



Wave Energy Industry Update

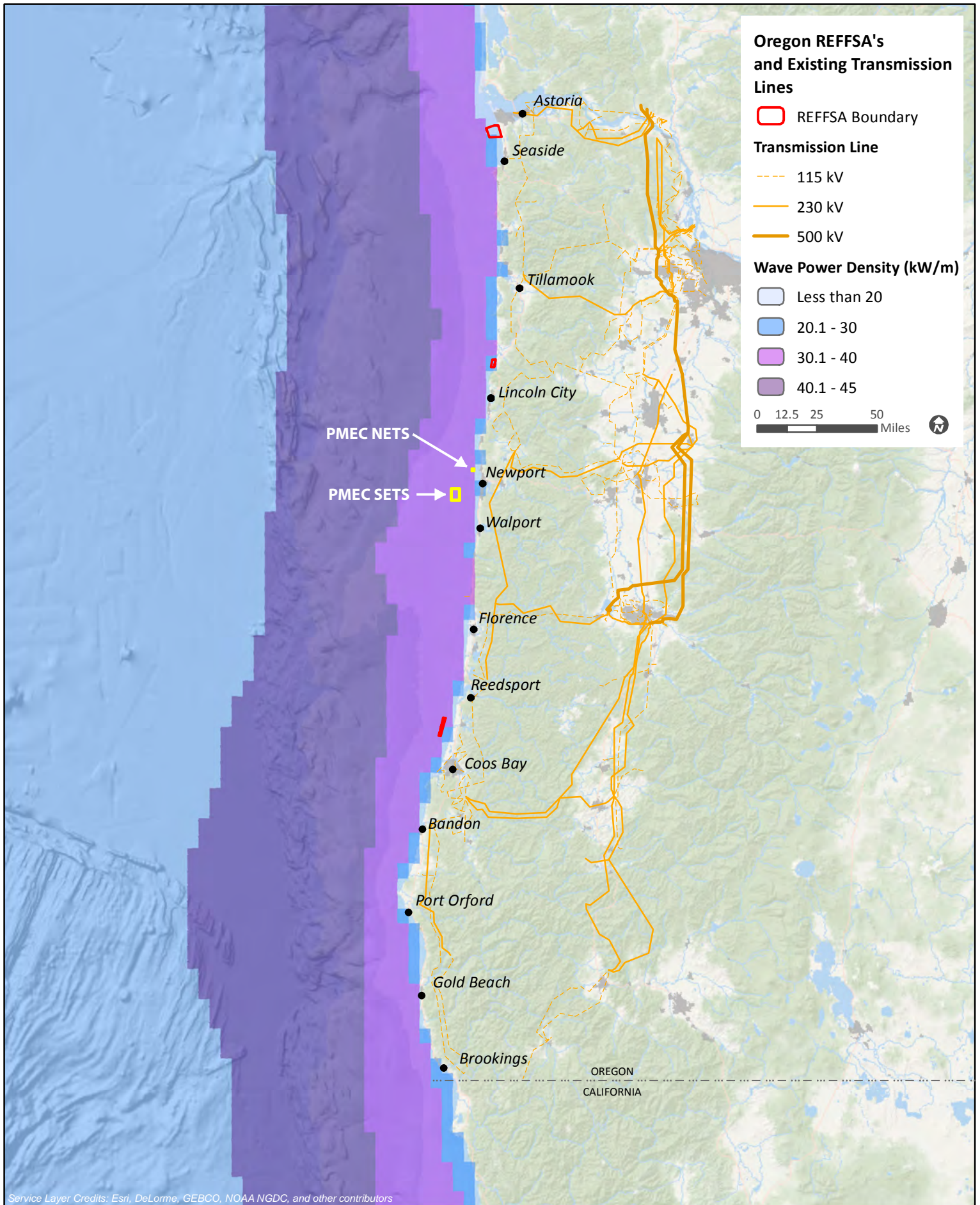
A Northwest US Perspective

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On behalf of Oregon Wave Energy Trust

August, 2015

This work was funded by the Oregon Wave Energy Trust (OWET). OWET was funded in part with Oregon State Lottery Funds administered by the Oregon Business Development Department. It is one of six Oregon Innovation Council initiatives supporting job creation and long-term economic growth.

Oregon Wave Energy Trust (OWET) is a nonprofit public-private partnership funded by the Oregon Innovation Council. Its mission is to support the responsible development of wave energy in Oregon. OWET emphasizes an inclusive, collaborative model to ensure that Oregon maintains its competitive advantage and maximizes the economic development and environmental potential of this emerging industry. Our work includes stakeholder outreach and education, policy development, environmental assessment, applied research and market development.



Acknowledgements

The authors thank the Oregon Wave Energy Trust for making this study possible and giving us the opportunity to explore the fascinating world of ocean energy. The work was greatly enhanced by personal interviews conducted with experts in the field. Views and errors in this report are the sole responsibility of the authors, but we thank everyone who kindly took time to speak with us regarding aspects of this report:

Ian Andrews, PacifiCorp

Kevin Banister, Principle Power

Belinda Batten, NNMREC

Chris Dieterle, Portland General Electric

Jarret Goldsmith, DNV-GL

Dan Hellin, NNMREC

Sara Hunt, US Department of Energy

Betsy Kaufmann, Energy Trust of Oregon

Paul Klarin, Oregon Department of Land Conservation and Development

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Oregon Based Northwest Energy Innovations Azura Hawaii Deployment
Image Source: Azura Wave



Preface

This report was commissioned by the Oregon Wave Energy Trust (OWET). Its purpose is to provide current information on the status of the wave energy industry for Northwest power system policy makers, management, and analysts; and to pose recommendations for the prudent advancement and support for wave energy commercialization. This work is the product of literature research and extensive personal interviews conducted with experts and practitioners in the wave energy and Northwest regional electric utility industries. The Northwest is a hub for the wave energy industry due to the high quality of wave energy resource off the Northwest coast, a supportive knowledge base and infrastructure, and the government policies supporting development of that resource.

1. Executive Summary

Wave energy holds much promise as an abundant, clean renewable resource available to much of the world's population centers. The Northwest coast has an especially rich wave energy resource. As a renewable resource, wave energy exhibits certain advantages over the more prevalent wind and solar resources that are now taking center stage. Wave energy is far more predictable and less variable than wind resources. Its seasonality better matches the Northwest's pattern of energy use than solar resources. In addition, energy production along the coast would provide benefits to the grid as a whole. Development of coastal resources would:

- Reduce the need for new transmission to serve coastal loads and relieve congestion on transmission through the Cascade Mountains to coastal load centers.
- Improve the stability of the transmission system, improving power quality in coastal areas.

Several regional utilities, both consumer- and investor-owned, have recognized these values and invested both time and money to support wave energy development.

With two grid-connected units in regular operation worldwide today, wave energy remains an emerging technology. The industry continues to support a range of diverse technological approaches in its search for reliable and efficient designs that can deliver power at low cost. The diversity of designs reflects both some uncertainty as to what may be the best technological solutions, and the fact that different approaches may be better suited to different wave energy resource characteristics, siting and economic drivers, and stakeholder concerns.

Pushing commercialization to the next level is a central focus of the industry. Wave test centers represent a key to commercializing wave technology. The Northwest is a center for testing facilities, including the Pacific Marine Energy Center South Energy Test Site (PMEC SETS) being developed off Newport, Oregon with support from the US Department of Energy, the Oregon Wave Energy Trust, and Oregon State University. Test facilities are crucial to perfecting and proving the emerging ocean energy

technologies and providing transparency on their performance to potential investors. Without test facilities, the already daunting cost of development would be prohibitive for many technology developers.

In addition to test facilities, funding and support for technology developers comes from several sources, including:

- US Department of Energy grants,
- The State of Oregon through the Oregon Wave Energy Trust and enabling policy,
- Venture capital, and
- Utility research, development, and demonstration programs.

Despite this support, the industry faces challenges in developing and deploying commercial projects. Venture capital and other funding sources are limited and development efforts among the various parties are not entirely coordinated today. The first markets for commercially viable wave energy technologies will be found in high value niches—e.g., remote isolated systems, and resiliency applications. Once a reliable technology is developed and applied in high value niche markets, economies of scale can take hold to reduce costs for more widespread adoption.

Recommendations

Notwithstanding the challenges, wave energy appears to be on the precipice of commercialization. While successful commercialization cannot be guaranteed, two factors seem key:

- Ensuring a consistency of financial and policy support, and
- Focusing available resources on regionally agreed priorities and projects.

Consistent and Sustainable Support

A lesson from wind energy development is that ensuring long-term policy and financial support is necessary to the successful development of emerging technologies. Although the US made important progress in developing wind energy technology in the 1970s and early 1980s, the more consistent support in Europe led more rapidly and directly to commercialization there.

While it is important to identify points at which additional investment may be required or may no longer be warranted, it is at least equally important to determine a sustainable level of support up until such decision points are reached. Consistent and sustainable support is important to realizing a potentially significant economic opportunity for this Northwest resource.

Focusing Available Resources – Regional Collaborative Approach

It is vitally important that the region collectively determine priorities for its limited resources and work together to invest those resources. The region is endowed with valuable assets that can be leveraged. These include:

1. A significant wave energy resource;
2. The creation of a grid-connected test facility due to be operational in 2018;
3. A center for testing and innovation at Oregon State University;
4. The Oregon Wave Energy Trust;
5. Policies reflecting a commitment to reductions in carbon emissions;
6. Demonstrated interest in wave energy development by several Northwest utilities;
7. Oregon National Guard at Camp Rilea Armed Forces Training Center with demonstrated, high-value interest in wave power as both a low-carbon source of energy, and to achieve enhanced power system resiliency during emergencies; and
8. The Territorial Sea Plan, a streamlined permitting process for siting marine renewable projects.

These assets could be marshaled in a more effective way. The idea of a collaborative effort among utilities and other stakeholders emerged from interviews conducted for this report. Such an effort would most logically be led by the Northwest Power and Conservation Council and could include:

- The Bonneville Power Administration and other Northwest regional utilities
- Energy Trust of Oregon
- Oregon State University
- Oregon National Guard
- Wave technology developers
- Oregon Department of Energy
- US Department of Energy
- Oregon Wave Energy Trust and other advocacy organizations

The purpose of the collaboration would be to connect the utility community, developers, funders, and other stakeholders to develop a unified approach to development and, ultimately, commercialization. Development projects could be undertaken and underwritten by multiple parties both to spread the risk of investments in this emerging technology, and to maximally share information gained from those developments.

Conclusion

The future of wave energy appears bright and relatively near term, but significant challenges remain. The most often asked questions center on the possible timing of commercialization and project cost. The latter issue will likely only come clear after reliable technology designs emerge and the prospect of economies of scale is better understood. The resource and the region would be best served if interested parties could determine a stable and sustainable level of support to achieve initial development and undertake a concerted effort to get to that stage.

2. The Wave Power Resource

Waves are created when wind blows across the ocean through time and over large regions. Waves carry both kinetic energy (the orbital motion of water molecules below the sea surface) and potential energy (as masses of water lifted vertically from trough to crest). Waves lose little of their energy as they travel across the open ocean until they meet friction across the seafloor in shallow water, at depths of less than one half their wavelength (the distance between wave crests).¹

The amount of power contained in waves is primarily a function of wave height and wave period (the time taken for two consecutive wave crests to pass a stationary point). Wave power is typically characterized in terms of power flux, the average power per length perpendicular to the direction of travel, expressed as kW/m. Determining wave power flux in the irregular and at times chaotic wave environment of the open ocean can be complex. Therefore, wave power flux estimates make use of “significant wave height”² and “peak wave period”³ – concepts that address the fact that actual ocean waves are not as orderly as, for example, sinusoidal motion in a calm pond that can be more easily quantified.

Devices for capturing wave energy to produce electric power are commonly called wave energy converters (WECs). Various WEC technologies have been developed, but all seek to make use of some combination of the kinetic and potential energy aspects of waves to produce power. Part of the challenge for WEC technologies is to capture the available energy in its two forms, over multiple dimensions (e.g., pitch, yaw, roll), and over a wide dynamic range of wave heights and periods.

Globally, approximately 3 terawatts (TW) of wave power are recoverable, which is roughly double the total global installed capacity of all renewable power capacity in 2012.⁴ Of the 3 TW of wave power, 574 gigawatts (GW) could be recovered in Australia and New Zealand, 526 GW in South America, 286 GW in Europe, and 242 GW in North America. These figures do not include areas where power potential is below 5 kW/m (which is too low for extraction) and where WECs could not technically be deployed, such as in areas covered by ice (Mork et al., 2010).

2.1 An Abundant Pacific Northwest Resource

In a 2011 study, the Electricity Policy Research Institute (EPRI) estimated the wave energy resource to be 59 TWh annually (6,700 MWh) along Oregon’s inner continental shelf (at approximately 50m depth), assuming current WEC conversion efficiencies. This makes Oregon one of the most wave-energy rich

¹ Because waves are driven by wind, the energy itself ultimately derives from the sun. Solar radiation absorbed at different rates across the land and sea creates pressure differentials on the earth surface. Wind is the result of air moving to equalize the pressure differences, and wind moving across the ocean creates waves.

² Significant wave height is a representation of the upper range of wave height for “real seas” where wave heights are constantly changing and composed of the superposition of many individual wave components.

³ Peak wave period is the period of the component that has the highest energy content – based on a spectral analysis of waves over a set time period.

⁴ NREL estimates the 2012 installed capacity of renewable energy generators at 1,470 GW (DOE, 2012).

states in the US, with a theoretical potential of approximately 96% of its 2012 net electricity generation. Washington has a recoverable resource of 29 TWh, approximately 25% of its 2012 net electricity generation (EPRI, 2011).

Washington, Alaska, Hawaii and California also have very strong wave energy resources. The table below illustrates the relative resource potential in the United States, and distinguishes between the amount of energy that theoretically can be recovered by WEC technology in its current state and the wave energy that is available for recovery. Wave energy resource profiles, rather than other characteristics, such as siting considerations, determine the fraction of available energy that can be converted to electricity. This means that the amount of energy that is practically recoverable could be much lower than the theoretical, if for example, protected areas are excluded from the available resource.⁵

Table 1: Wave Energy Potential by State and Region

State/ Region	Recoverable at 2011 Technology Levels TWh/yr	Available at Inner Shelf TWh/yr	Recoverable Fraction Given Wave Energy Profiles	Average US Homes Powered /yr ⁶	Recoverable Percent of 2014 US Electricity Production ⁷	Recoverable Percent of 2012 State Net Electricity Generation ⁸
Alaska	434	803	54%	39,787,312	11%	6,242%
Oregon	59	143	41%	5,408,874	1%	96%
Washington	29	72	40%	2,658,599	1%	25%
California	114	205	55%	10,451,045	3%	57%
Hawaii	73	110	66%	6,692,335	2%	693%
East Coast	129	172	75%	11,826,183	3%	
Gulf Coast	47	60	79%	4,308,764	1%	
US Total	884	1,565	56%	81,041,438	3%	

⁵ The amount of recoverable energy depends, in EPRI's methodology, on a combination of wave power flux, measured in terms of MW/km across the inner continental shelf contour, and the amount of energy that, given the annual wave energy profile of an area, WECs could absorb. This evaluation is based on an array's maximum output, as well as the individual devices' threshold/cut-in operating condition and maximum operating condition (the level after which devices can no longer operate). According to the EPRI methodology, both the threshold and maximum operating conditions would be optimized to absorb the maximum amount of energy from the array (with the optimization limited to a 100-fold increase between threshold and maximum operating condition – which is a standard for off-shore wind). These issues are also covered in Section 3.

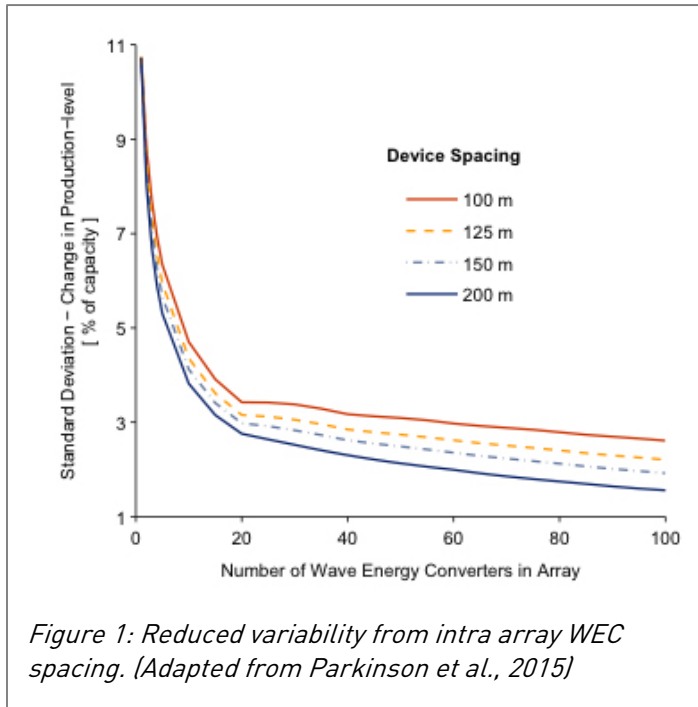
⁶ Based on an average United States residential electricity consumption of 10,908 KWh/yr. See: <http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3> - last accessed May 14, 2015.

⁷ According to the U.S. Energy Information Administration net electricity generation in 2014 was 4,092,935,000 MWh. See: www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_1 - Last accessed May 14, 2015.

⁸ Based on data retrieved from the United States Energy Information Administration state profiles. See: www.eia.gov/electricity/state/ - last accessed May 14, 2015.

2.2 A Less Variable Renewable Resource

Wave energy is an accumulation of wind energy interacting with the surface of the ocean over relatively large periods of time and geographic extent. The resulting wave energy is both more predictable and less variable than wind energy (CSIRO, 2012). While individual WECs experience substantial variability over periods of minutes and hours, wave energy arrays of many converters effectively smooth some of the



variability (EPRI, 2011).⁹ Further, a 2013 study in the *Journal of Renewable Energy* found that increasing the number of devices in an array significantly decreases the variability of electricity output up to about 20 individual wave energy converters, with additional variability reduction seen when devices within an array are spaced further apart from, for example, 100 m apart to 200 m apart for 1 MW devices (Parkinson et al., 2015).¹⁰

The same study showed that integration costs for wave power are likely a small percentage of wind integration costs for similar quantities for energy. This estimate was based on Bonneville Power Administration (BPA) data and integration cost methodology. The study concludes that “overall, the cost of integrating wave energy resources onto the grid appears to be low in

comparison to other project development costs, and low compared with the costs to integrate an equivalent amount of wind energy resources [at 29].”

Strategic deployment of buoys in an overall wave forecasting system would also likely increase forecast accuracy for wave energy because the regularity with which wave energy propagates across great distances contributes to its predictability (CSIRO, 2012). This point was also suggested by highly observed correlations between wave energy levels along the Oregon coast. Buoys as far as 350 miles away from one another along the coast have a correlation coefficient of 0.74. Parkinson et al. observed that “wind projects with a similar correlation would likely be within about 20 miles of each other” (Parkinson et al., 2015, at 26).

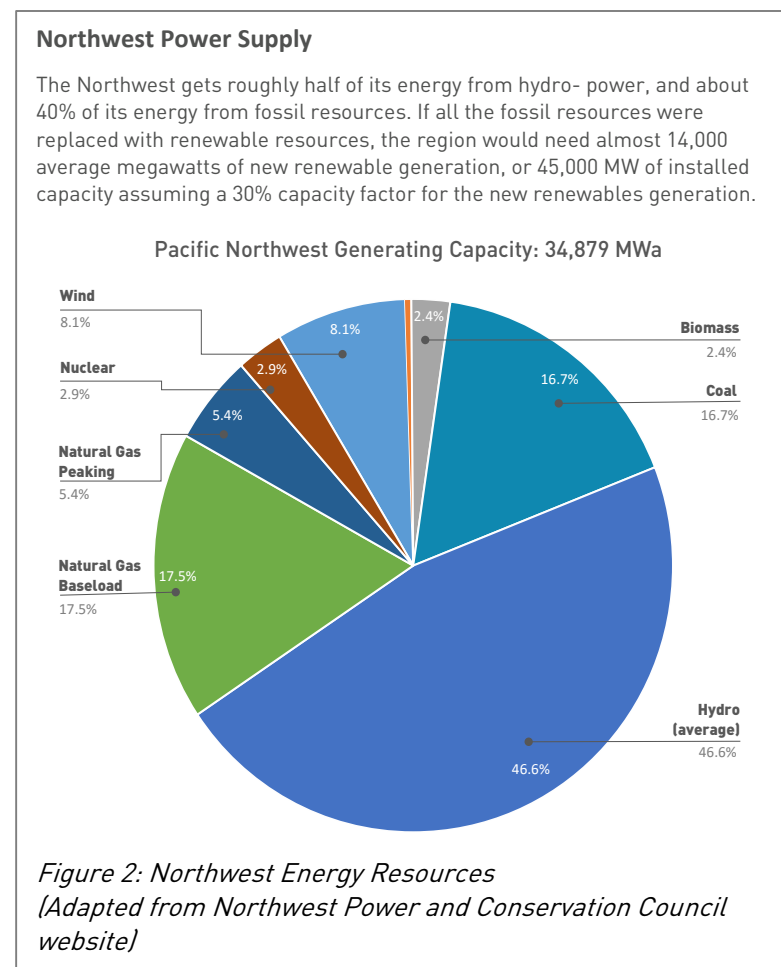
⁹ Utility-scale energy production, which is the primary focus of this study, requires devices to be deployed in arrays. The size of the array is dependent on the desired overall power output, the type of wave energy converter that is deployed, the power rating of individual converters, and the characteristic of the resource.

¹⁰ The study also examined the variability of modeled wave electricity production at 1-minute, 15-minute, hourly, and daily intervals using actual Oregon wave data from the National Data Buoy Center at 5 locations. The study found that while modeled electricity output by individual WECs experienced variability, this variability rapidly drops when the output was aggregated across the 5 locations.

3. Regional Industry Drivers

Demand for wave energy is driven by a strong future demand for renewable energy, reliability and congestion benefits to the transmission system arising from coastal electricity production, economic benefits of a local wave energy industry, and institutional support for technology development. These drivers are reflected in strong state-level policy positions, including a significant investment in state resources to amend the Oregon Territorial Sea Plan, funding for Oregon Wave Energy Trust (OWET), and other supportive legislation.

3.1 Benefits of Wave Energy in the Regional Renewable Energy Portfolio



Regional policy favoring carbon-free electricity generation will create continued demand for clean energy sources, such as wave energy. The primary regional policy drivers for a strong renewable energy demand are Oregon's and Washington's renewable energy portfolio standards, but also include the EPA's Clean Power Plan (Section 111(d) rules), and the planned retirement of the Boardman and Centralia coal plants by 2025 (ODOE, 2013a).

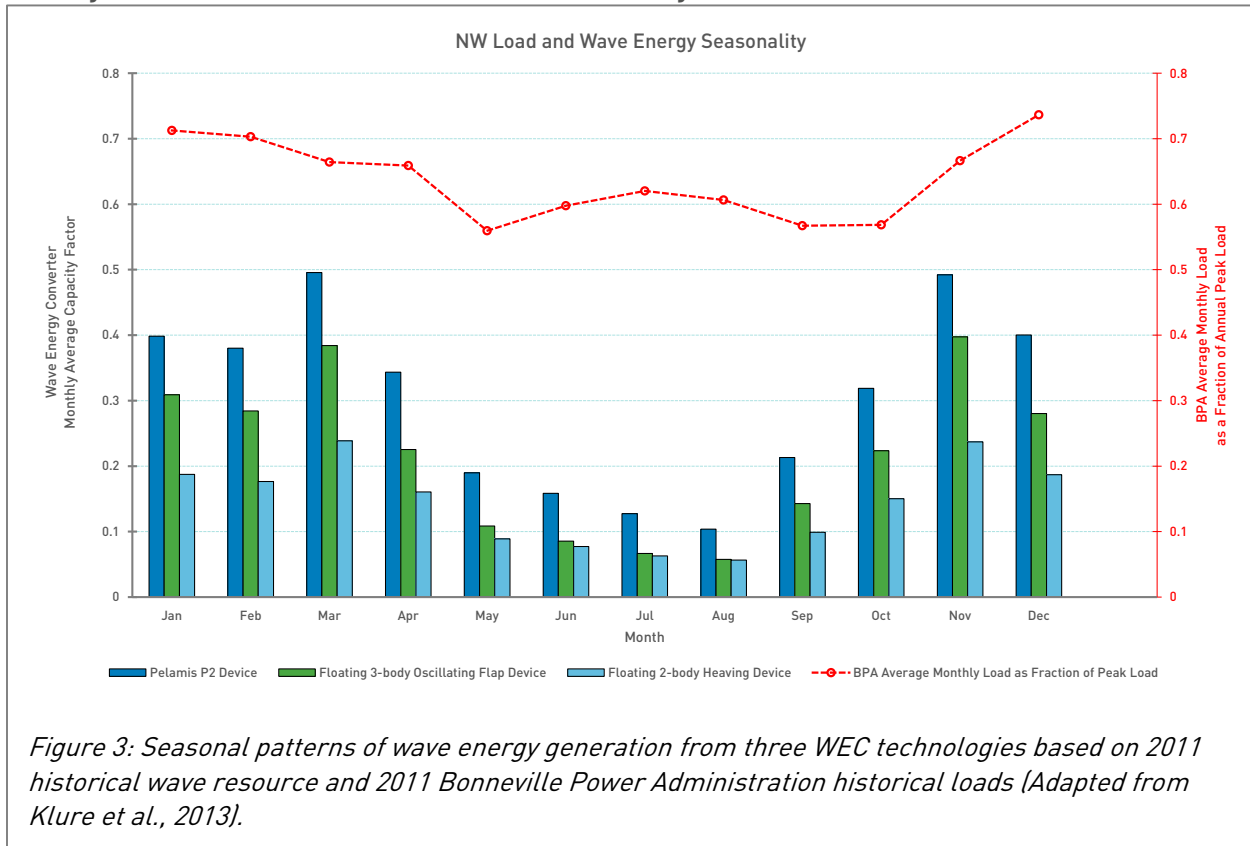
While established renewable energy technologies are likely to continue to play a lead role in meeting renewable energy demand, utilities value benefits derived from a diverse generation portfolio and resources with high capacity value.¹¹ The diversity benefits of wave energy were highlighted in scenario analysis of theoretical energy production from combined wind and wave resources in the Danish electricity market. The study demonstrated that

the balancing costs of a combined portfolio are 45% lower than in a wind-only scenario (Chozas et al., 2012). Another document described a wind-wave regime "near-baseload, dispatchable renewable

¹¹ PGE's presentation at the Ocean Renewable Conference IX (September 24-25, 2014) noted that "diversity has inherent value by reducing the net variability of intermittent resources", and that "new renewable resources can supply capacity during times when the power system is short on generation, they provide 'Capacity Value.'" (Lindsay, 2014).

generation” (BPA, 2014, at 33). In addition to the balancing benefits of wave energy, the seasonality of wave resources aligns well with the Northwest’s winter peak demand.

3.2 System Benefits of Coastal Electricity Generation



In addition to the diversity and capacity benefits of wave energy, adding coastal electricity generation to the grid could strengthen the transmission system there. System-wide benefits for coastal generation include:

1. Easing transmission constraints across the Oregon coastal range (and providing greater coastal security in the case of transmission line failure, such as was experienced in 2007);
2. Providing voltage support to the coastal portion of the electricity grid (and eliminating the need for expensive reinforcement projects);
3. Allowing for coastal load growth; and
4. Easing wider east-west transmission constraints by potentially serving Oregon’s central valley load with coastal generators.

In Oregon, population density is highest in the Portland metropolitan area and along the Northern half of the I-5 corridor. By contrast, coastal zone population makes up only approximately 6.5 percent of the state’s total.¹² While electricity currently flows from east to west in order to serve coastal loads, this flow

¹² U.S. Census Bureau. (2015). State and County QuickFacts. Retrieved from www.quickfacts.census.gov

could be reversed. Energy generated along the coast could flow across the existing transmission system to serve Oregon central valley loads and alleviate transmission congestion constraints further east.

A 2014 BPA presentation highlighted that coastal generation could benefit its transmission system because power generation serving the coast is remote and connected by hundreds of miles of a “long extension cord,” causing power quality to deteriorate toward the end of the line in Southern Oregon. In addition, coastal generation would make it less expensive to serve new loads “without new 230 kV and 500 kV transmission lines” (BPA, 2014, at 33).

Power quality issues related to extending its transmission lines to and along the coast without the benefit of local generation have already resulted in BPA needing to invest \$15 million to bolster voltages near Gold Beach in Southern Oregon (ODOE, 2013a). As far back as 1998, constraints on the coastal grid were highlighted when Nucor Steel proposed to build a 150 MW plant near Coos Bay, putting BPA in a position of needing to explore the possibility of building a new 500 kV transmission line to “reinforce the electrical service” on the Southern Oregon coast.¹³ While the company did not build a plant on the Oregon coast, the experience of studying how power could be provided highlighted some of the weaknesses of the coastal electricity grid.

In addition to the transmission system benefits of local generation, the Oregon coast is well suited for interconnecting wave energy projects. BPA, which owns most of the coastal transmission lines, already has experience conducting wave energy interconnection studies for the proposed Ocean Power Technologies (OPT) Reedsport project and the proposed grid-connected wave energy test site off the coast of Newport, Oregon. BPA’s 230-287 kV lines now serving the coast are appropriate for interconnecting wave energy projects in the 50 MW range. While smaller wave projects (in the 1.5 MW range) could be interconnected almost anywhere in Oregon, larger sites would require access to substations. BPA currently owns 15 substations along the coast, and the coastal grid has the capacity to “absorb at least 430 distributed MW of new generation without requiring infrastructure upgrades to cross-coast range transmission” (ODOE, 2014, at 5).

Adding coastal generation could help avoid transmission line and voltage-support build-outs, and provide BPA with a “non-wires solution” to these expensive and difficult options. However, these considerations may be hampered by the Pacific Northwest energy market structure. One respondent noted that “if you had an independent system operator and other entities that looked at big picture performance and had more operation control then possibly you would see more support for marine energy.”

It would help better understand the value of coastal generation if transmission planners considered local generation and other non-wires solutions in their transmission planning studies. HB 2187, a bill advocated for by OWET and passed by the Oregon Legislature in 2015, outlines the state’s policy position that marine renewable energy projects should be considered in transmission planning processes.

¹³ United States Department of Energy –DOE. (2015). EIS -0296: Notice of Intent to Prepare an Environmental Impact Statement. Retrieved from <http://energy.gov/nepa/downloads/eis-0296-notice-intent-prepare-environmental-impact-statement> - last accessed May 9, 2015.

3.3 State-Level Policy Support

The State of Oregon has shown significant support for the development of wave energy, having amended its Territorial Sea Plan to reduce ocean use conflicts in siting marine renewable energy projects along Oregon's coast, creating OWET, and passing enabling legislation.

Territorial Sea Plan Amendment

In January 2013, the Oregon Land Conservation and Development Commission (LCDC) amended the Oregon Territorial Sea Plan (TSP). The TSP sought to provide a policy framework for accommodating marine energy. The plan designated specific areas within Oregon's territorial waters (within three nautical miles from the coast) as Renewable Energy Facility Suitability Study Area (REFSSA), within which marine energy development would be encouraged. The plan, following extensive stakeholder consultations, established six zone types¹⁴, each with distinct permitting standards. The zone types with the least stringent siting standards for potential wave projects are the REFSSAs. The three REFSSAs are at Camp Rilea (11 square miles, the single largest area), Lakeside (near Reedsport), and Pacific City, for a total of 17 square miles (1% of Oregon's territorial sea). In addition to the REFSSA designation, the TSP amendment streamlines the permitting of marine renewable energy process through an inter-agency process, a Joint Agency Review Team (JART), led by the LCDC.

M3 Wave, LLC, an Oregon-based wave energy developer, tested its fully submerged device in 2014 at Camp Rilea. M3 Wave was the first wave energy project in Oregon to be issued a permit by the Oregon Department of State Lands after adoption of the TSP. The permit was issued after a six to seven week JART review process, and was, according to a state official, a "huge success story." The official noted that under the JART process "the level of scrutiny and speed [of the review] matched what was being proposed."

Oregon Legislation

The Oregon Legislature has shown significant interest in wave energy, regularly passing bills to provide transparency, clarity, and assurances for projects off the Oregon coast. Significant bills that were passed include HB 2187 (providing a policy position on the role of marine energy in transmission planning), SB 319 (exempting wave energy projects from traditional hydro licensing), HB 4042 (requiring net-metering to be available for wave energy projects), and SB 606 (requiring developers to assure removal of their equipment).

Senate Bill 606 was passed by the Oregon Legislature in 2013. The law requires owners and operators of wave energy facilities to demonstrate financial assurance for the cost of the closure and post-closure maintenance of their facilities, and requires a decommissioning plan for their devices prior to receiving

¹⁴ The six zone types are Renewable Energy Permit Areas (REPA); Renewable Energy Facility Suitability Study Areas (REFSSA); Renewable Energy Exclusion Areas (REEA); Proprietary Use Management Areas (PUMA); Resources and Uses Conservation Areas (RUCA); and Resources and Uses Management Areas (REMA).

deployment authorization from the State of Oregon¹⁵ (ODOE, 2013b). M3 Wave was the first developer to deploy its device under the law.

House Bill 4042, passed in 2014, establishes marine energy projects as eligible for net-metering, provided that they are interconnected directly to a service customer's premises. This provision would allow wave energy projects to be more easily interconnected to the electricity grid, potentially facilitating the development of wave energy generation off the coast of Camp Rilea.

House Bill 2187, passed in 2015, outlines Oregon's policy position that regional power transmission planning should take into consideration electricity generation from marine renewables within Oregon's territorial sea. The intent of the bill is to encourage the Federal Energy Regulatory Commission (FERC) Regional Transmission Planning entities (the Northern Tier Transmission Group and Columbia Grid) to undertake transmission planning studies that include wave energy generation as a potential resource.

Senate Bill 319, passed in 2015, requires the Department of State Lands to establish rules for authorizing ocean renewable energy projects, exempts ocean renewable projects from regulation as hydro-electric projects (removing barriers for ocean renewable energy projects that had been established to discourage the development of traditional hydro-electric projects), and requires developers to obtain a license from removing or adding material to the territorial sea. These changes are intended to make temporary R&D projects quicker and easier to authorize.

The Oregon Wave Energy Trust

Funded by the Oregon Innovation Council, OWET has been at the center of the wave energy development process in the Pacific Northwest since its inception in 2007. It has functioned as a vital clearing house for information relevant to the development of marine renewables (commissioning studies and hosting conferences), provided strong policy support and coordination work, and made grants to industry players and stakeholders for commercialization, education and outreach, environmental research, applied research, regulatory work, market development, and test site development. OWET was frequently cited as one of the primary drivers behind wave energy development in the region.

Since its founding, OWET has received over \$10 million in funding, which has enabled it to make 78 separate strategic disbursements of over \$6 million between 2008 and 2013, including to consulting companies, research institutions, and technology developers, among others (OWET, 2013). Its funding streams are arranged under a five-fold strategy to support:

1. Education and outreach,
2. Market development,
3. Applied research,

¹⁵ The law also required the Oregon Department of Energy (ODOE) to study underwater power transmission. ODOE released its report in November 2013.

4. Environmental research, and
5. Regulatory analysis.

OWET's initiatives have included mapping commercial and recreational fishing activities, wave energy resource characterization studies, and marine mammal acoustic studies (OWET, 2014). Many of the studies cited in this report were funded by OWET.

One of the particular strengths of OWET has been to use its funding strategically and to work with a wide range of wave energy stakeholders. Its matching grants program has, for example, leveraged over \$26 million in outside funding for Oregon projects (OWET, 2014), including for Oregon-based technology developers. Other initiatives include supporting the establishment of the proposed grid-connected wave energy test facility in Oregon (discussed in greater detail in Section 5.3) through supporting market research studies, and providing extensive support to the public outreach efforts around the TSP amendment.

3.4 Economic Benefits of Developing a Wave Energy Sector

A 2009 study by the consulting firm ECONorthwest modeled the potential economic impacts of wave energy development in Oregon under three scenarios. The study found robust potential economic benefits from establishing a wave energy industry in the state. The three scenarios included the creation of a R&D center, construction and operation of a 500 MW wave array, and establishment of an industrial wave energy sector in Oregon capable of selling 2,500 MW of wave energy generation capacity worldwide.¹⁶ Economic outputs included 48 jobs and \$114,200 in local and state taxes for the R&D scenario, 4,089 jobs and \$26 million in local and state taxes for the 500 MW array, and 6,032 jobs and \$42 million in local and state taxes for establishment of a wave energy sector in Oregon (ECONorthwest, 2009).

The experience of constructing the Ocean Power Technologies buoy for the proposed Reedsport wave energy array demonstrated that the local manufacturing sector would stand to make significant gains from the deployment of wave energy systems off the coast of Oregon. In 2009, when Oregon Iron Works was selected to construct the OPT buoys, it was estimated that the construction of a single power buoy would have created and sustained 30 jobs over nine months.¹⁷

As wave energy technology and business models mature, it will become clearer where and how wave energy devices are manufactured, transported, assembled, and deployed. It appears likely that greater economic benefits will accrue to the Pacific Northwest if devices are not only designed and engineered in the region, but also deployed locally. While the former scenario appears to be more likely in the immediate future, given many local companies' interest in pursuing high-cost electricity markets outside of the region, the latter scenario would accrue benefits not only to device developers but also to device

¹⁶ The assumptions for the three scenarios included a \$2 million opening and \$6.8 million annual operating cost for the R&D facility, a \$374 million construction and \$29 million annual operating cost for the 500 MW wave array, and an opening cost of \$626 million for the industrial cluster.

¹⁷ Business Wire. (2009). Retrieved from <http://www.businesswire.com/news/home/20091203006351/en/Ocean-Power-Technologies-Selects-Oregon-Iron-Works#.VXC53s-jOG5> – last accessed May 9, 2015.

manufacturers and the marine services industry for deploying, securing, operating, and maintaining wave energy arrays.

3.5 Institutional Support

Several Northwest institutions play an important role in driving the wave energy industry forward in the state. Oregon State University (OSU) provides the local wave energy sector with expertise and qualified engineering graduates with expertise in wave energy technology. Salem-based M3 Wave, for example, is a wave energy technology company founded by OSU engineering graduates who developed their initial concept while still studying at the university. Columbia Power has also developed its technology concepts, using the university as an important sub-contractor. Moving forward, OSU will continue to be an asset to local wave energy industry, with involvement in both campus-based wave test facility and active participation in the construction and operation of the grid-connected test facility.

The Oregon Military Department supports the testing of wave energy devices near Camp Rilea in partnership with Northwest National Marine Renewable Energy Center (discussed in greater detail in Section 5.3). While the department did not provide financial support to M3 Wave's 2014 test and does not plan on the Camp Rilea RREFSSA area becoming an official test site, it has expressed interest in powering its facilities with renewable energy. In addition to its experience with the M3 Wave project, Camp Rilea is exploring a possible future wave energy generation and desalination pilot project with Resolute Marine in 2015 involving two WECs to power both a 30 kW electricity generator and a 500 m³/day fresh water system.¹⁸ The military's strategic interests in off-grid and low carbon power makes Camp Rilea a natural focus as an early adopter for a technology with currently more limited appeal to regional utilities due to price.

The Energy Trust of Oregon (ETO) has a renewable energy program mandated to support above market costs for renewable energy projects. For example, ETO provided \$1.5 million in financial incentives to help the Oregon Technology Institute build a 1.75 MW geothermal power plant and assisted the City of Medford in upgrading its biofuel plant with a \$450,000 incentive grant. Funding from ETO is limited to projects smaller than 20 MW using commercial technologies. Wave energy technology would likely be deemed pre-commercial under current ETO guidelines. As the technology commercializes, wave energy projects may be able to take advantage of these programs.

¹⁸ Resolute Marine Energy. (n.d.) Retrieved from <http://oregonwave.org/oceanic/wp-content/uploads/2014/10/Pacific-Incubator-2-Report-on-Pacific-Northwest-Projects-Bill-Staby.pdf> -last accessed May 14, 2015.

4. Wave Energy Converter Technology Overview

WECs harness wave power by responding directly to the motion of waves, capturing elevated water mass, harnessing wave-generated air pressure, or using the differential underwater pressure caused by waves passing overhead. There are multiple design alternatives for converting wave power to electric energy and six principal device categories have emerged over the years. These are: point absorbers, oscillating wave surge converters, oscillating water columns, linear attenuators, overtopping devices, and submerged pressure devices.¹⁹

Each converter type requires specific siting considerations, as different WEC types can be designed for specific wave conditions. For example, some devices can be mounted to existing breakwater structures, such as an operational oscillating wave column system (which generates electricity from air pressure changes caused by waves crashing into the breakwater, as in a project in Spain). Other WECs are designed to be deployed off the coast in the open ocean, where wave power flux is highest. Possible wave energy converter device applications range from small-scale, off-grid devices powering buoys or other deep ocean energy needs, to integrating water desalinization with energy production, to utility-scale and grid-connected energy production. Wave energy is a part of the hydrokinetic energy resource family, which also includes tidal energy and run-of-the river hydroelectricity. Unlike WECs, tidal and riverine hydrokinetic technologies typically rely on submerged turbines to generate power.²⁰

4.1 Power Curves for Wave Energy Converters

The energy output from a WEC is a function of both the wave power input and the design parameters of the individual device. Similar to the design parameters of wind turbines, WECs have a threshold/cut-in condition (the wave conditions at which they begin producing electrical energy), a rated operating condition (the power input level after which the converters produce their rated output), and a maximum/cut-out operating condition (the level at which the device shuts down for self-protection and cannot produce power at all).

For wind power, this relationship is commonly expressed in two dimensions where power output is directly dependent on wind speed.²¹ However, because the power flux of ocean waves depends on both wave height and wave period, the wave power curve is three-dimensional. Achieving specific capacity factors or smoothing the variability of the power input is not only a question of where the device minimum, rated, and maximum operating conditions are set and what the wave power input is; they also depend on how the device responds to wave height and length.

Just as different wind turbine designs have different power curves that can be chosen to optimize the energy and economic performance of a wind project for a specific site, so too can the choice of WEC

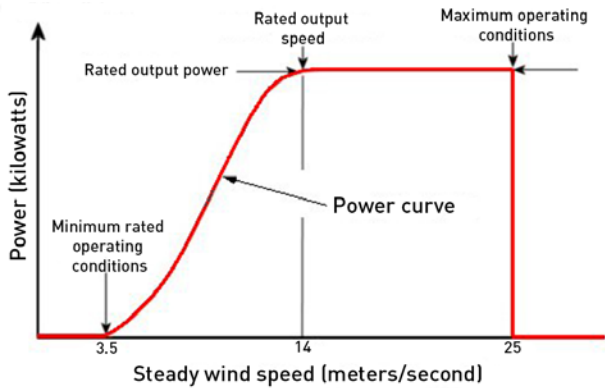
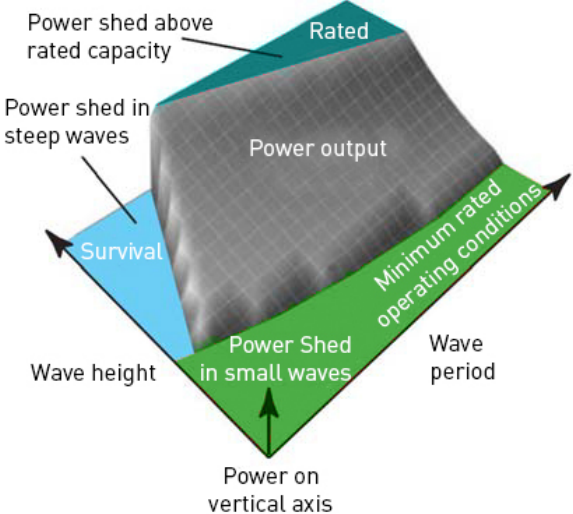
¹⁹ Appendix A provides a comprehensive description of how these WECs work, as well as graphical illustrations of their design.

²⁰ Appendix B provides a description of other hydrokinetic resources, as well as an overview of offshore wind power.

²¹ More complex relationships for wind generators also exist, taking into account wind direction and shear; wind speed approximation is useful for many purposes.

design and size be optimized for a particular wave environment. For example, the wave energy technology or device size most suited to the resource off Hawaii may be different than that best suited to the Pacific Northwest.

Table 2: Wave Energy Converter Characteristics

Wind Power Curve	Wave Power Curve
 <p>Typical wind turbine power output with steady wind speed</p>	
<p>This graphic demonstrates the relationship between wind speed and the power output of a wind turbine. Design specifications could allow a lower rated capacity level (achievable through longer turbine blades or smaller generators). This could result in a more steady power output - at the cost, however, of less total power output.</p>	<p>This graphic demonstrates the three-dimensional relationship between wave height, wave period, and device power output. At a specific wave height/period combination power output plateaus at the device power rating. After a maximum wave height or period level power output drops to zero. (adapted from Pacific Energy Venture, 2009)</p>

4.2 Wave Energy Converter Design Considerations

Because the energy in waves diminishes as they come into contact with the seabed at shallower depths, placing converters in a near-shore environment allows them to collect only a fraction of the potential wave energy further out at sea. This loss of potential power must be weighed against benefits of being able to mount devices to the seabed, reducing the length of transmission lines, allowing converters to pump water to shore, facilitating operations and maintenance, and reducing the impact stress of waves on the devices and their anchoring and mooring systems.²² In addition to losing power, waves also change shape as they come into contact with the sea floor, creating yet another design consideration (CSIRO, 2012).

²² Appendix C provides a description of underwater electricity transmission as well as WEC mooring and anchoring systems.

WECs must not only be designed to cope with the everyday stress of absorbing wave power effectively, but also to survive extreme outlier events, such as wave power surges that occur perhaps only once every 20, 50, or 100 years (Waters, 2008). Strategies for reducing the exposure of WECs include submerging parts (or the most expensive parts) of the device (CSIRO, 2012). Successful designs must also consider how to deal with the corrosive nature of seawater and how to minimize the difficulty of regular operations and maintenance (O&M), which is complicated by the marine environment. In addition, if devices are designed to face directly the prevailing wave direction, mechanisms allowing them to change alignment are important.

Issues that WEC technology or project developers need to consider include: the transmission cost of siting a project further off-shore, potential interference of an above-water system with other uses (such as recreational uses and navigation), visual impacts, conflicts with fishermen or other commercial interests over a WEC array's footprint, and wave energy levels in an offshore or near-shore environment. WEC technology developers need to consider these issues in their technology design processes.²³ The inherent trade-offs also help to explain why a plethora of design options exist. Different options will be appropriate for different resources and site constraints.

²³ For example: one WEC developer noted that a successful design must meet three criteria: It must be acceptable to stakeholders, cost effective, and available (i.e. survive winter storms, etc.). He noted that technical failure had occurred where all three conditions were not met. Another WEC developer noted that the biggest challenge was to strike the correct balance between extracting the maximum amount of wave energy and surviving in conditions where higher wave energy resources exist. Several developers noted that there would likely be no agreement on a single device-type, as various customers with different device needs exist. Some may require, for example, that a device be fully submerged.

5. Wave Energy Technology Development Trajectory

While many WEC designs show promise in harnessing wave power and addressing design trade-offs, they remain emerging technology and have only a few commercial projects successfully deployed worldwide. As a relatively new addition to a still-emerging clean energy sector, the WEC industry is still very dependent on public funding and support, although private investors have provided some financing for technology development.

Public policies pursued in developing other successfully commercialized clean energy technologies may provide insight into successful and less successful approaches to supporting WEC technology development. In a 2011 Harvard Business School study that analyzed wind technology development trajectories in the United States and Denmark, Denmark's efforts in developing wind technology stood out as an example of how consistent public policy support, incremental growth and learning within the industry, device testing, and transparency on device performance can advance a technology from infancy to full commercialization. In the United States, efforts to develop a wind industry focused on providing grants to large established contractors and incentivizing development of projects with still unproven technology. This approach was less successful than the one taken in Denmark (Jones & Bouamane, 2011).²⁴

Applying some of Denmark's approaches to commercializing wind technology, the US Department of Energy (DOE) provides funding for research and development (R&D) of emerging WEC technologies, facilitates the testing of devices, helps address potential stakeholder concerns, and supports development of international standards for WEC performance.

5.1 The United States Department of Energy Water Power Program

The DOE's Water Power Program, created in 2008, is a significant driver for innovation in the wave energy industry in the United States, and remains a critical source of funding for many US-based WEC technology developers. However, compared to other renewable technologies, the amounts allocated to wave energy development have been modest. While the DOE budget for expediting development and deployment of ocean energy technologies increased from \$31.6 to \$41.3 million from 2013 to 2014 (Ocean Energy Systems, 2014), the amount requested for water power in 2015 was just over half of what was requested for wind, and almost one-fifth of what was requested for solar.²⁵

The Water Power Program uses its funds to support development of environmentally safe and cost-competitive technology. The program's technology advancement pillars are 1) technology development, including funding device and component development, testing devices, and funding test sites; and 2)

²⁴ A more comprehensive analysis of wind energy development and a history of wave energy technology development can be found in Appendix D and E.

²⁵ The DOE's Energy Efficiency and Renewable Energy Office (which houses the Water Power Program) 2015 budget request for renewable energy generation was \$521 million. Of this amount \$62.5 million was requested for water programs, \$61.5 for geothermal, \$115 million for wind, and \$282.3 for solar. See: (DOE, 2014b). Retrieved from: www.energy.gov/sites/prod/files/2014/03/f8/eere_fy15_budget_breakout.pdf, - last accessed May 14, 2015.

market acceleration, which includes identifying barriers to industry development, funding studies on potential environmental impacts, and making resource assessments. (DOE, 2011a).

From fiscal year (FY) 2008 to FY 2014, DOE made awards to 95 marine hydrokinetic projects, totaling \$116 million. Of this amount approximately \$21 million (18%) was directed toward wave energy systems development, including R&D grants to WEC developers. \$30 million (26%) was allocated to the development and construction of test facilities, including the Northwest National Marine Renewable Energy Center (NNMREC). \$11 million (10%) funded a study of environmental impacts and siting issues, and \$2 million (2%) was directed towards resource assessments. Of the total \$116 million, \$13.8 million went to Oregon, \$13.3 million to Washington, \$18.3 million to Maine, \$9.7 million to Hawaii, and \$9 million to California (DOE, 2014a).

In addition to providing funds to specific developers to advance their WEC designs, the program also allocated funds to companies developing components that would be useful within the wave energy device supply chain, such as specialized power conditioners, energy storage devices, and sub-sea electricity generators. The DOE also allocates funds under the Small Business Innovation and Research (SBIR) program. The program allows small businesses to compete for federal R&D funding in a three-phase approach, moving from technology concept development, through R&D, to commercialization.²⁶

5.2 Technology Development Metrics

Technology Readiness Levels (TRL) is a concept originally developed by the National Aeronautics and Space Administration (NASA), and is used by DOE to evaluate the development trajectory of emerging WEC technologies. TRL can help track a device's development from concept, to pilot, to pre-commercial, to full commercialization; it can also provide a common, structured, comparable set of criteria for analyzing technology development. At the final TRL 9, the system will have been demonstrated to work over the full range of operating conditions and be ready for small-scale commercial trials. While TRL is a tool for public agency decision-making, it can also help a more general audience evaluate how far a technology has progressed toward commercialization.

In addition to TRLs, the Department of Energy now considers Technology Performance Levels (TPL) in its wave technology evaluation processes. The TPL concept is a tool for measuring the "techno-economic performance of a WEC system" (Weber, 2012, at 2). TPLs are defined by system acceptability, capital expenses, operational expense over a project life-cycle, and power absorption capability. A key difference between TRLs and TPLs is that the cost of energy for a device decreases at higher TPL levels (Weber, 2012). While TRLs are currently the more widely cited performance metric for WECs, TPLs provide an additional useful metric for assessing how a WEC moves through a development arc from concept design through, for example, open water testing of prototypes, to full-scale devices.²⁷

²⁶ For more information see: www.science.energy.gov/sbir/about/

²⁷ Appendices F and G provide additional details on the interaction between TPL and TRL, as well as more specificity on what each level measures.

5.3 Wave Energy Test Sites

Offshore test sites encourage “the development of ocean energy, facilitating the administrative and legal requirements and enabling practical experience of installation, operation and maintenance of prototypes” (Ocean Energy Systems, 2014, at 9). Test facilities assist developers in generating data on their devices’ survivability and power generation capabilities, and are instrumental in demonstrating TRL level advancement. In Denmark, for example, a wind test site played a critical role in the successful development of wind technology. Open water wave energy test sites are similarly important to WEC development.

European dominance in terms of the number of active firms is associated with its relatively larger number of publicly funded marine test sites. Of nine global test sites, seven are located in Europe (Marine Energy Matters, 2015). The oldest and most prominent of the world’s marine energy test sites is the European Marine Energy Center (EMEC), which is located in Orkney, Scotland. This center, which conducted the first grid-connected, offshore wave device test in 2004, offers a 14-berth full-scale, grid connected test site, as well as two scale testing sites. EMEC facilitated testing of five wave and seven tidal devices in 2014 (EMEC, 2013).

United States Test Sites

The importance of test facilities may be seen in the long backlog of devices requesting time at EMEC. The US has begun to develop its own testing sites with publicly supported wave energy test facilities in Hawaii and Oregon. The grid-connected Hawaii test site has hosted two different technologies, with three others planned for deployment in the next two years. The Oregon facility, which is not yet connected to the electrical grid, has hosted one company, Northwest Energy Innovations. Many WEC developers have advanced sufficiently to be able to demonstrate that their technology can produce usable power in the ocean. Demonstrating working devices also helps developers to attract investment. Test sites are therefore critical resources for developers to refine their devices and build investor confidence.

Hawaii

The US Navy’s Wave Energy Test Site (WETS), located at the Marine Corps Base Hawaii on Oahu, Hawaii, is currently the United States’ only grid-connected test site.²⁸ The Hawaii National Marine Renewable Energy Center (HINMREC), a part of the University of Hawaii, supports the Navy at WETS with the help of an \$8 million DOE grant (DOE, 2014a). One of the advantages of the WETS site is that the wave energy power density at the site is more constant and lower than other test sites throughout the year, but still has significant wave power spikes. This allows wave energy device testing under a relatively wide range of conditions, while also allowing devices to be deployed and retrieved throughout the year²⁹ (DeVisser et al., 2013).

²⁸ Grid connected device testing allows technology developers not only to demonstrate to investors or clients that their devices can generate electricity (which can be demonstrated at an unconnected site), but also that the energy that is created is conditioned to be usable by a local utility.

²⁹ An expansion of the site is planned that will allow testing 30m, 60m, and 80m depths. The two deeper sites will allow for higher levels of transmitted power (250kw at 4.16 kV and 1 MW at 11.5 kV).

Ocean Power Technologies tested a single 40 kW buoy at the WETS 30m test site from 2003 to 2011.³⁰ Northwest Energy Innovations was awarded a DOE grant to test its Azura prototype at the same 30m test site, and deployed the device in June 2015.³¹ In 2016, Columbia Power Technologies will be testing its utility-scale StingRAY for a minimum of 12 months³² and Fred.Olsen Renewables (FOR) will test its LifeSaver design.³³ In addition, Ocean Energy USA, LLC has also been awarded a DOE grant to test its oscillating water column technology at WETS.³⁴

Pacific Northwest Test Facilities

The Northwest National Marine Renewable Energy Center (NNMREC) is a collaboration between Oregon State University (OSU), the University of Washington (UW), and the University of Alaska Fairbanks (UAF). Each of the institutions supports hydrokinetic energy device testing primarily according to the water energy resource where they are located: OSU focuses on wave energy on the coast and in laboratories, UW focuses on tidal technology testing in the Puget Sound, and UAF focuses on riverine hydrokinetic testing in the Tanana River.

OSU supports scaled wave energy device testing at its Pacific Marine Energy Center (PMEC) in a laboratory wave pool and full-scale, open water testing off the coast of Newport, Oregon at its North Energy Test Site (NETS). NETS can accommodate up to 100 kW for grid emulation using its Ocean Sentinel buoy. Northwest Energy Innovations was the most recent company to conduct a test at NETS in 2012.

In 2014 OSU received a \$4 million grant from the DOE to develop a South Energy Test Site (SETS). The proposed site, to be located 6-7 nautical miles off the coast of Newport at a location identified in collaboration with the local fishing community will provide for grid-connected testing and device certification. It is planned to be operational in 2018. Deployment costs to developers will vary depending on a number of variables specific to the device. According to a market survey, there is a very strong demand for SETS among WEC developers, with most expressing a desire to expand demonstration projects there into full-scale commercial projects (Garra Hassan, 2013).

OSU also signed a Memorandum of Understanding with the Oregon Military Department to support wave energy device testing off the coast of Camp Rilea (near Warrenton, Oregon) at a near-shore, off-grid location. The Oregon Military Department has a particular interest in supporting the development of wave energy systems, given its commitment to the Department of Defense energy net-zero initiative: to

³⁰ See: Vega, L. (2015). Retrieved from www.hinmrec.hnei.hawaii.edu/nmrec-test-sites/wave-energy-project-at-mcbh/ - last accessed May 14, 2015.

³¹ See: NWEI (Northwest Energy Innovations). (2013). Retrieved from www.azurawave.com/projects/hawaii/ - last accessed May 14, 2015.

³² See: Columbia Power (2014). Retrieved from <http://columbiapwr.com/723/r> - last accessed May 14, 2015.

³³ See: reNEWS. (2015). Retrieved from www.renews.biz/81837/fred-olsen-lifesaver-sails-for-hawaii/ - last accessed May 14, 2015.

³⁴ See: Danko, P. (2014). Retrieved from www.breakingenergy.com/2014/11/05/wave-energy-developers-line-up-for-hawaii-test-site/ - last accessed May 14, 2015.

produce as much energy from renewable energy resources on its bases as it consumes there, and to be able to operate in the absence of the power grid during emergencies.

In the summer of 2014 the Salem, Oregon-based company M3 Wave successfully tested its submerged pressure differential device at Camp Rilea without financial support from the Oregon Military Department. The test was also significant because it was the first time that the Oregon Territorial Sea Plan (TSP) marine renewable energy siting process was applied³⁵, and the first time that a company had deployed a marine energy device following 2013 legislation requiring wave energy developers to provide financial assurances that their devices will be removed. Resolute Marine Energy is planning to test its wave surge converter technology in 2016.

One argument for the Pacific Northwest test sites is that they can provide a more energetic wave environment than the one found in Hawaii. Thus, the sites can provide a complementary service: first, developers can test and refine their products in an easier operating environment at Hawaii's WETS. Then they can demonstrate the reliability of their devices in the more difficult operating environment of the Oregon coast. An additional step could be to deploy excess transmission capacity to the sites, which could enable developers to expand into commercial projects.

5.4 Wave Energy Technology Standards

The International Electrotechnical Commission (IEC), responsible for electric industry standards, has taken on the task of developing a set of global performance standards under its Technical Committee (TC) 114. It notes that the "establishment of international standards will assist in mitigating the technical and financial risks associated with the diverse range of technologies that currently exist enabling a quicker uptake of commercial marine energy production."³⁶

The IEC is currently engaged in developing wave and other marine renewable energy device standards for system definition, performance measurement, survivability requirements, safety requirements, power quality, testing, and environmental impacts. The IEC established the TC 114 technical committee in 2007; while it has not formally adopted any standards, it has developed several drafts. The American Standards Institute and DOE are actively supporting the TC 114 process, and the US industry has supported standards development and monitored progress on TC 114 shadow committees.

As the IEC develops its international standards, wave energy technology developers continue to have the option to work with private firms like DNV-GL to provide technical due diligence reviews of their technologies and certifications, which helps secure investor confidence. Given the relatively low TRLs for many wave technologies, final device or array certification is likely to be an issue that will gain in importance as the industry matures. The need for making advances in device certification was highlighted by one study, which noted that "there have been numerous structural and system failures in devices and their associated moorings that have been subject to certification," and that certification systems "have some way to go before being considered reliable in the sector" (Aquatera Ltd., 2014, at 15).

³⁵ See section 3.3 State-Level Policy Support for more information on the TSP.

³⁶ IEC [International Electrotechnical Commission –]. (2013). Retrieved from www.iec.ch/cgi-bin/getfile.pl/sbp_114.pdf?dir=sbp&format=pdf&type=&file=114.pdf - last accessed May 6, 2015.

6. Wave Industry Overview

Small and medium sized enterprises are “the primary vehicle for [WEC] technology development” (Aquatera Ltd., 2014, at 13), with larger enterprises, such as large engineering companies, project developers, and utilities only becoming involved more recently as designs emerge from the prototype phase (Aquatera Ltd., 2014). According to one review there are currently 46 active WEC technology developers worldwide (Marine Energy Matters, 2015). Of these, twelve are based in the United Kingdom, seven in the United States, five in Sweden, four in Norway, four in Australia, and three in Denmark. The remaining companies are primarily located in other European countries, although Israel, Japan, and Singapore also host developers (Marine Energy Matters, 2015). The first full-scale device was deployed in Japan in 1980. This project was made possible through collaboration between Japan and the International Energy Agency (IEA).³⁷

6.1 Recent International Developments

Over the past few years the wave energy industry has contracted, with the number of WEC developers dropping by half since 2011. The industry

also recently experienced a decline in the number of full-scale prototypes, falling from nine in 2014 to seven in 2015. The trend toward increasing the scale of devices also reversed in 2014, the first year that the number of devices above 100 kW being tested declined. While the industry had seen lower TRL technologies drop out in the past, 2014 was the first year that the industry experienced the failure of a leading company: Pelamis. According to the UK trade group Marine Energy Matters, consolidation of the sector “is perhaps symptomatic of a global decrease in funding to deliver expensive design... and a continuing challenge to show results which will inspire investor confidence and take the pressure away from public sectors support” (Marine Energy Matters, 2015, at 4). It also notes that the WEC technology “sector still seems to be a long way from the

development of arrays” despite continuing development activities, and that the sector still needs to make progress on technology maturity and “associated investor confidence” (Marine Energy Matters, 2015, at 5).

Pelamis Bankruptcy

Pelamis, a Scottish company started in 1998, had developed the world’s first commercial-scale prototype to deliver electricity to the electricity grid in 2004. It filed for bankruptcy in 2014 after failing to secure enough funding to continue developing its linear attenuator devices. The German energy giant E.ON had pulled its own funding from Pelamis projects in 2013.

While the Pelamis P2 design had led the wave energy sector for years, having logged over 10,000 grid-connected hours of operation, it suffered from survivability issues and was unable to be left at sea in all wave/weather conditions. In 2008 three Pelamis P2 converters had been connected to the electricity grid off the coast of Portugal. The devices had to be brought to shore, however, after failing to perform as expected (Pacific Energy Ventures, 2009). The five-section Pelamis P2 device was 180m long, weighed 1,350 tons, and was rated at 750kW.

³⁷ Appendix E provides a comprehensive history of WEC device development.

The global drop in wave energy technology developers has not led to a convergence on design type. While point absorber technology developers experienced the most significant drop, they are still the most numerous, with 16 developers continuing to work on that design-type worldwide. Oscillating wave surge converter developers follow, with eight developers worldwide. Submerged pressure devices were the only technology type to see a global increase since 2014 (Marine Energy Matters, 2015). The continuing diversity of device types may, however, reflect the wide diversity in wave resources and siting conditions to which the different device designs may be best suited.

Active Wave Energy Arrays

While the Marine Energy Matters report stresses some of the obstacles to commercialization of wave energy, several functioning WEC arrays have already been deployed. One of the significant success



Carnegie Wave Energy's CETO 5 Unit #1 tow out to offshore site.

Image Source: www.carnegiwave.com



Mutriku oscillating water column.

Image Source: Ocean Energy Systems Annual Report 2014

stories in the wave energy sector is the recent launch of a commercial, grid-connected point absorber array in Western Australia. On 18 February, 2015 Carnegie Wave Energy, an Australian-based company, switched on the "world's first commercial-scale grid connected wave energy array."³⁸ This array consists of three 250 kW, 11m diameter point absorber buoys. The buoys pump water to onshore generators, where they produce electricity for a Western-Australian navy base, and also contribute towards the base's water desalination processes.

The company's CEO suggests that a 25 MW array of its technology could produce electricity at 30-40 cents/kWh, making it competitive with diesel-generated electricity. Moving forward, the company sees market opportunities in remote island communities and military bases where the cost of electricity is high, or energy independence is particularly valued³⁹.

Another active wave energy project consists of a 16-turbine oscillating wave column system that is attached to a breakwater on the coast of Spain, in Mutriku. The project, which cost \$3 million to install, has a capacity of 300 kW.⁴⁰ The project was commissioned by the Spanish Utility EVE and uses technology developed by Voith Hydro.⁴¹

6.2 United States Wave Energy Industry

According to OWET, DOE, and other industry documents, there are currently 12 wave energy technology developers active in the United States. Of these, nine have received funding from the DOE for developing

³⁸ Vorrath, S. (2015). Retrieved from www.reneweconomy.com.au/2015/worlds-first-grid-connected-wave-energy-array-switched-on-in-perth-77510 - last accessed May 6, 2015.

³⁹ Economist. (2015). Retrieved from www.economist.com/news/science-and-technology/21646176-new-project-coast-australia-may-make-wave-power-reality-looks-swell - last accessed May 6, 2015.

⁴⁰ "Frayer, L. (2012).. Retrieved from www.npr.org/sections/alltechconsidered/2012/11/26, - last accessed May 14, 2015.

⁴¹ "Hydroworld. (2011).. Retrieved from www.hydroworld.com/articles/2011/07/spain-mutriku-.html - last accessed May 16, 2015.

their technologies. Designs they are pursuing include oscillating wave surge converters, point absorbers, and submerged pressure devices. Some of the companies operate internationally and have offices in several countries. The Pacific Northwest hosts five WEC developers, including Columbia Power (with offices in Oregon and Virginia), Northwest Energy Innovations (Oregon), M3 Wave (Oregon), Ocean Motion (Oregon), and Oscilla Power (Washington).

Individual firms are pursuing innovative applications for their technologies, such as integrating device operations with desalination processes, connecting directly to and displacing diesel generators, or powering small devices at sea. None of the companies has yet deployed a commercial scale, grid-connected generator, although many are testing their devices in offshore test-sites in order to advance and demonstrate their designs.⁴²

While several developers see the need to function as both project developers and technology developers, at least in the immediate term, most wave energy companies see themselves first and foremost as technology developers, noting that other, larger companies may be better suited to develop and site wave energy projects. However, some companies may need to take on project development, targeting niche and high electricity cost markets, until they are acquired by larger entities or traditional project developers step forward to market and develop WEC arrays.



*Northwest Energy Innovations Azura
Hawaii Deployment
Image Source: Azura Wave*



*Columbia Power Technologies SeaRay
Puget Sound Deployment
Image Source: Columbia Power Technologies*

Industry and Market Developments in the Pacific Northwest

The Pacific Northwest continues to see ongoing industry activity, in terms of utility interest in marine hydrokinetics, device testing, and local marine renewable companies winning R&D grants. Three Northwest utilities, including Snohomish PUD, Central Lincoln PUD, and PNGC Power⁴³ and California's Pacific Gas and Electric (PG&E)⁴⁴ have actively participated in marine hydrokinetic projects. Oregon's Douglas PUD and Tillamook County PUD were early proponents of wave energy, filing for preliminary FERC applications in 2006 and 2007, respectively.⁴⁵ Portland General Electric (PGE) noted in its 2013 Integrated Resource Plan that wave energy could play a role in meeting future Renewable Portfolio Standard (RPS) requirements (once the technology is commercially available). Moving forward, some

⁴² Appendix H provides a list of United States WEC developers, as well as information on their technologies and levels of DOE funding.

⁴³ PNGC Power is an electric generation and transmission (G & T) cooperative owned by 14 Northwest electric distribution cooperative utilities operating in Oregon, Washington, Idaho, Montana, Utah, Nevada and Wyoming).

⁴⁴ PG&E was interested in developing wave energy projects in Northern California.

⁴⁵ They were granted preliminary FERC permits in 2007 and 2008, but did not develop the proposed projects. According to one person familiar with the situation, the 2008 economic recession had a strong impact on regional interest in wave energy project development.

regional utilities said they would consider joining an ocean energy development consortium in order to advance projects.

Snohomish PUD pursued a pilot project to deploy tidal generators in the Puget Sound, as part of its wider green-energy strategy beginning in 2005. However, cost overruns created by legal opposition by an adjacent subsea telecommunications company eventually contributed to the demise of that project. PG&E sought to build a wave energy test facility, WaveConnect, off the coast of Northern California, and secured \$1.2 million DOE funding, as well as California Public Utility Commission (CPUC) approval to expend \$4.2 million.

PNGC Power signed a power purchase agreement (PPA) with Ocean Power Technologies for its planned Reedsport project.

And PGE has supported the work of NNMREC by providing the center with small and strategically significant grants from its R&D budget.

Ocean Power Technologies Reedsport Wave Power Project

Ocean Power Technologies, a wave energy leader, secured all required state permits to deploy a commercial wave energy project 2.5 miles off the Oregon coast near Reedsport, Oregon, and was the first wave energy company to secure a FERC permit for a commercial project. Despite these regulatory achievements, and building a working WEC at Oregon Iron Works, the company withdrew from its plan to deploy up to 100 of its 150 KW PowerBuoys for what would have been the United States' first commercial wave energy array. According to news reports, despite spending over \$20 million of its own resources, the company ran out of money to move forward with the project. It cited a prolonged FERC-licensing process, which it began in 2007, and complications arising from poor weather for the cost overruns. Despite this setback, the extensive permitting and stakeholder consultation process associated with the project significantly raised awareness about wave energy in Oregon and paved the path for other companies to follow.

In 2011 PG&E decided to discontinue its WaveConnect program, citing "challenges related to project permitting, licensing, economics, and stakeholder concerns" (PG&E, 2011, at iii). While the utility decided to discontinue the project due to a more costly-than-anticipated permitting process, and strong environmental impact uncertainties related to general lack of experience with WECs, it noted that wave energy "is a predictable base-load resource" and that as wave energy "technologies mature, and regulatory and permitting agencies grow more familiar with their environmental

impacts, PG&E believes that wave power will merit further evaluation, demonstration and deployment" (PG&E, 2011, at ii).

While regional utilities have demonstrated interest in wave and tidal energy, many developers, noting that costs of wave energy are likely to be relatively high in the near-term, see the most immediate market opportunities in remote, off-grid communities, such as in Alaska and the Pacific Islands, where power is frequently primarily supplied by diesel powered generators, and wave energy can more easily compete

Snohomish PUD Admiralty Bay Tidal Demonstration Project

Snohomish PUD began the FERC licensing process for its Tidal Energy Demonstration Project in 2006, filing for its final pilot license in 2012. In receiving a FERC license it was allowed to deploy two 250 kW Ocean Renewable Power Company (ORPC) tidal turbines at 60m depth for 5-8 years. With matching funds of up to \$10 million from the DOE the PUD had planned to deploy the first tidal energy array in the United States. However, rising costs associated with the longer-than-expected FERC licensing process caused the PUD to decide not to move ahead with the project in September 2014.

with existing resources⁴⁶. The cost of diesel generation ranges from \$297 to \$332/MWh in these remote areas, roughly ten times Pacific Northwest wholesale market prices. Today's relatively low wholesale price of power from competing resources, such as wind and solar in the \$50-100/MWh range, provides a difficult competitive environment for new power generation technologies. Niche markets such as isolated coastal

towns and special needs for resiliency or other concerns (e.g., connectivity to a larger power system) represent the best near-term markets for wave energy technology.

Despite these cost issues and project setbacks, some Northwest utilities, both PUDs and investor-owned, have indicated their continuing interest in supporting ocean energy development. While these utilities have pursued initiatives individually since 2006, a regionally focused, multi-institutional effort could allow them to share benefits and risk, pool resources, and provide for incremental and strategic development of the wave energy resource.

⁴⁶ In 2010 approximately 15% of Alaska's electricity was produced by diesel generators (amounting to 1.7 million barrels of diesel fuel). Much of this electricity was produced in coastal communities. See: (Melendez & Fay, 2012).

7. Barriers to Commercialization

Despite the strong Pacific Northwest resource potential, the interconnected system benefits of coastal power generation, utility interest in marine hydrokinetics, and policy support for the sector, the economics of the wave energy industry dictates that it will continue to experience difficulties for the foreseeable future in reaching full commercialization and full scale array deployment in the Pacific Northwest. Barriers to commercialization center around developing a reliable technology that can compete with fully demonstrated and commercialized renewable resources such as wind and solar.

Achieving a full commercial design for ocean power generation is hampered by a balkanized system of financing and technology development. Although much attention is paid to project costs, those costs cannot be known until reliable designs are developed and deployed at scale. Arguably, the biggest impediment to reaching that goal is achieving reliable designs; that, in turn, is limited by access to capital in the pre-commercial development of such designs. It appears that more can be done to focus available resources, especially with respect to more active and broader utility sector involvement.

7.1 Demonstrating Reliability

Wave energy devices must be deployed in a highly energetic, corrosive, and difficult marine environment. Not only do devices have to be optimized to perform under a range of wave regimes, but they must also be designed to survive extreme conditions (i.e., severe storms). Designing cost-effective devices that can be operated, maintained, and survive in harsh marine conditions continues to be one of the significant challenges of the industry. Survivability and performance issues continue to be critical design challenges for emerging wave energy converters and each technology developer addresses them differently.

The presence of a test facility in both a moderately energetic and a highly energetic wave environment could allow developers to test and refine their designs in Hawaii before deploying them in the Oregon to demonstrate their survivability. With proper planning, grid connected devices and/or arrays at a grid-connected NNMREC facility could be developed into full-scale commercial projects.⁴⁷

7.2 Access to Development Capital

Wave energy developers face difficulties in attracting capital for their investments owing to the risks involved in early development work and an uncertain return on investment. There has also been a more general reduction in private investment in the renewable marine energy sector. Investors perceive the sector as risky, that technology is developing slowly, and that no consensus on device-type has emerged. One developer said that investors “don’t know where a reasonable investment prospect is. They are waiting to see which pony will pull ahead.”

⁴⁷ PG&E had envisioned such a strategy for its Wave Connect Project.

The bankruptcy of Pelamis, an industry leader for many years, demonstrates that the leading technology may not be the best bet, and that technologies currently at lower TRLs may emerge as offering a more reliable and cost effective device in the future. Less mature technologies can benefit from the experience of longer-lived devices, plugging into a more mature marine renewables sector and supply chain, and utilizing emerging research. Demonstrating the reliability and survivability of emerging devices is key to instilling investor confidence and attracting capital. In addition, information sharing and collaboration within the industry, and transparency regarding device performance can encourage successful innovation and attract venture capital.

7.3 Stakeholder Scrutiny

Unlike other renewable energy projects, which can be built on private property, wave energy devices and arrays are sited in a public environment where there may be multiple competing uses. While other energy projects are also sited in an offshore environment, wave energy projects are likely to face a higher degree of scrutiny than more established industries, given regulators' and the public's lack of familiarity with the environmental impacts of the technology.

Stakeholder scrutiny and skepticism exists, despite the fact that the risks of these projects are likely much smaller than risks associated with some offshore fossil fuel extraction (which were highlighted by the Deepwater Horizon oil spill in the Gulf of Mexico in 2010). Further, the process of siting marine renewable energy projects and addressing stakeholder concerns is complicated by regulators' reliance on rules and regulations that were developed for other offshore energy industries (Ocean Energy Systems, 2014).

One of the significant wave energy's competing uses is commercial fishing, a critical part of the Pacific Northwest's coastal economy. The Oregon Dungeness Crab Commission, for example, has been an important participant in the discussions regarding siting of wave energy devices and arrays, and had opposed the expansion of the OPT Reedsport project given the array's potential impact on fishing grounds.⁴⁸ Several interviewees noted that successfully managing the relationships with the fishing community was critical to the developing wave energy projects on the Oregon coast, and that the TSP amendment process may be useful to establish rules and provide transparency to avoid backlash against wave projects.

Given the many uses of the ocean, multiple stakeholder concerns should be addressed early in the process, so as to develop and deploy marine renewable energy devices sensibly. Interest groups may include recreational groups, such as Oregon's Surfrider Foundation (which was involved in the TSP amendment process), property owners who may object that siting wave energy projects obstructs ocean views⁴⁹, and others. When Snohomish PUD sought to deploy its tidal pilot project, for example, one of the major opponents to the project was a trans-Pacific cable company that did not want the project to be sited in proximity to its undersea fiber optic line.

⁴⁸ "KCBY. (2008). Retrieved from www.kcby.com/news/local/16583056.html - last accessed May 14, 2015.

⁴⁹ The TSP REFSSA near Pacific City is restricted, for example, to projects that do not attract attention.

While stakeholder scrutiny is a serious challenge to the deployment of wave energy projects in the Pacific Northwest, the region has made significant gains in alleviating concerns and finding models for interacting with other marine stakeholders on siting wave energy projects. As stakeholders gain familiarity with wave energy devices, it is likely that resistance to the “new kid on the block” will decline. Early development efforts, such as those pursued by Ocean Power Technologies and Snohomish PUD, have already greatly facilitated public understanding of marine renewable energy, and have highlighted the importance of keeping stakeholders informed of developments and building local partnerships.

7.4 Licensing and Permitting

The State of Oregon regulates marine energy within three nautical miles of the Oregon coast, as laid out in Part Five of the TSP. Beyond the Territorial Sea Plan purview, marine energy projects fall under federal jurisdiction and require a lease from the Bureau of Ocean Energy Management (BOEM). Any grid-connected project, regardless of location, requires a FERC permit.⁵⁰

The Energy Policy Act of 2005 provides BOEM with a framework for authorizing renewable energy projects, and BOEM conducts outreach to stakeholder groups early in its authorization processes in order to avoid potential conflicts.⁵¹ FERC issues preliminary permits, and standard (up to 30-50 years) and pilot project licenses for wave energy projects. As of April 2015 FERC had issued three wave project permits (two in California and one in Alaska) and no wave energy licenses.⁵²

PG&E, Ocean Power Technologies, and Snohomish PUD all noted that the licensing and permitting process was a cost driver in their planned projects, all of which were cancelled due to higher-than-projected costs. Some developers, however, have observed an improvement in the coordination between BOEM and FERC in the permitting process.

In addition, the TSP amendment was designed to align state-level requirements with FERC requirements in order facilitate the planning process. While a FERC permit was not needed for the 2014 M3 Wave Camp Rilea test, the efficiency with which the state-level siting processes took place demonstrated the success of the TSP interagency-process and REFSSA arrangement.

7.5 Cost Barriers

As noted earlier, power prices in the Pacific Northwest make it difficult for emerging technologies to compete. Even with significant grants from the DOE, some marine renewable energy companies have experienced difficulty in securing power purchase agreements from regional utilities. Low regional power prices have led many developers to consider higher value markets (e.g., where power is produced locally

⁵⁰ See: ODOE (Oregon Department of Energy). (2015). Retrieved from www.oregon.gov/energy/RENEW/Pages/marineenergy.aspx - last accessed May 14, 2015.

⁵¹ See: BOEM (Bureau of Ocean Energy Management). (2015a).. Retrieved from <http://www.boem.gov/Regulatory-Development-Policy-and-Guidelines/> - last accessed May 14, 2015.

⁵² FERC (Federal Energy Regulatory Commission). (2015).. Retrieved from <http://www.ferc.gov/industries/hydropower/gen-info/licensing/hydrokinetics.asp> - last accessed May 14, 2015.

from diesel generators) as early market entry points. One wave energy developer noted that “utilities are the wild card” for the prospects of developing wave energy projects on the Pacific coast, and that “everything depends on what utilities are willing to pay.” On the other hand, utilities have limited funds for research and development, with regulatory approval of long term power purchase agreements typically reserved for resources deemed least-cost and least-risk.

One expert noted that there is currently no regional driver for new resources, least of all for emerging technology. He described the difficulty of penetrating the Pacific Northwest electricity market as “real tough sledding.” He noted that before 2008 everyone thought loads would grow and that power prices would stay high, but that everything changed with the 2008 economic crisis, which had a dramatic effect on interest in deploying wave energy resources.

The advantage of pursuing high-cost markets is that deploying projects, even on a smaller scale, allows developers to demonstrate that their technology can survive and produce useful power, which can help to secure investor confidence for larger projects or at least wider deployments. One developer highlighted that the “only viable path for investor money is to locate projects where people can pay for high cost energy.” The disadvantage is that small markets in which small arrays are deployed do not allow developers to demonstrate technologies capable of achieving the economies of scale that is likely to drive down their power costs.

Estimates for the cost and the cost drivers of wave energy vary, especially since the various technology developers seek to reduce cost drivers in different ways. It is therefore difficult to characterize the estimated levelized cost for wave energy. However, some studies have estimated some of the cost drivers in general terms. One study estimates that marine generators can be cost competitive with other renewable energy resources by the mid-2020s, assuming targeted innovation in a stable policy environment (Carbon Trust, 2011). One study suggested that achieving cost competitiveness with other renewables requires, “significant cost reductions at all levels. Cost reductions traditionally occur through knowledge sharing, collaboration and joint ventures and that this must happen in this sector to drive down costs” (Ocean Energy Systems, 2014, at 37). One of the aims of PMEC-SETS facility will be to provide a venue to share lessons-learned.

In the near-term future it remains likely that WEC technologies will not be price-competitive with other renewable energy resources. However, Pacific Northwest wave energy projects can provide many benefits that currently may not be fully valued. Encouraging the growth and development of WEC technology and projects in the Pacific Northwest with a coordinated, risk-sharing approach might allow regional clean energy market players to by-pass traditional energy contracting mechanism (by, for example, finding ways to expand demonstration projects to medium, then full-scale arrays as WEC designs are proven and are refined), encouraging the development of technologies in the regional wave climate, increasing the likelihood that the first reliable designs are most effective here.

8. Summary, Conclusions, and Recommendations

The Pacific Northwest is a natural center for wave energy development. Not only does the region have an abundant wave energy resource, but the resource also has integration and capacity qualities that will make it attractive to utilities. The potential beneficiaries of wave energy resources are manifold: transmission providers and power consumers benefit from a more stable electrical grid; utilities benefit from more diversity in their renewable energy portfolios; the local economy benefits from high-tech, manufacturing, and services activities.

However, long-term regional engagement with wave energy shows that obstacles to the commercial deployment of WEC projects remain. A reliable and cost-competitive technology has not been proven, and progress on device development is hampered by limited access to capital. A more coordinated approach to setting priorities, combining capital sources, and spreading risks is warranted.

Although still an emerging technology, wave energy has made much progress in moving toward commercialization. Thanks to strong engagement by the State of Oregon, stakeholders and regulators are more familiar with ocean energy resources, and areas for development that offer minimal siting conflicts have been identified. Device manufacturers, and in particular Pacific Northwest companies, are advancing their designs, testing them in fully energetic environments and generating the kind of reliability and performance data that can both improve the technology and inspire investor confidence.

Regional utilities have long recognized the value of marine energy, pursuing the first FERC permits in 2006. However, utility engagement has been sporadic and somewhat balkanized. Combining expertise, interest, and capital, utilities can increase the efficiency of wave energy commercialization by working together with other backers and stakeholders. One such approach could be developing a regional consortium that jointly makes strategic investments and shares both risks and information. Experience from the wind industry has shown that sustained investment and policy support, incremental development, and transparency in sharing performance results can help propel a renewable energy technology to commercialization.

A regional collaboration might be led by the Northwest Power and Conservation Council and BPA to coordinate efforts among technology developers, government funding entities and utilities, help determine regional strategic priorities, determine reasonable and sustainable funding levels, and to identify and recommend projects meriting broad utility participation.

Appendix A: Wave Energy Converter Types

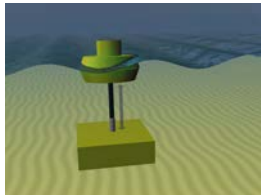
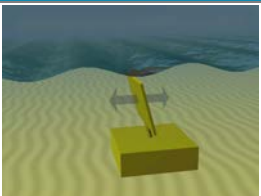
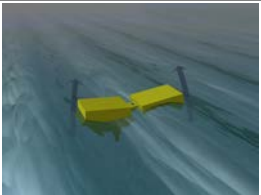
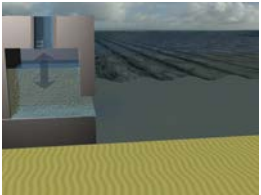
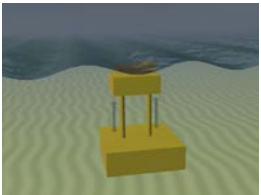
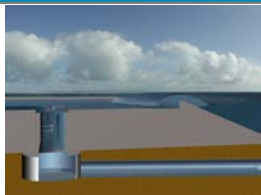
Point Absorbers	
Point absorbers capture wave power at a single point. A float connected to a relatively fixed point moves with the lateral and/or horizontal motion of the waves. The relative motion of the float to the fixed point powers an electricity-producing generator or pumps water to an on-shore generator. Because point absorbers can be either free-floating or attached to the seabed, they can be found in a range of ocean depths.	
Oscillating Wave Surge Converters	
Oscillating Wave Surge Converters capture power by connecting a flap to the ocean floor. Wave surges move the flap forward, converting the motion into electricity via a submerged generator, or pumping water to an on-shore generator. Because these devices are mounted to the seabed they are primarily designed for near-shore environments.	
Linear Attenuators	
Linear Attenuators are aligned with the incoming waves. The incoming motion of the waves moves floating components of the WEC system relative to each other. A generator at the hinges converts this relative motion into electrical energy.	
Oscillating Water Column	
Oscillating water columns convert wave energy to electrical energy by utilizing the pressure of the waves to push air and pull air through a column. The differential air pressure spins an air turbine that powers a generator. These devices can be attached to land to capture wave impacts or can be free-floating systems found in the ocean.	
Submerged Pressure Devices	
Submerged pressure devices are attached to the near-shore ocean floor. They capture wave energy by utilizing the pressure differential created by the changing level of the sea as waves pass overhead. The pressure differential drives fluids through an electricity-generating turbine inside the device. These devices are attached to the seabed and are designed for near-shore environments.	
Overtopping Devices	
Overtopping devices take advantage of wave surges to collect water in a reservoir that is elevated relative to the mean water level. When water flows out of the reservoir it engages an electricity-generating hydro turbine. Overtopping devices can be both free-floating structures or can be attached to the shore.	

Image Source: Aqua-RET

Appendix B: Other Marine Renewable Technologies

The wave energy technology sector exists in the wider space of marine renewable energy, and is often discussed relative with other systems, such as tidal energy, riverine hydrokinetic energy, and offshore wind energy.

Tidal Energy

Tides offer a highly predictable energy resource as they are produced by regular astronomical patterns. Projects seeking to extract energy from the flow of water created by tides focus on semi-enclosed bodies of water, where tides have the most significant amplitudes (CSIRO, 2012), and areas where natural features force water through narrow channels or around headlands (Georgia Tech, 2011), such as the Puget Sound. Underwater turbines or turbine arrays, such as the one that had been pursued by the Snohomish PUD (Snohomish County PUD, 2014), can capture the kinetic energy of these tidal flows. Tidal energy can also be extracted by filling up a reservoir at high tide and using that water to power turbines at low tide, as the ocean water recedes (CSIRO, 2012).

Although the overall energy potential of tidal flows in the United States is not known, a 2005 EPRI study estimated a resource of 16 TWh/yr (1,800 MWa) in Alaska and 0.6 TWh/yr (70 MWa) in the Puget Sound. A 2011 study estimated that Alaska had the highest number of locations with high tidal energy potential, followed by Maine, Washington, and Oregon (Georgia Tech, 2011). While tidal energy extraction offers predictability and no visual impacts (as the turbines are situated on the seabed), being fully submerged or mounted to the seabed can make operating and maintaining these facilities difficult. Currently 13 full-scale turbine prototypes have been developed in a global industry composed of 34 active firms (this includes riverine hydrokinetics, which are discussed below) (Marine Energy Matters, 2015). One of the leading companies in this sector is Ocean Renewable Power Company, based in Maine, which had been proposed for Snohomish PUD's Puget Sound project and currently operates a grid-connected tidal project in Maine.⁵³

Riverine Hydrokinetic

Similar to tidal devices, riverine hydrokinetic turbines capture the flow of water with underwater turbines in rivers. According to the 2012 EPRI assessment the United States had a 120 TWh/yr riverine hydrokinetic potential, enough to cover approximately 3% of the United States' electricity, and almost 8% of the estimated wave energy resource. 9.2% of this riverine resource was estimated to be in the Pacific Northwest, while the lower Mississippi region held 47.9% and Alaska held 17.1% (EPRI, 2012).

Riverine hydrokinetic energy offers a highly predictable resource as the flow rate in rivers usually does not change substantially from day to day and may have low environmental impacts. However, the resource suffers from low efficiency rates (Pham, 2014).

⁵³ For more details see Ocean Renewable Power Company website: www.orpc.co

Offshore Wind

Of the offshore marine energy sectors, the offshore wind industry is the most advanced, having been able to draw from onshore wind turbine designs. At the end of 2014 the global installed offshore wind capacity was 8,759 MW, with 91% of the installations found in Europe and the remaining 9% primarily in China.⁵⁴

While there are currently no offshore wind projects operating in the United States, the National Renewable Energy Laboratory (NREL) estimates that the gross offshore wind power resource is 4,223 GW: roughly four times the capacity of the United States electrical grid. While wind speeds off the Pacific Coast are highest, the shallower waters in the Atlantic make development there more accessible. Approximately 90% of the wind resource on the outer continental shelf occurs in waters that are too deep to site projects without floating support structures.

Besides offering an extremely abundant potential power resource, offshore wind also tends to blow more uniformly, making energy generated there from turbines less variable and more predictable than onshore wind. Offshore wind turbines are larger than onshore turbines, ranging generally from 2 MW to 5 MW nameplate capacity to benefit from significant economies of scale.⁵⁵

Principle Power, a Seattle-based company is developing a floating platform that can host wind turbines, allowing for deep sea deployment applicable to Northwest coastal waters. The company has received a DOE grant to demonstrate this technology with an up to 30 MW project off of the coast of Coos Bay, and is currently seeking a power purchase agreement for the project, which would allow the project to move ahead.

⁵⁴ Global Wind Energy Council (2015). Retrieved from <http://www.gwec.net/global-figures/global-offshore/> - last accessed May 5, 2015.

⁵⁵ The information on offshore wind was largely drawn from the BOEM (Bureau of Ocean Energy Management) (2015bOrego). Retrieved from <http://www.boem.gov/renewable-energy-program/renewable-energy-guide/offshore-wind-energy.aspx> - last accessed May 5, 2015

Appendix C: Associated Systems

Deploying offshore wave energy projects requires advanced mooring systems for floating devices. Both seabed-mounted and floating array systems require under-sea transmission cables to interconnect the devices with the on-shore electrical grid. While the technology for undersea electrical transmission is relatively advanced, mooring systems designs for holding wave energy converter arrays in place are still undergoing active research and investigation.

Undersea marine transmission cabling is a reasonably mature technology in regular use to connect islands to on-shore grids and connect transmission systems across rivers. Undersea transmission is typically High Voltage Alternating Current (AC) rather than High Voltage Direct Current (DC) (which is more efficient but more expensive) as DC transmission lines must typically be longer than 50 miles in order to be economical.

Despite its relative maturity, offshore transmission remains costly and time-consuming to deploy, in part because cables are subject to be buried closer to shore in order to avoid conflict with other marine activities. Deploying undersea transmission cables, which requires specialized vessels (currently limited in availability on the West Coast), takes approximately an hour per 0.1 mile and costs approximately \$2 million per mile (ODOE, 2014).

Europe has significant experience connecting offshore wind generators and deploying offshore transmission grids, with 11 grids currently operational. These grids connect wind farms to a single undersea sub-station at 20-33 kV. The substations boost the voltage level to the 132 or 150 kV for export to the on-shore transmission system (ODOE, 2014). Some studies are investigating advantages of low frequency transmission for underwater applications.⁵⁶

Mooring and Anchoring Systems

A WEC's anchoring and mooring system is an "integral part of the wave energy device system and its interaction and influence on wave buoy behavior and performance must be considered during the selection and design process" (Sound and Sea Technology, 2009). Wave energy developers can draw on extensive existing technology from other offshore applications to create mooring designs and configurations, and multiple options exist for anchorage systems for different seafloor compositions and water depths. In addition there are many possible mooring arrangements, supporting buoys, and lines (Sound and Sea Technology, 2009). The exact appropriateness of the options will be determined by the specific environmental and social constraints of a site, as well as the specific needs of the device or array.

Anchoring systems need to ensure that WECs can withstand severe weather and must take into account that the devices are by nature oriented to absorb the maximum amount of energy from a wave. Smaller

⁵⁶ See for example, Chen, H., Johnson, M., & Aliprantis, D. (2013)

devices (such as point absorbers) might require thousands of individual connections to devices when they are deployed in arrays, which according to one study could increase O&M and installation cost (CSIRO, 2012).

While the offshore oil and gas industry has significant and long-term experience with mooring and anchoring heavy offshore equipment, these mooring systems may not always be appropriate for the specific designs of wave energy devices, given wave devices' specific mass, distributions, wave profiles, and array footprints (Weller et al., 2012). Thus, advancing anchoring and mooring systems specific to offshore wave energy devices is an ongoing research effort, requiring sea-trials and testing in line with those being conducted for the WECs themselves (Harnois et al., 2012).

A 2013 report notes that while there are similarities between mooring systems for existing offshore equipment and large-scale ocean marine devices (such as floating wind turbines) that allow developers to draw on existing mooring technology, smaller wave energy devices, such as point absorbers, have specific design constraints, such as being responsive to a greater range of motions to extract wave energy while not being so responsive as to allow collision with other devices in an array. This makes it less straight forward to apply existing offshore mooring practices and guidelines. The relative evolving state of WEC mooring technology was highlighted by the failure of two devices' anchoring systems in 2004 and 2010 (Weller et al., 2013).

Appendix D: Lessons from Wind Energy Development

The parallel effort to develop a reliable wind turbine design in the US and Denmark provides a useful crucible to view different technology development approaches. The Danish model ultimately succeeded in producing a reliable wind turbine model that forms the basis for wind turbine designs today.

The history of producing electricity from wind energy dates back to the early 20th century when individual electricity-generating windmills were deployed in rural areas with limited access to the grid. Both in Denmark and the United States (early leaders in wind energy development) rural areas not connected to the electrical grid were important early market drivers. However, scaling up wind energy beyond off-grid applications stalled in the post-war boom years because of cheap fossil fuels and the rapid expansion of the grid (Jones & Bouamane, 2011).

The energy crisis of early 1970s prompted a strong policy interest to promote renewable energy, which was crucial for the emergence of the wind energy industry, a significant driver of renewable energy production worldwide (Jones & Bouamane, 2011). Accordingly, wind only began to penetrate commercial electricity markets in the 1970s: first in Denmark, followed by California in the 1980s, and Spain and Germany in the 1990s (NREL, 2012).

While both Denmark and California were early adopters of commercial-scale wind generation, the countries followed different trajectories in developing their respective industries. In the United States, the 1970s energy crisis prompted a “sudden government intervention into wind energy” that followed an approach taken by the United States Department of Defense to develop aircraft. The department “selected subcontractors to build and test machines that would be commercialized” (Jones & Bouamane, 2011, at 24).

In order to develop the wind industry, DOE primarily selected leading aerospace companies as subcontractors. Between 1973 and 1988, \$380 million of government funding was spent on wind turbine development, compared to \$15 million in Denmark during the same timeframe. The DOE R&D funding was primarily directed towards the development of multi-MW turbines in order to make the technology attractive to utilities (Jones & Bouamane, 2011).

In addition to the heavy investment in R&D with leading aerospace contractors, California’s investment tax credit turned wind energy into a lucrative business opportunity for project developers (Jones & Bouamane, 2011). The California Public Utility Commission (CPUC) established 30-year standard offer contracts in 1982, which required California utilities to make long-term purchase agreements for renewable energy. However, the CPUC stopped requiring these contracts a mere three years later, resulting in fewer utilities signing contracts to buy wind power. (AWEA, 2015). Yet this brief period was enough time to spur a “wind rush” in California. The first large wind projects on Altamont Pass had 6,200 turbines by 1986, totaling 583 MW. However, according to a Harvard Business School study, investment incentives into untested technology resulted in the deployment of unreliable designs:

The problem for most of the California wind companies was the quality of much of their equipment. There was also limited cooperation within the industry on standards and testing. Companies resisted “quality” standards when they were proposed, partly because they feared such standards would require costly design modifications to machines they wanted to sell. The use of untested designs caused many wind farms to experience major reliability problems. In 1986 60 US firms produced turbines, but within three years this had fallen sharply as poorly managed firms struggled under the costs of repairs, warranty issues and complaints (Jones & Bouamane, 2011, at 32).

US efforts slowed in the aftermath of DOE and Department of Defense funding drying up and the California machines largely broke down. Commercialization of wind energy was ultimately the result of a different set of policies in Denmark.

Denmark’s Success

While United States firms saw strong project development and significant investment in the 1980s, Denmark eventually emerged as the global leader in wind turbine manufacturing. Danish turbine manufacturers developed from relatively small agricultural equipment makers that were able to leverage their knowledge of building agricultural equipment for a rural market as they searched for new business opportunities.

Danish firms engaged in “incremental innovation”, applied “collaborative learning networks”, and benefitted from being able to directly service their turbines, which provided additional opportunities to learn and to demonstrate that their technology worked. Additionally, the Danish Wind Turbine Owners Association published performance and reliability data, as well as an annual opinion survey about the quality of the turbines (Jones & Bouamane, 2011, at 23).

The Danish wind turbine technology development process stands in stark contrast to the United States’ approach. The Harvard Business School study notes that “the entry of agricultural machinery manufacturers proved positive for the development of the Danish industry, the entry of US defense contractors and aerospace firms resulted in a technological dead-end... The large turbines that were built experienced multiple technical failures. By the end of the 1980s they had almost all been discontinued” (Jones & Bouamane, 2011, at 26).

However, the success of Danish wind turbine manufacturers was not the result of successful innovation processes alone. Policy also played an important role. US federal spending on the wind industry was scaled back dramatically under the Reagan administration, leaving little legacy from the era of federal support. Government support in Denmark remained consistent over the decades (Grobbelaar, 2010).

Beginning in the 1970s, Denmark initiated comprehensive, prolonged public policy support for the wind industry that continues to this day. The Danish government set aggressive national targets for bringing increasing amounts of wind energy online, combined with market stimulation incentives and sustained R&D funding. Market incentives included a subsidy covering 50% of the total cost for installing a wind

turbine and tax refunds. In 1978, the government established the Risø National Laboratory for Sustainable Energy test station to research and develop turbines for commercial use. Government subsidies for developers were conditioned on the systems being approved by Risø, and those standards are often cited as a primary reason for the success of the Danish wind industry (Grobbelaar, 2010).

In the early stages of wind turbine development, the primary design considerations included horizontal versus vertical blades, rotors oriented upwind versus downwind, and the number of blades. Various designs were experimented with during the 1970s, but the superior design proved to be the 3-bladed, horizontal, upwind turbine. This design was largely a result of the government funded R&D work at Risø, and thus became known as the Danish concept. Consensus was reached in the early 1980s that the Danish concept was the superior turbine design, but optimizing that design in terms of tower height and relative generator and rotor sizes would still take another decade.

As the industry developed in the 1990s, “technological development resulted in commercial production of larger, more efficient turbines. There was an increase in the size of commercial wind farm developments. Whereas in 1995 three-quarters of sales of wind turbines were single or small wind farm sales up to 5 MW, by 2002 nearly 65 per cent of the sales were commercial and utility owned wind farms” (Jones & Bouamane, 2011, at 52).

During that same period, “deployment of wind power is also correlated with significant reductions in the cost of wind-generated electricity. Between 1980 and the early 2000s, wind power installation costs fell by more than 65% in the United States and 55% in Denmark. As a result of these dramatic cost reductions, wind energy, in some parts of the world, has achieved costs that are competitive with prevailing market prices without policy support” (NREL, 2012, at 1). This cost reduction was demonstrated in the declining levelized cost of energy (LCOE) of wind power, falling from more than \$150/MWh to approximately \$50/MWh between 1980s and the early 2000s (NREL, 2012).

The Danish experiences suggest that sustained government support for determining a reliable design was key. Further commercialization was accomplished through incrementally larger and better designs by a diversity of technology developers who were able to find sufficient funding to build and prove out their early designs. A tipping point seems ultimately to be met where the cost of the resource, though still high, finds sufficient markets to sustain continued design improvements through market competition that ultimately led to a low cost power source.

Lessons from Other Offshore Energy Sectors

While the offshore renewable energy industry operates under different constraints and conditions (such as siting locations and required motion allowances) than the offshore oil and gas industry, it has had the opportunity to draw on knowledge and experience from that industry. This includes not only mooring and anchoring technology and system design, and protection against corrosive sea water, but also device performance modeling (which can also draw on wind turbine power-train and power take-off system designs. This is relevant because both wind and wave generators produce electricity from a variable resource).

Appendix E: Early Wave Energy Developments

While there are several wave energy patents that are hundreds of years old, and oscillating water columns to power navigation buoys were first commercialized in Japan in 1965, commercial electricity generation from wave energy was not seriously pursued until the global energy crisis of the 1970s. During that period Japan, Norway, and the United Kingdom became early developers of wave energy devices, with the United Kingdom Department of Energy launching its research program in 1975 and producing a prototype in 1978 (McCormick, 1981).

The first full-scale (2.5 MW oscillating wave column) device was deployed in Japan in 1980. The Kaimei platform was made possible by a collaboration between the Japan Agency Marine-Earth Science and Technology Center and International Energy Agency (IEA) members Canada, Ireland, Norway, Sweden, the United Kingdom, and the United States. The Japan Agency Marine-Earth Science and Technology Center's R&D program for wave energy was established in the 1970s and continues to this day (Bhattacharyya, 2003).

The United States' contribution to the Kaimei project accounted for most of the DOE's early funding for wave energy. Between 1979 and 1996, the DOE spent approximately \$240 million on its ocean energy program. Only approximately \$1.5 million was devoted to wave-related activities, with two-thirds of that amount spent on building and testing a prototype 125 kW counter-rotating air turbine as part of the IEA's contribution to the Kaimei project (Bhattacharyya, 2003). The Kaimei test program did not, however, end up achieving successful power output levels at this early stage of WEC technology development.

By 1981 there were over 1,000 WEC patents on file in Japan, North America, and the United Kingdom, reflecting nine basic mechanisms mirroring the basic features of the devices that are available today, although at that time a different terminology was applied (McCormick, 1981).

Policy support for wave energy development in Europe began to slow in the early 1980s. The UK's government-sponsored R&D program was significantly reduced, and progress on many of the devices that had been started in the 1970s stopped altogether without this needed support (Bhattacharyya, 2003). Government funding in Norway also peaked in 1980 and declined in the following years, which also caused a decrease in device development. Norway did succeed in deploying two wave energy devices that began supplying electricity to the grid in 1985 on the peninsula of Toftestallen (Bhattacharyya, 2003). The test sites were, however, destroyed a few years later by storms.

Wave energy development in Europe received a significant boost in 1991 when the European Commission (EC) decided to include wave energy in their renewable energy R&D program (Bahaj, 2012). The EC has since funded more than 30 projects, a number of which involved collaboration between international teams. The European Union (EU) also provides an additional layer of support through the JOULE program, which prioritizes research of non-nuclear energy (Bhattacharyya, 2003). This supranational support has significantly bolstered wave energy development in Europe.

Policy support in the UK began to rise again in the late 1990s following reports about the need to reduce carbon and the potential value of exporting wave energy devices. A shoreline-based oscillating water column device called LIMPET came online in 2000 with a 15-year agreement to supply electrical power to major public utilities in Scotland (Bhattacharyya, 2003). Portugal also deployed a shore-mounted oscillating water column off the tiny island of Pico, thanks to a collaboration between universities, the two island utility companies, and funding from the EU (Bhattacharyya, 2003).

Initially most wave power devices were located near the coast, but deep water offshore methods were being considered by the early 2000s (Bhattacharyya, 2003). In 2001, the IEA established an Implementing Agreement on Ocean Energy Systems (IEA-OES, presently with 18 member countries). Its mission is to facilitate ocean energy research and development as well as demonstration projects through international cooperation and information exchange (Bahaj, 2012).

Appendix F: Technology Preparedness and Readiness Levels

According to Jochem Weber's framework, the cost of developing a system increases with each TRL, as larger and more advanced systems and prototypes are tested. If focusing on increasing TRL levels is limited to solving operational issues associated with the technology and not on performance issues, a technology developer may need to readdress system fundamentals after reaching advanced TRL levels.

Moving up TPLs theoretically does not increase development costs as steeply as increasing TRLs. While theoretically it would be optimum to develop a technology system to the highest TPL first, and then focus on increasing TRL, this may not be practical. A survey of current wave energy technology suggests that developers are pursuing a TRL-first trajectory. Accordingly, developers may be best suited to develop their technologies by first focusing on TPL and moving to TRL at an intermediate stage (Weber, 2012).

TRL #	Characteristics ⁵⁷	TPL #	Characteristics ⁵⁸
9	An actual system has operated over the full range of expected environmental conditions and is ready for commercial trials. For wave energy this would include open-water testing of multiple device arrays.	7-9	Technology is economically viable and competitive as a renewable energy form
7-8	The system is shown to work in its final form. This would include testing of a final full-scale device in open water.		
6	Engineering-scale devices are tested in relevant required operating conditions. For wave energy this would require a small scaled device to be tested in open water.	4-6	Technology features some characteristics for potential economic viability under distinctive market and operational conditions. Technological or conceptual improvements may be required.
5	Technology components are integrated and a scaled device is tested in laboratory conditions. For wave energy devices this could include device prototype testing in a wave tank.		
4	First step in the engineering phase of device development. At this level there should be a physical demonstration that the components of the device will work together.	1-3	Technology is not economically viable
1 - 3	At these stages the concept is discovered and initial observations about the concepts viability to produce energy outputs are tested in a laboratory environment.		

⁵⁷ Adapted from: DOE (U.S. Department of Energy). (2011b).

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⁵⁸ Characteristics quoted from: Weber, 2012, p. 3.

Appendix G: List of United States Wave Energy Technology Developers

State	Company	Device	TRL	DOE Funding (\$) ⁵⁹
CO	Atargis Energy Corporation	Cycloidal Wave Energy Converter: fully submerged device vertical axis propeller	4	400,000
VA/OR	Columbia Power Technologies, Inc	StingRAY: Hybrid design	5/6	8,400,000 ⁶⁰
CA	Ecomerit Technologies, LLC	Centipod: Point Absorber	N/A	500,000 ⁶¹
OR	M3 Wave Energy Systems	APEX: Submerged pressure device	5/6	240,000
OR	Northwest Energy Innovations	Azura: Point absorber	5/6	2,517,519
NJ	Ocean Energy Industries	WaveSurfer: Point absorber	N/A	-
CA	Ocean Energy USA, LLC	OE Buoy: Oscillating water column buoy	N/A	991,662
OR	Ocean Motion International	OMI Combined Energy System: Point-absorber high pressure water pump	3	-
NJ	Ocean Power Technologies, Inc	Powerbuoy: Point absorber	N/A	9,277,293
WA	Oscilla Power, Inc	Triton: Multi-mode point absorber	4	1,300,000 (SBIR) ⁶²
TX	Resen Waves	Lever Operated Pivoting Float: Point absorber	N/A	-
MA	Resolute Marine Energy	SurgeWEC: Wave surge converter	6	1,235,225

⁵⁹ Figures taken from (DOE, 2014a) unless otherwise noted.

⁶⁰ This figure includes SBIR funding in addition to grants from the DOE Water Power Program.

⁶¹ Not recorded in (DOE, 2014a), but noted on United States: DOE (U.S. Department of Energy website at : www1.eere.energy.gov/water/m/news_detail.html?news_id=19575 - last accessed May 8, 2015.

⁶² See: SBIR Source. (2014). Oscilla Power Inc. SBIR Award Summary. Retrieved from www.sbirsource.com/sbir/firms/24351-oscilla-power-inc - last accessed May 8, 2015.

Appendix H: The Oregon Territorial Sea Plan Amendment

In 1991 the Oregon Legislature established the Ocean Policy Advisory Council (OPAC), which is composed of ocean stakeholders, local governments, and state agencies, in order to provide the state government with input on policy matters related to the ocean. The legislation also gave the Department of Land Conservation and Development (LCDC) authority for marine planning and assisting OPAC. OPAC was tasked with drafting the Oregon TSP for managing the resources in Oregon's territorial sea. In 2013 the TSP was amended to include Part 5, which addresses the siting of marine renewable energy projects within Oregon's Territorial Sea.

Under the TSP Amendment, LCDC coordinates the review of applications for marine renewable energy projects by convening a Joint Agency Review Team (JART), composed of representatives of the Departments of Fish and Wildlife, Parks and Recreation, Environmental Quality, Land Conservation and Development, Water Resources, Geology and Mineral Industries and Energy, as well as coastal local governments, and federal agencies, and allows for the invitation of local interest groups and advisory committees during deliberations on permit applications.⁶³

The amendment also designated REFSSA areas, with the least stringent siting guidelines. The designation of REFSSAs followed an extensive public hearing process, which was led by LCDC and OPAC. The two bodies conducted public hearings starting in 2010 and reviewed documentation including fishing maps, marine ecosystem maps, seafloor maps, and recreational use surveys. The REFSSA areas were established in areas that were sought to have a minimal impact on ecological, economic and social marine resources, and were suitable for wave energy technologies.

The REFSSAs and review standards were developed in line with Goal 19 of Oregon's Statewide Planning Goals and Guidelines to "conserve marine resources and ecological functions for the purpose of providing long-term ecological, economic, and social value and benefits to future generations,"⁶⁴ and follow Governor Kulongoski's Executive Order of March 2008, requiring the amended TSP to "identify appropriate locations for future wave energy projects that minimize adverse impacts to existing ocean resources and resource users."⁶⁵ In early 2008 FERC and the State of Oregon signed a memorandum of understanding in order to "coordinate the procedures and schedules for review of proposed wave energy projects in the Territorial Sea of Oregon."⁶⁶

⁶³ The review of the TSP amendment is based on an examination of the "Findings on the Adoption of an Administrative Rule to Amend the Oregon Territorial Sea Plan, Department of Land Conservation and Development: 14 January (DLCD, 2013.)."

⁶⁴ Oregon's Statewide Planning Goals & Guidelines, GOAL 19: OCEAN RESOURCES, OAR 660-015-0010(4).

⁶⁵ Office of the Governor, State of Oregon: Executive order No 08-07, p. 1.

⁶⁶ Memorandum of Understanding between the Federal Energy Regulatory Commission and the State of Oregon, 26 March, 2008, p. 1.

Subject Matter Experts Interviewed

This report was informed by interviews with subject matter experts in the Pacific Northwest Wave Energy community. The study authors are grateful to the respondents who made themselves available for conversations. The findings and conclusions of this report do not necessarily reflect the views of the individuals (or those of the organizations in which they work). Organizations from which current or former employees were interviewed include:

Bonneville Power Administration

Columbia Power

DNV-GL

EDP Renewables

Energy Trust of Oregon

M3 Wave LLC

Northwest National Marine Renewable Energy Center

Northwest Energy Innovations

Oscilla Power

Oregon Department of Land Conservation

Pacific Northwest National Laboratories

PacifiCorp

PNGC Power

Portland General Electric

Principle Power

Resolute Marine Energy

Snohomish Public Utility District

United States Department of Energy

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Selected Annotated Bibliography

This annotated bibliography describes some of most important sources of information used in this report. It does not include all 40 studies that are noted in the comprehensive bibliography, but focuses on the frequently cited sources, or reports that are otherwise considered particularly noteworthy. While some of the studies annotated here may overlap on issue areas, they are presented here according to the report sections where they have been most useful to the authors.

The Wave Power Resource

EPRI. (2011). *Mapping and Assessment of the United States Ocean Wave Energy Resource*. Palo Alto, California.

This report by the Electric Policy Research Institute seeks to quantify the available and recoverable wave energy resource in the United States by using wave energy hind-cast model (wave energy data modeled using other available weather observations) projections over a 51-month period. The study provides information on how much wave energy is available on a state and regional basis in the United States, as well as how much wave energy can be recovered using current technology at both the United States' inner and outer continental shelf. The report's methodology also touches on relevant topics, such as device spacing within wave energy arrays and wave power curves.

Parkinson, S., Dragoon, K., Reikard, Garcia-Medina, G., Ozkan-Haller, T., & Brekken, T. (2015). *Integrating ocean wave energy at large-scales: A study of the US Pacific Northwest*. *Renewable Energy*, 76, 551-559.

This paper is a study of wave energy integration costs, and resource and production variability in Oregon. It is a version of a study that was originally commissioned by OWET. The study evaluates the variability of wave energy production under a range of timeframes and wave energy device array configurations, as well as combinations of arrays operating along the Oregon coast. The study uses actual wave conditions for energy production simulations and variability evaluations, and generates hypothetical, modeled energy production schedules in order to evaluate forecast errors and associated integration costs. It concludes that wave integration costs are low compared with wind integration costs for equivalent amounts of energy, and that wave generation is more predictable than wind.

Wave Energy Converter Technologies and Wave Energy Industry

Aquatera Ltd. (2014). *Oregon Wave Energy Supply Chain Analysis*. Stromness. Portland, Oregon.

This report was prepared by Aquatera, Ltd for OWET in 2014 to examine supply chain requirements for the proposed NNMREC grid-connected test site on the Oregon coast, to evaluate the status and future supply chain to meet the test site's demands, and identify strategies to fill any gaps. The study builds on a previous OWET-commissioned report that investigated infrastructure and supply chain capacity in Oregon

to support commercial wave energy project deployment generally. While the previous study focused broadly on technology specifications, port specifications, roads and rail links, among other issues; this report focuses on the specific needs of the test site, broadens the scope of the supply chain, and draws on recent experience at the European Marine Energy Center. The report provides useful insight into industry maturity, the wave energy supply chain, policy players, R&D efforts, certification of wave energy devices, and wave energy cost drivers.

CSIRO. (2012). *Ocean Renewable Energy 2015-2050: An Analysis of Ocean Energy in Australia*. Dickson, Australia.

This comprehensive Australian National Science Agency report explores the potential for Ocean Renewable Energy (ORE) to provide significant amounts of renewable energy in Australia by 2050. The extensive analysis covers the basic mechanism of ORE extraction, including basic physics and mechanical options for wave energy conversion. It also covers an industry breakdown by country (providing then-current lists of companies and country-specific policy support) and provides an overview of the challenges in developing ORE projects, including competing uses of ocean resources, energy output variability and forecasting, and converter design considerations.

Garrad Hassan. (2013). *Market Analysis Report For the Pacific Marine Energy Center South Energy Test Site*. Portland, Oregon.

This report was commissioned by OWET to conduct a wave energy market analysis in order to identify potential users for the newly proposed NNMREC grid-connected test facility on the Oregon coast, and to evaluate their needs. The findings of the report were intended to inform infrastructure design and services offered at the proposed test site. The report was laid out in three parts and includes a wave energy sector profile (including current and future needs of the industry), a section on stakeholder consultation (surveys and interview results drawn from a pool of 37 potential users), and gap analysis (comparing stakeholder consultation results with current SETS plans).

Marine Energy Matters. (2015). *Marine Energy Global Technology Review 2015*. Devon, United Kingdom.

This global market review covers both wave energy and tidal energy companies. The industry status update, which MEM has been conducting since 2009, is based on literature reviews and discussions with industry insiders. The report includes an update on the most significant industry development and data on the relative number of wave energy companies in operation since 2009 (including the countries in which they are active), as well as the device types being pursued by the companies. The short report also includes analysis of industry trends.

Ocean Energy Systems. (2014). *Implementing Agreement on Ocean Energy Systems Annual Report*. Paris, France.

The annual report for 2014 of Ocean Energy Systems (the International Energy Agency's ocean energy technology initiative) is largely a descriptive report about the agency's 2014 activities. In addition, it contains a section in which three ocean energy developers answer questions regarding the process of commercializing their technologies. It also includes country reports for each of its member-countries. The country reports were drafted by agencies of that country (for example, the US report was drafted by the US DOE), and include insight into the policy and industry developments there.

Pacific Energy Ventures. (2009). *Utility Market Initiative: Integrating Oregon Wave Energy into the Northwest Power Grid*. Portland, Oregon.

This comprehensive document was commissioned by OWET in 2009 and includes an assessment of the wave energy resource in Oregon, the electricity marketplace, and grid interconnection opportunities. The report is a compendium of studies created by Pacific Energy Ventures, Ecofys, the Electric Power Research Institute, Energy Focused Resources, Groundswell Energy, Garrad Hassan, Loren Baker Consulting, and Powertech Labs. The study addresses wave energy technology status, the Oregon wave energy resource, wave energy standards, interconnection rules, the level of wave energy that can be integrated into Oregon's electrical grid, and technical and operational barriers.

PG&E (Pacific Gas & Electric). (2011). *PG&E WaveConnect Program Final Report*. San Francisco, California.

This report was drafted by the California utility Pacific Gas & Electric after it discontinued its United States Department of Energy and rate-payer funded WaveConnect project in Northern California. The report provides an in-depth review of the utility's experience in pursuing the wave energy facility, and includes insights and lessons-learned on issues including site selection, permitting, stakeholder concerns, and industry readiness.

Wave Energy Technology Development

Bhattacharyya, R. (2003). *Elsevier Ocean Engineering Book Series, Volume 6: Wave Energy Conversion*. Melbourne, Australia.

This book explains the concepts behind wave energy and provides an overview of converter device types. It also provides a comprehensive summary of key industry developments by country, beginning in the 1970s up to the early 2000s. Supportive policy is cited as the driving factor for most countries' wave energy activity. The book concludes that wave energy is currently only competitive in niche markets, but the industry is still in its infancy. Notable niche markets include power for isolated coastal communities, desalination plants, and navigation buoys. Further innovation and technological development is required before it can be introduced on a large scale in the general energy market.

Jones, G. & Bouamane, L. (2011). *Historical Trajectories and Corporate Competences in Wind Energy*. Harvard Business School. Cambridge, Massachusetts.

This paper provides a historical account of the wind turbine industry. It focuses primarily on Denmark and the United States, where rural areas without grid access prompted early innovators to develop wind turbines in the 20th century. The national governments of both countries took a renewed interest in wind energy after the 1970s oil crisis, yet each took a different path to developing the industry. While Denmark invested in long-term research and funding, support in the US was more sporadic and focused less on design standards. Sustained policy support in Denmark resulted in the “Danish concept” (the horizontal, 3-blade design) becoming the global industry standard. Modern history includes the entry of Germany, Spain, and China as major industry players, also supported by favorable policy.

Weber, J. (2012). *WEC Technology Readiness and Performance Matrix – Finding the Best Research Technology Development Trajectory*. 4th International Conference on Ocean Energy, Dublin.

This study was released for the 2012 International Conference on Ocean Energy by the wave energy company WaveBob. The report provides a wave energy technology assessment framework that is complementary to the widely applied Technology Readiness Levels (TRL). The introduced concept is a measure of Technology Performance Level (TPL), which is inversely related to the cost of energy. The paper introduces technology development strategies taking into account both TRL and TPL levels. The purpose of distinguishing between TRLs and TPLs is to develop what Weber believes are more optimal paths to commercialization.

Regional Industry Drivers

ECONorthwest. (2009). *Economic Impact Analysis of Wave Energy: Phase One*. Portland, Oregon.

This study was commissioned by OWET and conducted by the consulting firm ECONorthwest in order to evaluate the potential economic impacts of developing a wave energy industry in Oregon. The study applied an input-output model to evaluate economic benefits of a three-stage wave energy industry development in Oregon, including an R&D stage, a commercial project stage, and an industrial stage. Economic impacts were evaluated on the basis of total industrial output, employee wages, business income, taxes, and jobs created.

ODOE (Oregon Department of Energy). (2014). *Marine Transmission in Oregon: Report to the Oregon Legislature*. Salem, Oregon.

This report was drafted by the Oregon Department of Energy in response to a request by the Oregon Legislature in 2013 SB606 (an Act that also addresses financial assurances for the removal of marine energy devices). The report focuses on issues related to the transmission of electricity from wave energy facilities and devices, and addresses opportunities for ownership and financing of transmission lines, barriers to development, costs and benefits of consolidated transmission capacity, and risk management of decommissioning transmission lines.

Barriers to Commercialization

Carbon Trust. (2011). *Accelerating Marine Energy*. London, England.

This report by a British nonprofit is primarily focused on the barriers to developing marine energy in the United Kingdom, with applicable information for the industry globally. It identifies the biggest challenge to be lowering the cost of generating energy, provides a breakdown of the various cost components, and outlines ways the cost of energy could be reduced: through developing better, more efficient devices. The report argues that with supportive policies to spur technological innovation, wave energy could be competitive with other renewables by the mid-2020s.