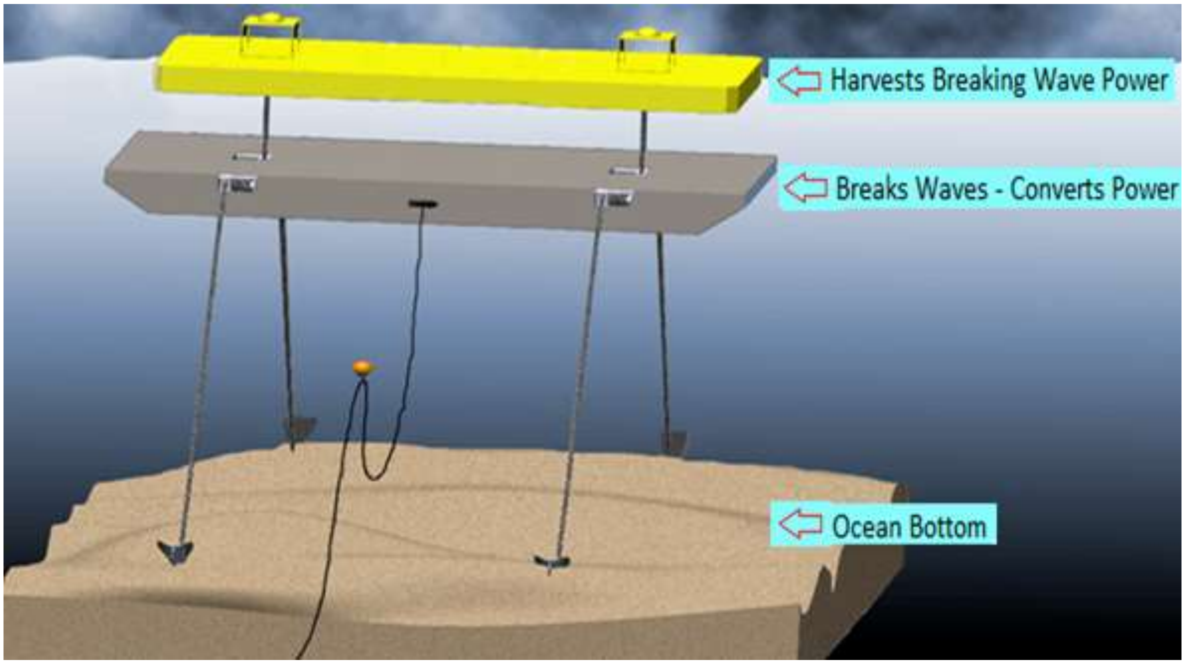


Figure 4: Surf-making Wave Energy Converter (SurfWEC)

The SurfWEC consists of two prime components; one freely moving component (float, point-absorber, “the bobber”) and one moored component (the variable-depth barge or “the base”).

The SurfWEC system works by raising or lowering the base below the water surface until the passing waves achieve optimal height and surfing wave shape. The bobber is moved by these surfing waves and the wave energy is converted to electricity using a regenerative braking system inside the base.

The SurfWEC system causes the bobber to move back and forth 10 to 30 meters per wave in average conditions (5 to 10 second period waves) where the bobbers in other existing WEC systems only move 1 to 3 meters per wave in identical offshore wave conditions. This extreme change in bobber motion is achieved by creating surf waves offshore.

Unlike the surfer near shore, this system sets up an oscillating motion between the bobber and base as the waves pass on their way towards shore. When the bobber has surfed as far as the wave can push it, the power takeoff (PTO) winch lines connected to the bobber are quickly rewound and pay out again as the bobber passes over the base heading towards the next incoming wave.

The motion control and energy conversion subsystem is the most complex component, but is based on a modified regenerative braking system that is used in hybrid cars and tractor trailers that are achieving very high levels of reliability. The other components are very typical marine components (semi-submersible barges, marine winches, synthetic lines, marine-rated generators, floating oil platform anchors, seafloor power cables used for offshore wind systems). The system is an integration effort and technically challenging, but has no significant ocean engineering challenges.

Ocean wave energy conversion involves the simple relationship between mass and velocity. The term "marine hydrokinetic" is often used to describe these systems and abbreviated "MHK" systems. The more water mass a WEC displaces per second, the more power it puts into the energy storage and conversion subsystems.

The biggest problem in Wave Energy Conversion is that ocean waves are not easy to harness efficiently and safely. SurfWEC converts offshore seas and swell to surf waves in mild to moderate waves to address the efficiency issues and lowers itself near the seafloor to avoid damage from waves in storms to address the safety issues.

Once mild to moderate waves are converted to surf, the energy is concentrated and the bobber can be moved forward and backward much farther per wave than in swell or seas. When storm waves begin impacting the bobber, the base automatically lowers itself near the seafloor, which gives the bobber more line to move and eliminates almost all of the wave energy impacting the base. The bobber can be flooded and lowered beneath the surface in less than 10 minutes to continue harnessing wave energy in extreme storms and raised back to the surface in less than 4 hours using bilge pumps after the storm passes.

The SurfWEC design addresses a number of the traditional Wave Energy Converter problems:

1. A "regenerative braking" control subsystem is continually tuned, which allows it to harvest all waves of all sizes and frequencies more effectively.[5]
2. The base-and-bobber, two-part system, creates surf and the bobber moves one direction while the base moves the other direction which creates maximum power takeoff. This is called Two-Body Harmonic Motion where the parts move 180 degrees out of phase. The Two-Body Harmonic Motions were discovered during wave tank testing at Stevens Institute of Technology and submitted as part of the "continuous phase control feature" in the Wave Energy Harnessing Device, US patent 8093736B2, which is the basis for the SurfWEC design. (To see Two-Body Harmonic Motions go to: https://web.stevens.edu/seahorsepower/video/)
3. SurfWEC units are easy to deploy. SurfWEC units fit into existing marine infrastructure allowing multiple units to be towed to mooring sites with one tugboat.
4. The depth control subsystem allows the variable-depth base to convert a very wide range of incoming waves to surf. The four-point mooring allows the base deck to be sloped to create optimal surf conditions for power conversion. The only conditions where the base will not convert incoming waves to surf are in completely flat seas and in extremely large waves. In extremely large wave conditions, the base will lower itself near the seafloor, which extends the distance between the base and float to give the float a wider range of motion to keep

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[5] The tuning of this system is an excellent neural network application.

generating power. Converting incoming waves to surf is not needed for power conversion in large wave conditions.

5. The base compartments are pressurized to compensate for surrounding pressure from seawater. Pressure sensors continuously monitor the surrounding seawater and inert gas is used to keep pressure inside the base slightly higher than seawater pressure outside the base to stop seawater from getting into the base. The inert pressurized gas and hydraulic fluid distribution system is a closed-loop system, which connects pumps, motors, compressors, gas cylinders, accumulators, valves, filters, and storage tanks. The large storage tanks allow the unit to operate for long periods of time, up to a year, without routine maintenance. Major overhauls at five years have been included in the operational budget.
6. The energy conversion system incorporates an energy storage subsystem in each unit capable of storing over 500 kilowatt-hours of energy. In some scenarios, energy storage is commercially important and enables SurfWEC operators to sell both electric power and electric power capacity.
7. The units do not require specialized vessels or large staging areas for installation and maintenance like offshore wind turbines. Standard tugboats are sufficient for all installation and maintenance operations.

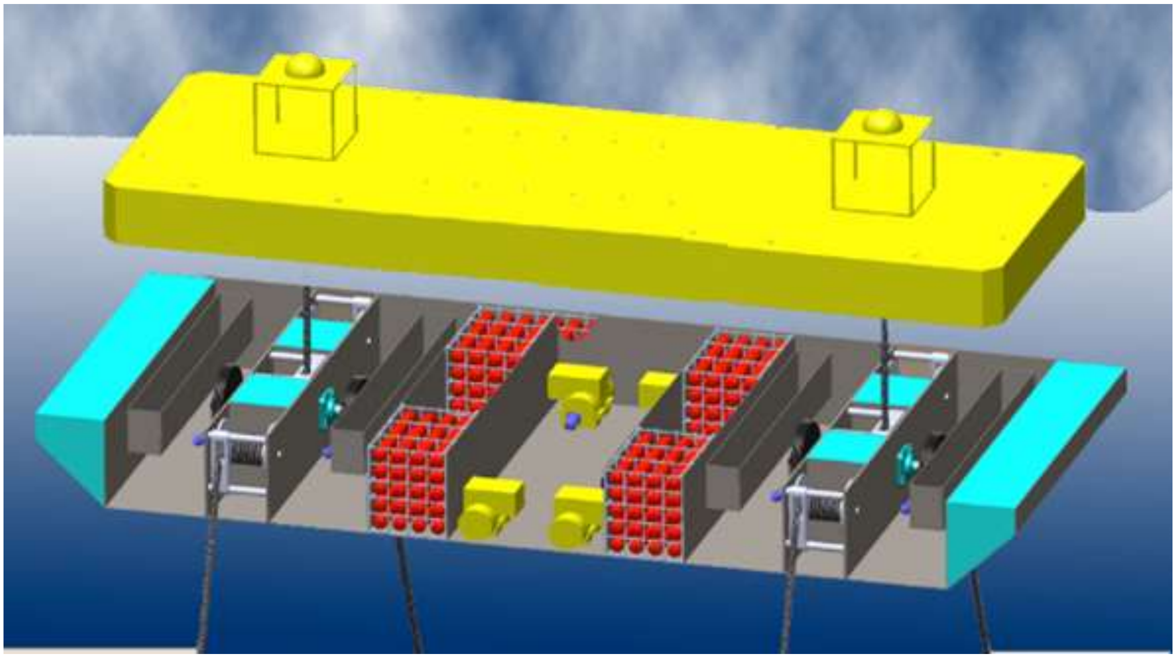

Figure 5: SurfWEC full-scale internal components

Very often inventions cannot be commercially developed because there are missing technological components, but this system is an assembly made completely of existing technologies. All the supporting technology for the SurfWEC is readily available today, which means that today is the time to put the pieces together and to add wave energy recovery to the commercially viable sustainable energy basket in the United States and globally.

SurfWEC ECONOMIC EVALUTION

SurfWEC is remarkably cost effective. A 5 MW name plate capacity unit will cost about $7.5 million ($1.50/Watt) to build and deploy at commercial scale (200+ units). Deployed off New Jersey, one unit would produce an average power output of 1 MW or more on an annual basis (8760+ MWh per year).

To achieve this average level of power output off the East Coast of the United States, the base from Figure 1. needs to be 60m long x 30m wide to create surf from all directions and the yellow bobber (essentially a non-hydrodynamic, large surfboard to absorb maximum wave energy) needs to be 50m x 20m x 2m.[6]

The average wavelengths off the East Coast are approximately 60 meters to 100 meters (6 to 8 second period "deep water" waves). Mooring the units broadside to the predominant wave direction and converting 0.5 meter to 1 meter-high waves to surf waves would displace the bobber approximately 24 meters from the still water position, in an oscillating motion (12 meters forward then 12 meters back) in 8 second waves for an average bobber velocity of 3 meters per second (3 m/s).

A very wide range of wave conditions provide an average bobber velocity of 3 m/s due to the displacement to wave period relationship. (This is one of those weird mathematical realities where the bobber surfs for about 1/4 of the wavelength). This movement (Mass with Velocity) provides power that is harnessed by the PTO system. A small portion of the energy stored during payout of the PTO winch lines is used to rewind the PTO winch lines as the wave is not pulling on the bobber after the wave crest passes the bobber.

At a one-meter draft, the bobber displaces approximately 1,000,000 kg of water.

The average kinetic energy in the oscillating motion of the bobber-base system will then be:

1,000,000 kg x ((3m/s)^2)/2 = 4,500,000 joules of energy

The reason we can use the linear equation for kinetic energy for this calculation (KE = (mv^2)/2) is that the calculation is only accounting for wave surge, a forward and backward motion along a line. Like a surfer, the bobber is lifted by the surf wave then surged forward. The lift is a small percentage of the total motion, so we do not use it in the power conversion calculations.

The SurfWEC design dimensions are optimized for US Atlantic and Pacific offshore conditions where Wave Energy Conversion is economical, which reduces the need for multiple SurfWEC sizes.

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[6] The shape and dimensions of the unit continue to be optimized, but the overall size (displacement) will always be the same for Atlantic Ocean waves.

Harnessing and converting this energy to electricity at an overall conversion efficiency of 24% (taking into account the hydrodynamics, PTO efficiency, generator efficiency, and power use during rewind), results in the following output:

4,500,000 joules x 0.24/second = 1.08 Megawatts (MW) annual average electricity production

This equates to 9460 Megawatt-hours (MWh) per year. This calculation accounts for flat sea periods, as more than 1.08 MW will be produced during times when wave heights exceed 1 meter, which will compensate for time when seas are flat. Historically, hours per year with waves over 1 meter high off New Jersey (at potential SurfWEC locations) are more than 10 times the hours per year when seas are flat.

A billing rate of $125 per MWh (12.5 c/kWh) is a reasonable near-future projection for a carbon-free electric power production source.

The electricity produced by this system then produces significant revenue (9460 MWh x $125 per MWh ($0.125 per kWh) = $1,205,000 per unit per year). That revenue allows for $205,000 per unit, per year, for maintenance and $1 million per unit, per year for amortization and profit.

Since ocean wave energy conversion is a carbon-free form of electricity production, it should also qualify for renewable energy credits, which are near $200 per MWh for SREC in New Jersey as of August 2018, which would make the system even more cost effective. The Offshore Renewable Energy Certificates (ORECs) currently being negotiated for Offshore Wind Farms connected to the grid in New Jersey will have similar values to the New Jersey SREC program, and WEC systems should be included in this program.

A unit like this would cost about $1.5 per watt of name plate capacity to build, install, and connect to the U.S. power grid ($7.5M/5 MW) at industrial scale (200 or more units), which is very cost effective against wind (at $3 per watt) and PV solar (at $5 per watt). This lower cost is due to the large power capacity, availability, and efficiency of each SurfWEC unit. The SurfWEC units do not require land purchase and will have no visual impact from shore, based on proposed installation locations off New Jersey. There are also tremendous economies of scale if multiple units are installed as farms.

In a Levelized Cost of Energy (LCOE) approach, the SurfWEC graphs as follows:

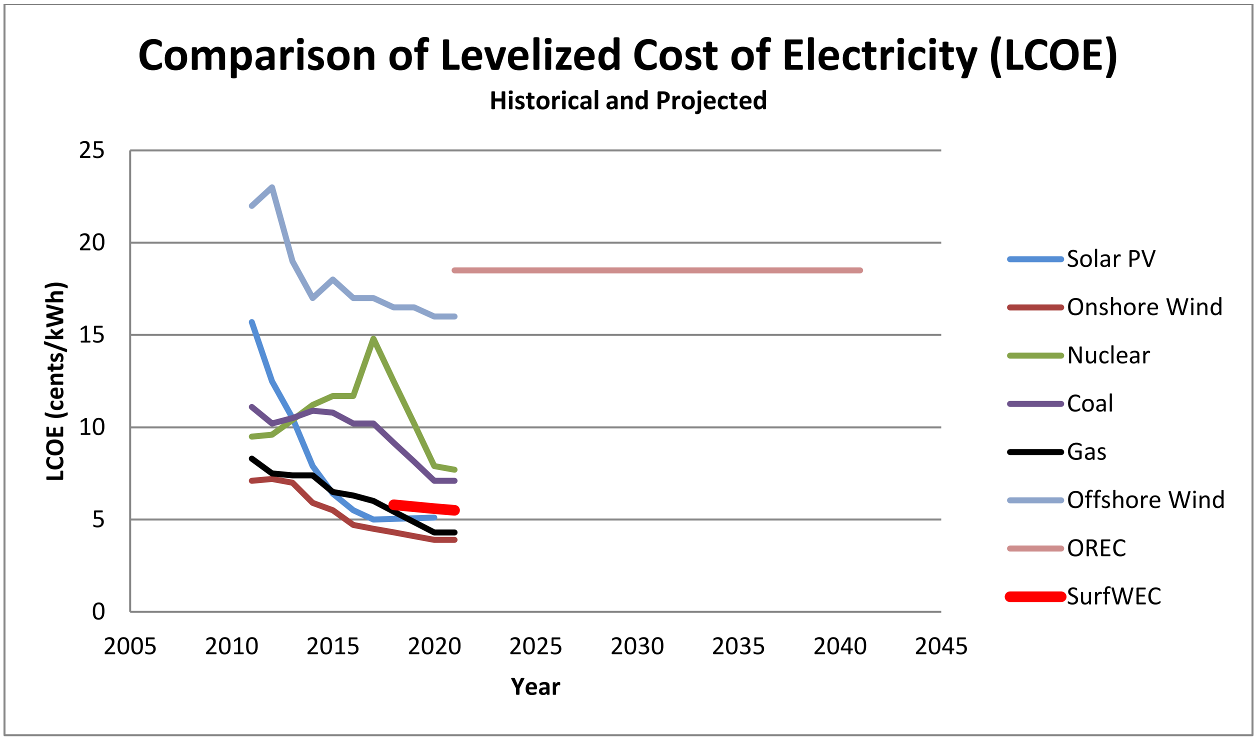

Figure 6: LCOE for SurfWEC as compared to the other technologies

SurfWEC IN A POWER PLANT CONFIGURATION

Large power generation projects require consideration by a large number of stake holders. It is of interest to consider the configuration of a SurfWEC power plant. A truly powerful wave farm is analogous to positioning a swath of 200 SurfWEC units over an area of 12 miles (North to South) by 2 miles (East to West) off an ocean coast over a continental shelf.

A wave farm like this produces 200 MW on average and up to 1000 MW in optimal conditions. In New Jersey, this wave farm will produce 200 MW or more 80% of the time.

Figure 7 depicts the arrangement of such a farm off the coast of New Jersey, positioned 24 miles offshore. The wave farm has a high voltage seafloor cable that ties into a static inverter substation and then into the grid. For the sake of this example, the seafloor cable ties into the decommissioned Oyster Creek Nuclear power plant infrastructure. The Oyster Creek plant had a capacity of 619 MW. As such, this wave farm provides comparable levels of power. At a distance of 24 miles, the wave farm would be invisible from shore.

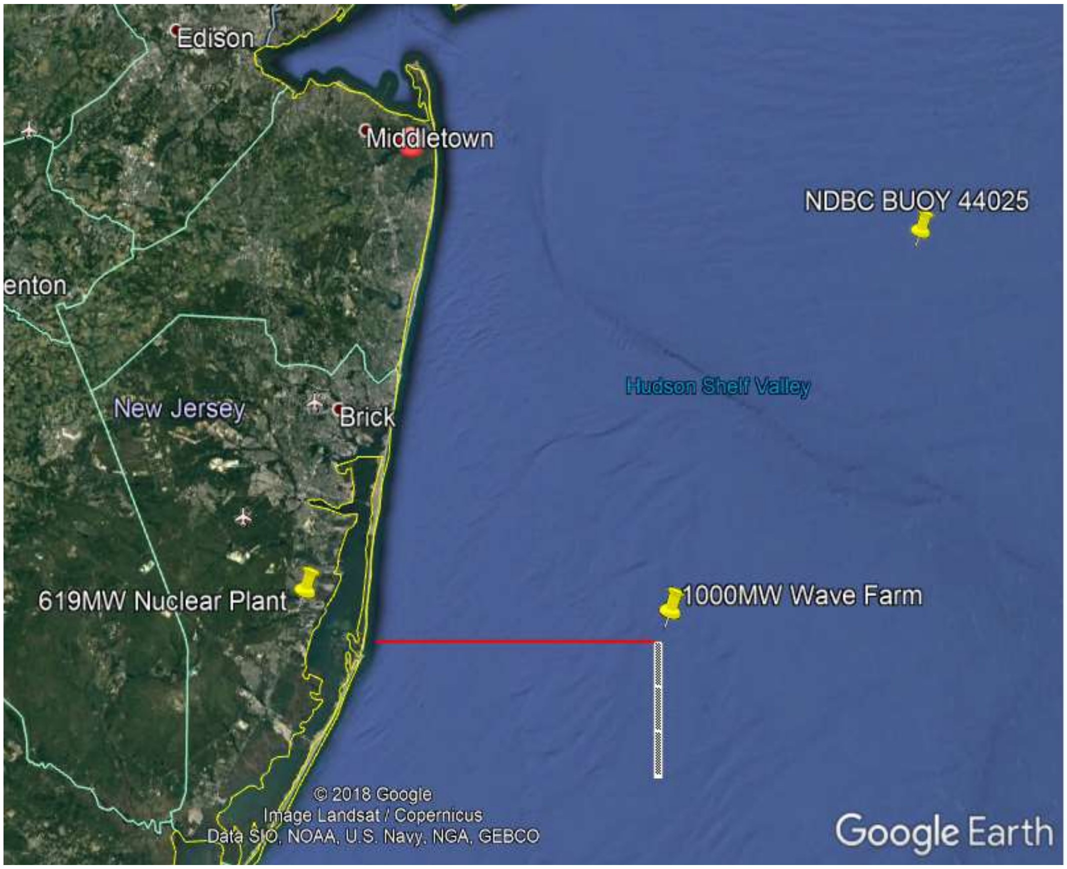

Figure 7: Scaled view of a 1000 MW wave farm off New Jersey

The system is designed to remain fully operational in waves over 10 meters (33 feet) high off New Jersey. The minimal mooring depth for industrial scale electricity production is 20 meters (66 feet). There is no maximum mooring depth, but installation costs increase with mooring depth, and most practical installation sites are over the US Outer Continental Shelf.

A SurfWEC installation like this is not a solid wall of SurfWECs, but rather a dispersed field of SurfWECs with large gaps between them.

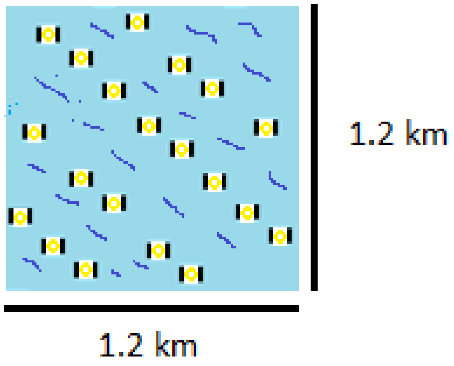

Figure 8: Typical Relative distance between SurfWEC units in a BOEM Aliquot

This wave farm only harvests a small portion of the waves that arrive at New Jersey shores. As long as there is back country distribution for electrical power, this wave farm approach can provide a significant portion of the electrical power for the US Northeast. Especially during peak production periods, wave farm power can also be used for hydrogen or ammonia production thereby providing transportable fuel for more distant or mobile uses. (See: https://martinottaway.com/rhemmen/hydrogen-as-the-ultimate-fuel-part-2/). There is sufficient space along the New Jersey Coast for 8 or more of these wave farms, while leaving ample space and gaps for fishing and ocean navigation.

Wave farming provides a significant economic opportunity for a state like New Jersey. Many of the SurfWEC components are high value components and some are large and benefit from local assembly, which by itself would skew to local production. At the very least, SurfWEC maintenance will be locally performed. It is expected that SurfWEC will require shore maintenance once every four years, which would be accomplished in a shore facility near the wave farm. The moving and maintenance of these units are maritime jobs, which tend to be higher paying, higher skill jobs, which is inherently attractive to an economy like New Jersey.

The beach/reef like configuration of these SurfWECs will enhance ocean life and allow it to function as nurseries thereby enhancing US economic zone fisheries.[7]

While the primary design function is industrial scale electricity production, harnessing wave energy reduces wave energy behind the wave farm; therefore, wave impacts behind the wave farm are reduced, which is something to consider in a global warming environment.

SurfWEC to SUPERCHARGE OFFSHORE WIND

While a standalone offshore wind farm can be a cost-effective solution for providing sustainable energy, combining SurfWEC with an offshore wind farm is a much more interesting approach.

Offshore infrastructure is expensive, especially with regard to seafloor cable installation and shore inverters and to combine wind and wave provides some very significant cost advantage.

The following cost savings are envisioned:

1. Reduced lease costs due to multi use for a single lease
2. Reduced permitting cost
3. Reduced infrastructure cost
4. Potentially, offshore stored energy capacity for both wind and wave energy
5. Enhanced power availability for the system since wind and wave energy are related, but do not necessarily coincide at one point in time
6. Reduced logistics costs with regard to maintenance
7. Possible reduced wave impact on offshore wind farms

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[7] Since SurfWECs are drag devices antifouling coatings are not required.

As such, an integrated wind/wave approach on OREC certificate investment would be significantly more profitable, or allow viable offshore power production at a lower OREC cost.

CONCLUSION

Sustainable energy development and production is marching along rapidly. Wave Energy Conversion has trailed these developments due to technical and physical barriers that have only recently been surmounted. A relatively modest investment in utility level WEC technology today can provide tremendous economic and social benefits in the next decade. While utility level WEC has significant potential with regard to return on investment (ROI), co-location with offshore wind shows even more significant economic potential.

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