POTENTIAL MARINE RENEWABLE ENERGY RESEARCH AND DEVELOPMENT OPPORTUNITIES AT PACIFIC MARINE ENERGY CENTER

by
Steve DeWitt

A capstone submitted to Johns Hopkins University in conformity with the requirements for the degree of Master of Science in Energy Policy and Climate

Baltimore, Maryland
December 2017

Executive Summary

This capstone project is closely aligned with the professional goals of the author as an engineer within the Department of Energy's (DOE) Water Power Technology Office (WPTO). The WPTO has two primary branches, conventional hydropower and marine hydro-kinetics (MHK), which includes energy derived from tidal, wave, ocean current and ocean thermal systems. The author's responsibilities within the WPTO are primarily focused on managing various MHK projects including the design and construction of Pacific Marine Energy Center - South Energy Test Site (PMEC-SETS). PMEC-SETS is an open ocean, grid connected wave energy test facility that is currently in the design phase, and scheduled to begin operations off the coast of Newport Oregon in 2021. This project is a collaborative effort amongst Oregon State University, the lead organization, the DOE National Renewable Energy Laboratory, the European Marine Energy Centre, and various other industry partners.

The Johns Hopkins Energy Policy and Climate Change Master of Science degree program has helped prepare the author for employment with the DOE, and is a good complement to the author's engineering education. The curriculum focus on energy and environmental policies is particularly useful in understanding the numerous policy challenges faced in obtaining the necessary permits, and gaining concurrence from federal and state regulatory agencies, as well as local stakeholders, to build an offshore energy facility such as PMEC-SETS. If the DOE elects to further develop the testing capabilities at PMEC-SETS, as discussed in this paper, significant effort would be required to work through the potential federal regulatory and local stakeholder issues.

Acknowledgements

I would like to recognize the inspiration and advice from my wonderful wife Francine. Her encouragement to tackle a new degree, and her support in my academic endeavors have been invaluable. She understands and appreciates my passionate interests in renewable energy technologies and climate change, and listens patiently to my many stories about new things that I learn every day.

My studies at Johns Hopkins have been enlightening, and in the words of Albert Einstein, “The more I learn, the more I realize how much I don't know.”


Table of Contents

Introduction

The Department of Energy (DOE) has estimated that the total recoverable wave energy resource along the United State (U.S.) continental shelf of 1,170 TWh/yr or approximately thirty percent of the nation's total annual electricity usage (Hagerman & Scott, 2011). This estimate is based on many assumptions regarding wave energy device density and wave directionality, and is currently under review at the DOE, but the estimate is good measure of the magnitude of the resource relative to the U.S. electrical load. These energy sources are particularly valuable since 50% of the U.S. population lives within 50 miles of the coast, thus minimizing the electrical transmission costs between the source and load. Globally, approximately three billion people that live within 200 km of the coast, and migration is likely to cause this number to double by 2025 (Huckerby, Jeffrey, de Andres, & Finlay, 2016). Wave energy resources are also particularly valuable since they are capable to provide more consistent power levels, compared to wind and solar resources, and thus in general require less energy storage electrical power.

The Marine Hydrokinetic (MHK) industry is still in the research and development stage of technology development, but the global wave and tidal energy market is forecasted to reach 300 GW, powering 250 million homes, and to create over 680,000 jobs globally by 2050 (Huckerby, Jeffrey, de Andres, & Finlay, 2016). Because of their sustained economic investments in offshore marine renewable energy research and development, at least 100 GW of that growth will projected to come principally from the United Kingdom (U.K.) (Magagna & Uihlein, 2015).

In order for the U.S. to compete in this global market, sustained government investment is required to establish MHK energy technologies as a cost competitive alternative within U.S. energy markets. Determining the most efficient means to extract ocean energy from the waves requires a significant amount of research and development (R&D). The U.S. has recently made a $35M investment in wave energy advanced technologies to fund the construction and initial operation of a full scale, open-ocean, grid connected wave energy test facility off the coast of Newport Oregon referred to as Pacific Marine Energy Center - South Energy Test Site (PMEC-SETS). The design and development of this test site, led by Oregon State University (OSU), will complement the OSU indoor wave energy test facilities and their faculty expertise in oceanography R&D.

Testing offshore energy technologies under realistic conditions is a necessary endeavor to optimize design concepts. Successful testing and demonstration of different design concepts helps shorten innovation time and development activities. Testing enables increased efficiency and reduced the levelized cost of energy (LCoE). It also is important in the increased understanding of environmental impact and in the development of environmental monitoring technologies. Lastly is important in the demonstration of sustained reliable operations and the development of maintenance strategies and procedures.

The objective of this study is to answer the question: is there a consensus amongst industry, academic, and government personnel working in offshore renewable energy regarding what renewable energy technologies, in addition to wave energy, would benefit from testing in the open ocean environment at PMEC-SETS? To determine if there exists a consensus regarding what technologies would benefit from open ocean research and development testing at PMEC-SETS, a survey was utilized to provide an objective measure of stakeholders' recommendations.

Methods

The survey issued to stakeholders listed six potential offshore renewable energy technologies that could benefit from testing at PMEC-SETS as part of U.S. research and development programs. Specifically:

1. Offshore compressed air energy storage systems integrated with wave energy array for power smoothing to improve grid integration
2. Hydrogen generation systems
3. Floating wind turbines (FWTs)
4. Arrays compromised of both wind turbines and wave energy converters (WECs)
5. Hybrid system of offshore wind turbines on platform stabilized by WECs
6. Hybrid system of offshore solar panels on platform stabilized by WECs.

These ideas for future opportunities were developed based on review of academic and commercial literature of potential future enhancements of renewable offshore energy power systems for electrical grid applications as well as applications for alternate wave energy applications such as hydrogen generation. The survey also allowed for the participants to suggest technologies other than the six listed here.

To enable the survey participants to objectively score the potential increases in testing capabilities at PMEC-SETS, various attributes were identified in the survey based on the some of the more salient advantages and challenges of testing in an open ocean environment. The survey participants were directed to score each attribute for each of these six technologies, and any other technologies that they recommended for inclusion in PMEC-SETS testing infrastructure as high, medium, or low. The scores where converted into scores of 3, 2, 1 respectively and transferred to an excel database for statistical analysis. The entire survey, including the attribute scoring table, is contained in appendix one.

The survey was provided to the participants via an email with the survey table as an attached document. The survey was also distributed by the European Marine Energy Centre (EMEC) via their listserv to technology developers in the European Union and U.K. In addition to the commercial technology developers, survey participants also included personnel working within U.S. federal government in the renewable marine energy sector such as the DOE national laboratories, DOE headquarters, Bureau of Ocean Energy Management (BOEM), National Ocean and Atmospheric Administration (NOAA), and U.S Fish and Wildlife Services (USFWS). Survey participants also included personnel from non-government organizations, university research organizations, electric utilities, as well the personnel working directly on the PMEC project. Survey participants were asked to forward the survey to any other interested personnel not included on the original distribution, which did result in increased participation. This method was particularly effective in reaching out to wave energy technology developers in the U.K., who are further along the development spectrum compared to the U.S., but for whom I did not have a lot of contact information. A complete list of organizations that responded to the survey is contained in appendix two.

To help ensure all survey participants knew the pertinent physical characteristics of the PMEC-SETS test berths, some of the more relevant characteristics were provided as background information. The survey also allowed the participants to rank the different technologies with respect to testing at PMEC-SETS to help differentiate the rankings of the recommendations. Lastly, the survey asked for participants to provide amplifying information to help explain the rationale for their recommendations. An informal polling of survey participants indicated that the survey on average took 20-30 minutes to complete.

Results

The below results in table one reflect the average scores from the respondents ranking of which capabilities they recommend for future development at PMEC-SETS. These rankings of the technologies provide their recommendations relative to one another. They do not imply that the respondents endorse any future increase in PMEC-SETS capabilities as "no change in capabilities" option was not included as part of the survey.

The results displayed here demonstrate that there was very little differentiation between the respondents' recommendations regarding different testing capabilities.

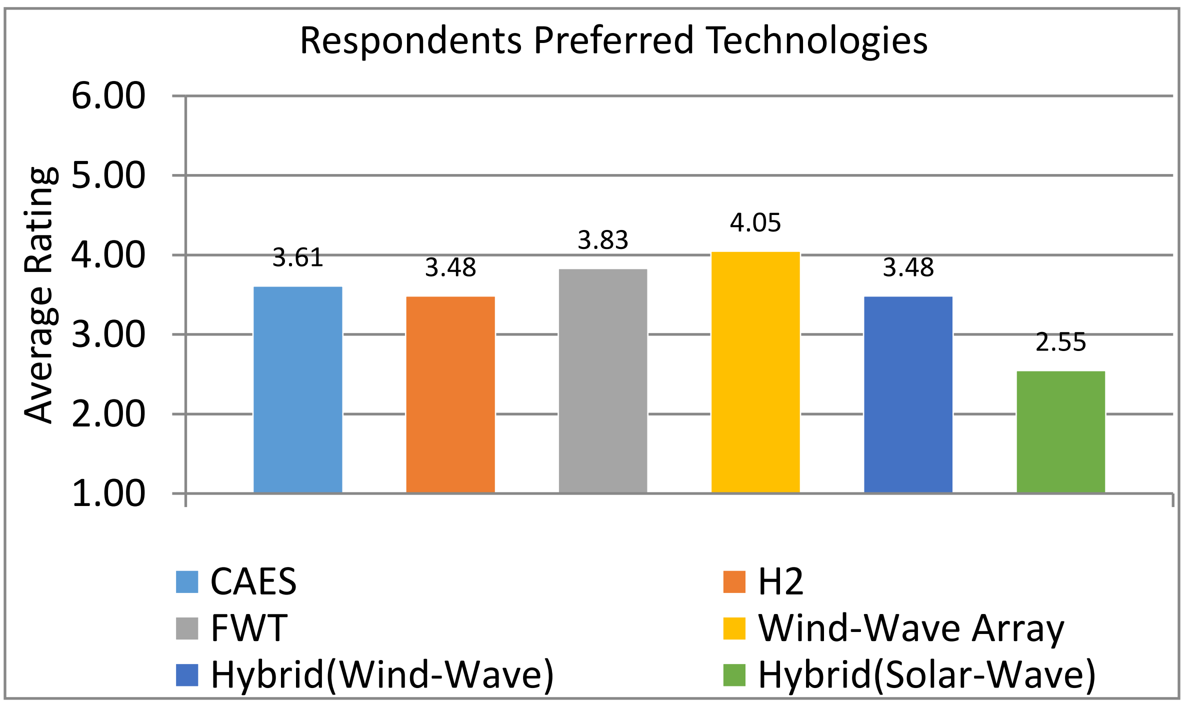

Table 1: Respondents' rankings of technologies for testing at PMEC Highest recommendation corresponds to score of six.

Only one technology, the hybrid system that integrates solar panels on an offshore platform stabilized by WECs, had an average score that was significantly different from the average scores of the other technologies. The combined average of the scores for all technologies was 3.50, as expected given choice of ranking 1-6 since 3.5 is the average of 1, 2, 3, 4, 5, 6. The hybrid solar-wave technology, with an average score of 2.55, was an outlier in that it was approximately two standard deviations (i.e., 2 x 0.52) from the composite mean score. This implies that the respondents clearly did not recommend developing the capability to conduct open ocean demonstrations of a hybrid solar-wave technology at PMEC-SETS. This does not totally discount the future value of this technology, as it might function well in an offshore wave environment that has consistently lower energy levels compared to PMEC-SETS.

The score for the array comprised of a mixture of FWTs and WECs arranged within an array to optimize total output power had an average score (4.05) that was slightly above one standard deviation (0.52) from the composite average scores of the other technologies (3.5) as shown in table two below. With a score that is greater than one standard deviation from the composite mean score, the respondents have indicated a preference for further developing this array concept through testing at PMEC-SETS compared to the other technologies. Though other considerations could preclude development of this testing capability at PMEC-SETS, the respondents consistently scored for this technology higher than the others. This consistency is shown in table two as this technology had the lowest variance (1.51) in the recommendation scores provided by the survey participants. Because there were only 35 respondents to this survey, there is not a high degree of confidence that these rankings are an accurate representation of the industry stakeholders.

	CAES	H2	FWT	Wind-Wave Array	Hybrid-Wind-Wave	Hybrid-Solar-Wave	Average
Technical R&D	2.09	2.16	2.22	2.19	2.06	1.53	2.04
Cost Reduction	2.00	2.06	2.19	2.16	2.00	1.47	1.98
Array Testing	1.94	1.84	1.94	2.09	1.97	1.47	1.88
Attract Investors	2.25	2.28	2.25	2.25	2.13	1.56	2.12
Environmental	2.28	2.31	2.38	2.38	2.19	1.69	2.20
Physical limits	2.06	2.13	1.97	2.00	2.00	1.72	1.98
Local Stakeholders	2.16	2.22	1.94	1.97	1.81	1.69	1.96
Federal Stakeholders	2.19	2.28	2.13	2.19	2.00	1.88	2.11
Average	2.12	2.16	2.13	2.15	2.02	1.63	2.03
Variance	2.38	2.78	1.90	1.51	2.14	2.04	

Table 2: Respondents' average rankings of each attribute for all technologies

The average scores for all the other technologies are within the range of 3.48-3.83, which is well within one standard deviation of the composite mean (3.5 +/- 0.52 = 2.98-4.02). This indicates that the respondents do not demonstrate a preference for developing any of these technologies at PMEC-SETS relative to one another. The scores associated with these technologies, which include offshore compressed air energy storage systems, hydrogen generation systems integrated with wave energy, FWTs, and hybrid system of FWT platform integrated with WECs, are essentially indistinguishable from one another with a total variance of 0.35 (=3.83-3.48), which is less than 6% of the total range of scores (= 0.35/6.0).

Another relevant point to make from this data set is that the two most preferred systems amongst the survey respondents both included FWTs, specifically the stand alone FWTs and the FWTs included within an array with WECs. The composite average of these two technologies equals 3.94 (= average of (3.83, 4.05)); which is approximately twenty percent above the composite average of the other four technologies, which equals 3.28 (= average of (2.55, 3.48, 3.48, 3.61)). To evaluate this difference between the composite averages of these groupings, and the other results noted above, an analysis of the survey results utilizing the specific attributes provided in the survey is warranted.

As discussed in the methods section above, the survey participants objectively scored the potential increases in testing capabilities at PMEC-SETS based on various attributes that were identified to reflect some of the more salient advantages and challenges of testing in an open ocean environment. As it turns out though, the survey data regarding the attributes did not provide any meaningful amplifying data. The average scores for each of the different technologies, excluding the hybrid solar-wave platform technology, across all attributes ranged from 2.02 to 2.16. The possible scores allowed for these categories 1, 2 and 3 corresponding to low, medium and high recommendations respectfully. This small variance in average scores directly reflects shows that for each attribute approximately the same number of survey participants recommended the technology as low as the number of survey participants that rated their recommended the technology as high, and thus the average scores were all approximately equal to the average of the possible options, i.e., two is the average of 1, 2, 3. The complete data table for all attribute averages is also shown in table two.

This was the case for each of the technologies, again excluding the hybrid solar-wave platform which had an average score of based on the attributes of 1.63. Again the solar hybrid scored significantly lower than the other technologies, and is not a viable consideration in evaluating future test capabilities at PMEC-SETS. In general, this technology scored low or medium for most attributes in all surveys resulting in a low composite score.

The highest score based on attributes was the 2.16 score associated with hydrogen generation. This was only slightly higher than the other technologies. This technology scored near the composite average in the respondents' preferred technology rankings, so in both scoring system is was near the average of other technologies, and not considered particularly important for future PMEC-SETS testing. The slightly higher composite score based on attributes of the hydrogen generation system directly reflects the slightly higher scores it received on average for the permitting attributes with both local and federal stakeholders, and on the expectation of lessons learned from environmental impact assessments.

Lastly, one other noteworthy result from the average scores of attributes is that the ability to gain valuable lessons learned with respect to the environmental impact of operating the various technologies at PMEC-SETS was consistently the highest score of all the attributes for all the technologies. The scoring for the environmental attribute was not significantly higher compared to the other attributes, but it is noteworthy because it is consistently higher. The average score for the environmental attribute across all technologies was 2.20 compared to the total range of scores for all technologies across all other attributes of 2.16-1.63.

Other specific technologies proposed by survey participants beyond the six that were included in the survey are as follows:

1. Desalination was suggested eleven times. Some participants raised the issue that for relatively large scale water production, a system designed to operate in shallow water by pumping water ashore for reverse osmosis plants, instead of using electricity, would be a more cost effective design. To test those designs additional berths that are shallower than PMEC-SETS are required. Similarly two respondents suggested sea water cooling water for buildings as an R&D area to consider, but the point was made that these systems also are in general better suited for shallow water.

2. Offshore aquaculture containing fin fish, clams, oysters, seaweed, macro-algae, etc. and powered by wave energy devices or floating wind platforms was suggested thirteen times. The point was made by some respondents that these types of alternate technologies do not need to connect to grid, and thus are not utilizing the power cables and electrical test capabilities of PMEC-SETS. One respondent commented that those these ideas do not necessarily use PMEC-SETS cables, they still might be good use of berths if otherwise the berths would remain empty to help generate the necessary revenue to sustain the facility.

3. Autonomous Underwater Vessels (AUVs) and Autonomous Surface Vessels (ASUVs) re-charging stations, ocean sensors, data centers, navigation aids, other national defense and non-defense low power applications in remote areas, all powered by WECs were mentioned fourteen times. Again more than one respondent commented that those these ideas would not necessarily use PMEC-SETS cables, but could be powered in parallel with the shore side load centers.

4. Ammonia production or other potential fuel (non-hydrogen) generation, e.g. synthetic gas from hydrogen, and transportation ashore was mentioned twice, and advanced and scaled prototype testing of ocean mineral resource extraction coupled with wave energy conversion was mentioned once. Again these do not directly utilize the PMEC-SETS cables.

5. Wave energy conversion system for disaster resilience was mentioned twice. One respondent mentioned that such a system could utilize ROVs to install mooring systems for rapid deployments. Again this does not directly utilize the PMEC-SETS cables.

6. Three respondents mentioned different variants of hybrid systems that utilize WECs and other offshore marine renewable energy systems. These hybrid design ideas included suggestions for systems with some combinations of wave energy and marine current turbines, tidal energy devices, and solar panels.

7. Six respondents suggested research and development efforts for wave energy systems that are integrated with energy storage at sea on an offshore platform/substation either above or below water or on shore. Some possible energy storage technologies include flow batteries or other suitable battery technologies such as super capacitors or fly-wheels. One respondent pointed out that such systems could be optimized based on the requirements of the grid system.

8. Three respondents suggested research and development efforts for different technologies that utilize WECs to power support systems for uses such as environmental monitoring and wave forecasting.

9. Lastly, one respondent suggested developing systems that utilize wave energy devices for carbon sequestration in the ocean.

The recommendations for these technologies were, in general, either high or medium for all attributes included in the survey. The average composite score for these suggested technologies across all attributes was 2.57 compared to the average scores or 2.03 for all other technologies specifically listed in the survey.

Discussion

The experience of the survey participants is informative to help evaluate investment priorities over the planned twenty-five life span of the PMEC-SETS test facility, and potential for future development opportunities of offshore energy Research and Development (R&D) at PMEC-SETS. Investment decisions for research and development organization are driven strongly by the commercial potential of emerging technologies, and this is driven largely on the projected levelized cost of energy (LCoE) for either the grid or alternate applications. It is only through full scale testing at an accredited test facility that investors will have the accurate and reliable data that they need to build the business case to justify their investments. Open-ocean testing to demonstrate the technical feasibility of complex systems operating in a very demanding environment is thus a critical element in the commercialization of ocean renewable energy technologies.

The survey results demonstrate that there is not a strong consensus amongst stakeholders working in the offshore renewable energy industry regarding what technologies would benefit from open-ocean R&D testing at PMEC-SETS test berths. Contributing to the lack of consensus amongst the stakeholders is that there are strong arguments both for and against expanding the testing capabilities at PMEC-SETS because of the inherent complexity of these systems as well as the permitting and financial challenges associated with testing large scale devices in the ocean. Only the array comprised of FWTs and WECs had an average score that was noticeably higher than the composite average scores of the other technologies. Since the score was one standard deviation from the composite mean score, the respondents have indicated a preference, though not what would be considered a strong consensus, for wave-wind array testing at PMEC-SETS.

To understand the challenges with building arrays of WECs and wind turbines, an appreciation of the challenges associated with design and operation of FWTs is required. FWTs are much more complicated to build and operate, and are exposed to a much larger loads, compared to offshore bottom fixed wind turbines. The additional complications and costs are balanced by their ability to capture the higher velocity wind energy found at further distances offshore. FWTs are typically required in water depths greater than fifty meters.

The main challenge for offshore FWTs is to build a structure capable of operating efficiently in the highly energetic ocean environment while producing electricity at a cost comparable to other renewable energy sources. By its nature, operating any technology in the open ocean is a complex and high risk endeavor, and adding significant complexity by having the wind turbine operate on a structure designed to remain relatively stable in the open ocean only further compounds that risk.

FWTs are highly engineered machines designed with components built to withstand the stresses induced by significant aerodynamic and hydrodynamic forces of the wind and waves. FWT designs must utilize advanced technology, materials and innovative designs to reduce component weight, maximize stability and optimize power generation. To reduce the significant financial risk associated with full scale production, rigorous testing of reduced scale prototypes is required to demonstrate reliable energy production for extended periods under real world conditions. In general, renewable energy technologies must develop innovative designs that increase power generation efficiency while achieving costs parity with other forms of electricity generation.

While many of the FWT's thousands of components are tested individually to ensure that they operate within their design limits, complete integrated system testing in the ocean environment is essential as part of the transition to commercialization. Typically, reduced scale testing is used to confirm and supplement the results of advanced aerodynamic and hydrodynamic computer models built to evaluate system operating dynamics. The design phase involves an iterative approach; both complex computer simulation models and reduced scale testing to advance designs. Lastly, full scale system testing, designed to test the dynamic response to the wind and wave forces the FWTs will potentially experience over their life cycle, is also necessary to assess the components' operation and reliability at commercial scale. The results of all these tests are used to demonstrate the reliability and cost-effectiveness of FWTs required for project financing.

Building arrays made of both WECs and FWTs such that the WECs are positioned to absorb energy from the waves before the waves interact with the FWT platform is thought to offer multiple advantages as listed below.

1. The offshore wind farms would obtain enlarged weather windows for Operation and Maintenance (O&M) tasks, by positioning the WECs to reduce the sea state in

the vicinity of the FWT. This minimizes downtime for maintenance and the associated costs by reducing the wave energy in the vicinity of the FWT and thus increasing the accessibility to the FWT via a service vessel. One study from 2015 showed that the wave height reductions achieved from placing WECs to absorb the majority of the wave energy brought an “improvement in the accessibility to the wind turbine by up to 18%, reaching levels of availability over 90%”. (Astariz & Iglesias, 2015)

2. The inclusion of co-located WECs into wind farms could accelerate the development of wave energy technologies, which would lead to reductions in the cost of wave energy as production levels increase as per a typical new technology learning curve.

3. In general, WECs are designed to continue to generate power even in storm conditions, while wind turbines are often designed to shut down in extreme wind conditions.

4. Having WEC absorb the wave energy will reduce the motion of the FWT platform, and thus the motion of wind turbine tower, compared to operating without the WECs. This in turn will increase the output power from the wind turbine as it operates more efficiently when the tower is steadier.

5. The combined output power from the wind and wave devices will have a less oscillations compared to the power output from only one type of these renewable

devices. Not only is the power output smoother, but it is there are also less periods of zero power output. The more constant the output power, the less reserve capacity generation is needed to ensure that there is sufficient generation power to meet expected demand. As the percentage of renewable energy suppling the grid increases, it is important to derive energy from diverse renewable energy sources that tend to balance out their individual oscillations. This reduction in the output power uncertainty enables grid operators to more effectively predict available generation power available to meet forecasted demand. The optimal mix of renewable energy sources at the lowest costs to the rate payers, depends on the specific resource availability in the area of interest.

All of these synergies from combining the wind and wave devices into a single array compensates for the additional costs of adding WECs.

One offshore wave energy R&D test site, Wave Hub, a grid-connected site approximately ten nautical miles off the north coast of Cornwall United Kingdom, completed the permitting requirements in 2014 to test a FWT in one of their four berths originally planned for wave energy device testing only. Because Wave Hub test berths were not fully utilized, investing in the ability to test FWTs was necessary to increase the facility's revenue. The decision was based on the projected growth in the "global cumulative capacity is expected to reach 11,800 MW by year-end 2015, and a forecast that the cumulative global offshore wind capacity could grow to more than 47,000 MW by 2020" (Tsouroukdissian, et al, 2016), and the ability to achieve an "LCOE as low as

£85/MWh by 2025" (Bradley, 2016). The multi-year permitting study approved the installation of a 6 MW offshore wind turbine generator in one of the berths. Eventually the decision was made not to test a FWT at the Wave Hub site based on concerns raised by the U.K. Ministry of Defense.

Integrating WECs directly into a FWT platform is another method to use WECs to stabilize a FWT platform and increase the power output of the wind turbine. It also has the added benefit of using the energy absorbed through stabilization to generate electricity from the WECs. Using WECs in this manner is significant engineering challenge as the WECs are typically designed to maximize their motion in response to the wave action to maximize power output, which is in conflict with the goal to stabilize the platform. To demonstrate the feasibility of this technology, a Danish Company, Floating Power Plant (FPP), has designed a hybrid wind-wave floating platform, shown in conceptual drawing on the left in figure 2 below. This design is projected to generate a maximum power of 11.6 MW depending on specific design parameters. It is constructed from a floating platform with an 8 MW wind turbine, a mooring system that allows for 360-degree rotation, and WECs for an additional 3.6 MW (Laursen, 2017). This design is largely based on lessons learned from the deployment of the floating wind-wave prototype that FPP built as shown on the right in figure 2.

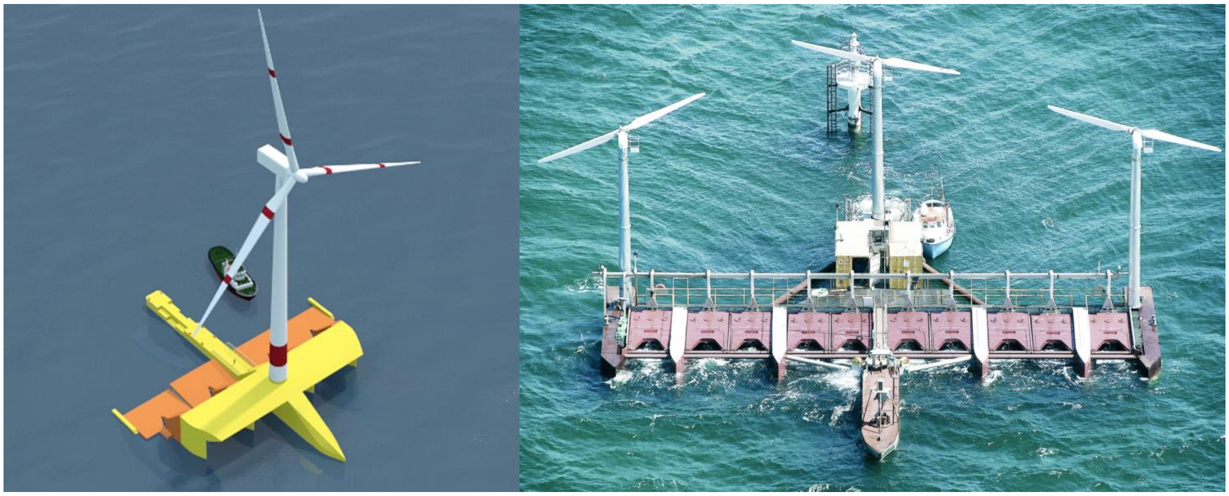

Figure 2: Conceptual Design Hybrid Wind-Wave Floating Platform (left) and Prototype Hybrid Wind-Wave (right)

http://www.floatingpowerplant.com/

Much more research is required to determine if WECs are the optimal way to stabilize the FWT platforms. There could very well be much more simple designs to stabilize the platform that do not introduce the added risks of mechanical failure by including WECs in the platform design. WECs are still in the early stage R&D phase, and integrating them with more mature wind energy technologies is not recommended by a majority of the survey respondents because of the difference in LCoE and technology immaturity.

PMEC-SETS has some constraints that will limit the ability to test FWT designs, specifically the 70-80 meter water depth at the berths and the 5 MW limit per berth based on the export cable specifications. It should be noted that the PMEC-SETS cable design should allow for higher power limits of approximately 8 MW when higher export voltages are utilized depending on the final design specifications. Another potential constraint is the size of the berths, which are each rectangles with the dimensions of 0.5 miles across the wave front boundary and 1.0 mile deep. If desired, an array of wind turbines and WECs could be positioned such that the complete system occupies two berths, and utilizes the two export cables associated with these berths. If there was interest in developing this capability, a detailed evaluation, given the physical constraints of PMEC-SETS berths, would be required. The results of this analysis might conclude that additional berth space is required, or that combined wind-wave arrays testing is only possible at a reduced scale. This analysis would be used to determine optimal placement of the WEC's relative to the FWT to minimize the wave energy impacting the FWT platform for various wave heights and periods.

To establish PMEC-SETS as a testing site that could include FWTs would create significant permitting challenges. To begin with, gaining agreement with local stakeholders for wind turbines is much different than getting agreement for WECs as wind turbines would be much more visible from the shoreline when operating at six nautical miles from the coast. There would also be challenges in federal permitting to operate a FWT at PMEC-SETS. PMEC SETS will only be permitted to test WECs, and not FWTs or hybrid wind-wave devices based on the compliance documents. To gain permits for FWTs, the Bureau of Ocean Energy Management (BOEM) would be the lead federal agency to ensure compliance with all environmental regulations and to meet the statutory requirements and environmental impact as required by the National

Environmental Policy Act (NEPA). As such, the addition of testing capabilities for FWT, or hybrid wind-wave energy devices, would require starting the permitting process from the beginning. Though some environmental studies and biological assessment documents could be reused in evaluating wind turbines, many more studies would be required and the time and costs required for this additional permitting would be significant.

There are economic advantages to the local community that would result from expanding PMEC-SETS to include floating wind turbine R&D, and engagement with the local community would need to emphasize these advantages. The FWT technologies are much more mature than wave energy, and have recently started commercial operation fifteen miles off the coast of Peterhead, Aberdeenshire in Scotland. This system, referred to as Hywind Scotland, is capable of supplying 30 MW with 'turbines that stand 253 m tall in total (around 830 ft), with 78 m (250 ft) of that bobbing beneath the surface' in a water depth of approximately 130 meters (Alexandra, 2017). Even with this commercial success there are still benefits to testing in the U.S. environment and providing power to the grid in accordance with U.S. grid IEEE standards and requirements.

The global market demand for FWTs is significant as wind turbines fixed to the seabed are generally limited to maximum depth of 50 meters, and "80% of potential offshore wind sites are in waters more than 60 meters deep" (Alexandra, 2017). Similarly in the U.S., a recent National Renewable Energy Laboratory (NREL) study estimates that there are over "4000 GW in offshore wind potential, including over 2400 GW theoretical power potential in areas with average wind speeds greater than seven m/s at water depths greater than sixty meters, where FWTs are more likely to be deployed" (Musial, et al, 2016). Stated in a different way, compared to onshore wind, "offshore wind power with integrated energy storage could satisfy greater than 20% of world's electricity demand because of its higher capacity factor and proximity to densely populated areas" (Musial, et al, 2016). Note that this resource characterization includes energy storage as part of the offshore wind system as storage is necessary to meet grid integration requirements in most cases.

Though the survey results did not show a consensus among participants that PMEC-SETS develop the capability to test offshore energy storage facilities, the integration of offshore with energy storage systems with either wave and wind energy devices is an important area of research and development. In general, the integration of renewable energy technologies into the grid is challenging because of the intermittent nature of the resources, and some degree of energy storage is required. This becomes even more important as the total percent of renewable energy on the grid increases.

One frequently proposed solution to mitigate this energy storage problem is the use of a compressed air system that captures the output energy of the device and reduces the variability of output power. Such systems are referred to as compressed air energy storage (CAES). To recover the stored energy, the compressed air is typically released from the system through a turbine to generate electricity. By utilizing a CAES system as the input into a turbine driven electrical generator, this type of system generates a more constant output power that is more easily integrated onto the grid.

These systems are still in the R&D development stage to optimize their efficiency and minimize energy lost through heat transfer.

This is shown in the graphic below, figure 3, which illustrates that different types of energy storage systems are preferred depending on the rated power of the system and the discharged time required for power smoothing (Zhou, et al, 2013). This figure shows that CAES is best for power smoothing for array of devices that require power smoothing over the period of hours, e.g. tidal systems. For the more rapid discharging of WECs during the period between successive waves, using flywheels or capacitors is the preferred choice.

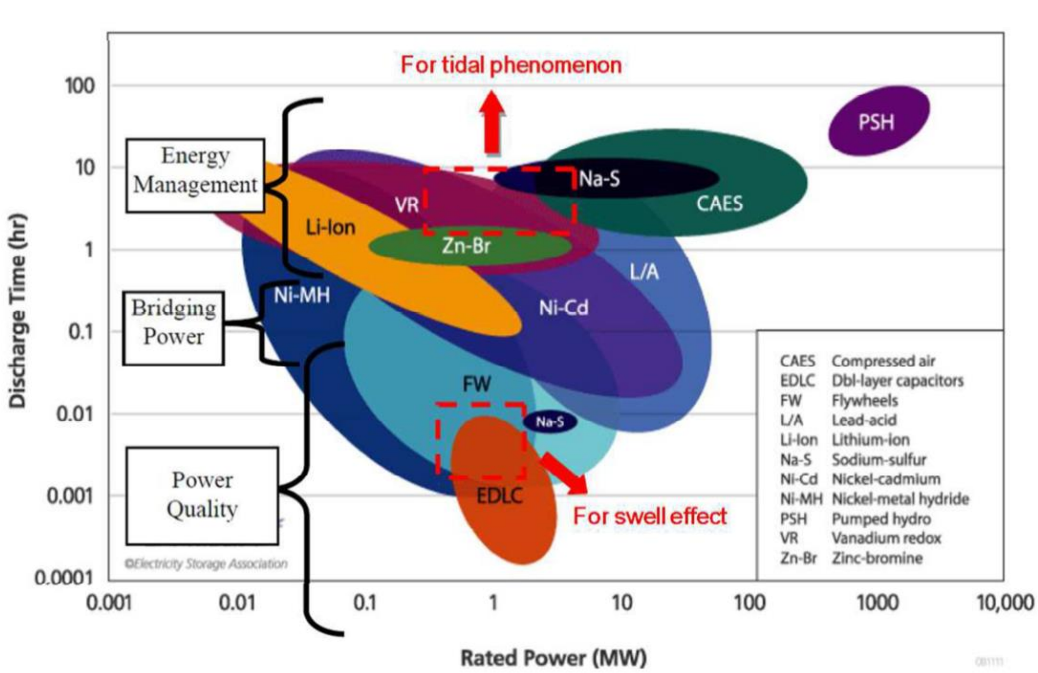

Figure three: Energy Storage technologies for Different Marine Hydro-kinetic systems

Within the CAES system category there are many different types of designs. Depending on the size of the CAES system, which can vary in size from single 4000 cubic feet flexible energy bag structure to system that holds air inside large underground caverns, and other design parameters, CAES systems are able to compensate for power variations for a wide range of different time scales. Conventional CAES methods store large volumes of air under high pressure that are utilized to feed a gas turbines utility generation stations during peak power demands on the order of hundreds of MWs. Other methods utilized large arrays of flexible bags that take advantage of the high pressure of deep water to pressurize the air. For these designs the depth of the water is an important parameter, and typically depths for prototype systems are much deeper than the depth at PMEC-SETS.

CAES systems enable the designer to reduce the size and costs of the electrical generator and transmission components by designing these electrical components based on a more constant average output power, instead of a highly variable power with large peaks when no energy storage is utilized. The EMEC wave and tidal energy test center in Orkney Scotland obtained the necessary permits to test such a system. More specifically, they tested a cable-reinforced fabric five meter diameter CAES system anchored to the sea bed and submerged at a depth of 25 meters (Pimm, et al, 2014). Development of this type of testing capability at PMEC-SETS may eventually become necessary as wave energy technology advances and developers begin to test devices in an array with CAES system used to integrate the WECs within the array. Since the WECs contained within an array are expected to have power peaks that are not in sync with one another, they would each charge the CAES independently keeping the system at a more constant internal pressure.

Conclusions

The goal of this study was to identify if there is consensus regarding potential PMEC-SETS increased capabilities to further advance global efforts in offshore energy R&D. Comments provided by the survey participants represent a diverse set of recommendations and considerations regarding future enhancements to the testing capabilities at PMEC-SETS. Only the array comprised of floating wind turbines and WECs had an average score that was substantially higher than the composite average scores of the other technologies.

The business goal for PMEC-SETS is to be self-sustaining after the initial two years of operation without direct federal supplemental funding. As such, it is necessary to attract multiple sources of funding to fully utilize the test facility to generate sufficient revenue to compensate for the costs to operate and maintain the facility. Judicious evaluation based on multiple in depth technical, environmental and financial analyses is required before any increase in capabilities is seriously considered. As a research organization, OSU investments will continue to push the boundaries of what is technically viable within the offshore energy industry, and the ability to test a combination array of wind turbines and WECs could prove to be a win-win combination for the advancement of both technologies. Financial investments in future enhancements at PMEC-SETS to provide additional offshore energy R&D testing capabilities and supporting infrastructure is not without risk, but the upside of these investments are significant based on the projections for offshore energy market growth discussed above.

Appendix 1

An Evaluation of Opportunities for Future Development at Pacific Marine Energy Center to Enhance Offshore Renewable Energy Research and Development

Instructions

For each of the six technologies listed below, use matrix A below to indicate your recommendation (“High”, “Medium” or “Low”) for developing the capability to test each of these technologies at PMEC-SETS with respect to the attributes listed in first column of the matrix.

1. Offshore compressed air energy storage systems integrated with wave energy array
2. Hydrogen generation systems powered by wave energy
3. Floating wind turbines
4. Arrays compromised of both wind turbines and wave energy converters
5. Hybrid system of wind turbines on platform stabilized by wave energy converters
6. Hybrid system of solar panels on platform stabilized by wave energy converters

Matrix A: Assessment of Six Technologies

Attributes that characterize the objectives of open ocean testing	**Importance of Open Ocean Prototype Testing (High, Med, Low) for Different Technologies**					
	Offshore compressed air integrated with array of wave energy converters	Hydrogen Generation Systems	Floating Wind Turbines	Array of both wind turbines and wave energy converters	Hybrid system wave energy converters & wind turbines	Hybrid system wave energy converters & solar panels
Technical need to optimize system performance through prototype testing						
Ability to reduce system costs through testing						

Attributes that characterize the objectives of open ocean testing	Offshore compressed air integrated with array of wave energy converters	Hydrogen Generation Systems	Floating Wind Turbines	Array of both wind turbines and wave energy converters	Hybrid system wave energy converters & wind turbines	Hybrid system wave energy converters & solar panels
Ability to test devices in an array to improve performance and costs of commercial scale systems						
Ability to attract investors based on successful full scale open ocean testing						
Ability to better understand environmental impacts						
Ability to test at PMEC based on water depth, wave conditions, wind speeds and other physical constraints						
Ability to gain concurrence from local stakeholders						
Ability to gain concurrence from federal regulatory agencies						

Please add any other technologies, not included in matrix A, for potential development in PMEC research and development capabilities that you would recommend e.g. aquaculture. List each technology in the header of columns 2, 3 and/or 4 in matrix B, and score your recommendations utilizing “High”, “Medium” or “Low”.

Matrix B: Assessment of Other Recommended Technologies

Other Capabilities Recommended:			
Technical need to optimize system performance through prototype testing			
Ability to reduce system costs through testing			
Ability to test devices in an array to improve performance and costs of commercial scale systems			
Ability to attract investors based on successful full scale open ocean testing			
Ability to better understand environmental impacts			
Ability to test at PMEC based on water depth, wave conditions, wind speeds and other physical constraints			
Ability to gain concurrence from local stakeholders			
Ability to gain concurrence from federal regulatory agencies			

Using scoring sheet C below, please provide an overall ranking for the capabilities you would recommend developing at PMEC. Use “1” to designate the highest preference.

Scoring Sheet C: Overall Ranking

Technology	Overall Ranking
Offshore compressed air energy storage systems	
Hydrogen generation systems	
Floating Wind Turbine	
Wind/Wave Array	
Hybrid system of offshore **wind turbines** on platform stabilized by wave energy converters	
Hybrid system of offshore **solar panels** on platform stabilized by wave energy converters	

Thank you for your help in this study, and please provide any additional comments to help clarify your rationale, and any references you believe would improve the quality of this study.

Also, please let me know if you would like to further discuss your thoughts regarding offshore energy development via phone.

Appendix 2

Universities
University of Hawaii
University of Washington
University of Manchester
Virginia Tech University
Oregon State University

Technology Developers
CalWave
Maritime Alliance
PMI Industries
Pacific Energy Ventures
Maine Marine Composites
Resolute Marine
H. T. Harvey & Associates
M3Wave
Resen Waves
Waves4Power
Aqua harmonics
Columbia Power
Ocean Energy
Marine Renewable Collaborative
Hydrokinetic Energy
Marine Energy Corporation
Ocean Renewable Power Company

Federal Government
Sandia National Laboratory
Pacific Northwest National Laboratory
National Renewable Energy Laboratory
Department of Energy
Bureau of Ocean Energy Management
Naval Facility Engineering Command

Utility
Portland General Electric

References

1. Astariz, Sharay; Iglesias, Gregorio. 2015. "Enhancing Wave Energy Competitiveness through Co-Located Wind and Wave Energy Farms. A Review on the Shadow Effect." Energies 8, no. 7: 7344-7366

2. Bradley, Stuart. (2016). Floating Wind insights. 10.13140/RG.2.2.14805.83683.

3. Hagerman,G., Scott, G. 2011. Mapping and Assessment of the United States Ocean Wave Energy Resource. EPRI Report ID1024637. Page 176

4. Huckerby, J., Jeffrey, H., de Andres, A. and Finlay, L. 2016. An International Vision for Ocean Energy. Version III. Published by the Ocean Energy Systems Technology Collaboration Programme. https://testahemsidaz2.files.wordpress.com/2017/03/oes-international-vision.pdf

5. Laursen, Wendy, March 8, 2017, The Maritime Executive. New Floating Platform Harvests Wind and Wave Energy. https://www.maritime-executive.com/features/new-floating-platform-harvests-wind-and-wave-energy

6. Ma, Alexandra, August 3, 2017, Business Insider. The world's first floating wind farm is being built off the coast of Scotland — here's how it works. http://www.businessinsider.com/hywind-scotland-glimpse-into-worlds-first-floating-wind-farm-2017-8/#here-are-the-experimental-turbines-that-will-form-the-floating-wind-farm-1

7. Magagna, D., Uihlein, A. 2015. Ocean energy development in Europe: Current status and future perspectives, International Journal of Marine Energy, Volume 11, Pages 84-104. ISSN 2214-1669. https://doi.org/10.1016/j.ijome.2015.05.001

8. Musial, Walter; Heimiller, Donna, Beiter Philipp; Scott George; Draxl, Caroline. 2016. 2016 Offshore Wind Resource Assessment for United States (Technical Report). NREL/TP-5000-66599. National Renewable Energy Laboratory (NREL), Golden, CO (US) https://www.nrel.gov/docs/fy16osti/66599.pdf

9. Pimm, A., Garvey, S., de Jong, M. 2014. Design and testing of Energy Bags for underwater compressed air energy storage. Energy. 66. 10.1016/j.energy.2013.12.010.

10. Tsouroukdissian, R., Lackner, M., Cross-Whiter, J., Park, S., Pourazarm, P., La Cava, W., and Lee, S. 2016. "Smart Novel Semi-Active Tuned Mass Damper for Fixed-Bottom and Floating Offshore Wind (Paper)." In United States. http://www.osti.gov/scitech/servlets/purl/1254153.

11. Zhou, Z., Benbouzid, M., Charpentier, J., Scuiller, F., Tang,T.. 2013. A review of energy storage technologies for marine current energy systems, In Renewable and Sustainable Energy Reviews, Volume 18,Pages 390-400, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2012.10.006.

Steven M. DeWitt   Curriculum Vitae

Technology Manager; Department of Energy, (2017 – Present)

I am responsible for the management of a research and development portfolio of advanced testing and demonstration of marine hydro-kinetic technologies to ensure all projects achieve technical milestones and deliverables within project schedules.

Operations Deputy Department Head; Naval Warfare Center Carderock, (2015 –2016)

I was responsible for the management and oversight of Human Resources, IT/Cybersecurity, Facilities, Safety, Corporate Communications, Security, and Business Operations.

NAVSEA Division Director of Shipyard Operations; Washington Navy Yard, (2011 –2015)

I provided policy guidance, management oversight, and technical assessment of nuclear powered aircraft and submarine maintenance and modernization ship overhauls. I closely supervised project planning and execution to drive completion of these projects on time and within budget. I provided leadership assessments of all aspects Naval Shipyard operations, including project management, engineering management, resource management, and financial management. I coordinated implementation of improved policies across amongst all stakeholders.

Business Manager, Trident Refit Facility, Kings Bay, GA, (2007 –2010)

I managed the business operations and financial management, to include contracting, commercial sales agreements, future year budgeting, reimbursable funding, business management analysis, development of budget estimates, and allocation of available funding for strategic long range priorities. I was responsible for supervising four branches including TRIDENT submarine maintenance scheduling, workload forecasting, IT technical data systems, and Trident class ship alterations program management.

Engineering Officer, Trident Refit Facility, Kings Bay, GA, (2003 –2007)

As Department Head, I directed the efforts of 155 civilian personnel, including engineers, physical science technicians, logistics specialists, naval architecture technicians, quality assurance specialists, and technical document planners, providing marine engineering, Quality Assurance/Non-Destructive Testing (NDT) for submarine maintenance.

Various Naval Nuclear Engineering positions within Department of Navy, (1989 –2003)

Deputy Project Superintendent for shipyard CNO availabilities. Submarine Department Head and Division Officer on multiple submarines, was responsible for nuclear operations, maintenance, and training and qualification programs.